Environmental & Water Quality Operational Studies

TECHNICAL REPORT E-82-9

SUPERSATURATION OF NITROGEN GAS CAUSED BY ARTIFICIAL AERATION IN RESERVOIRS

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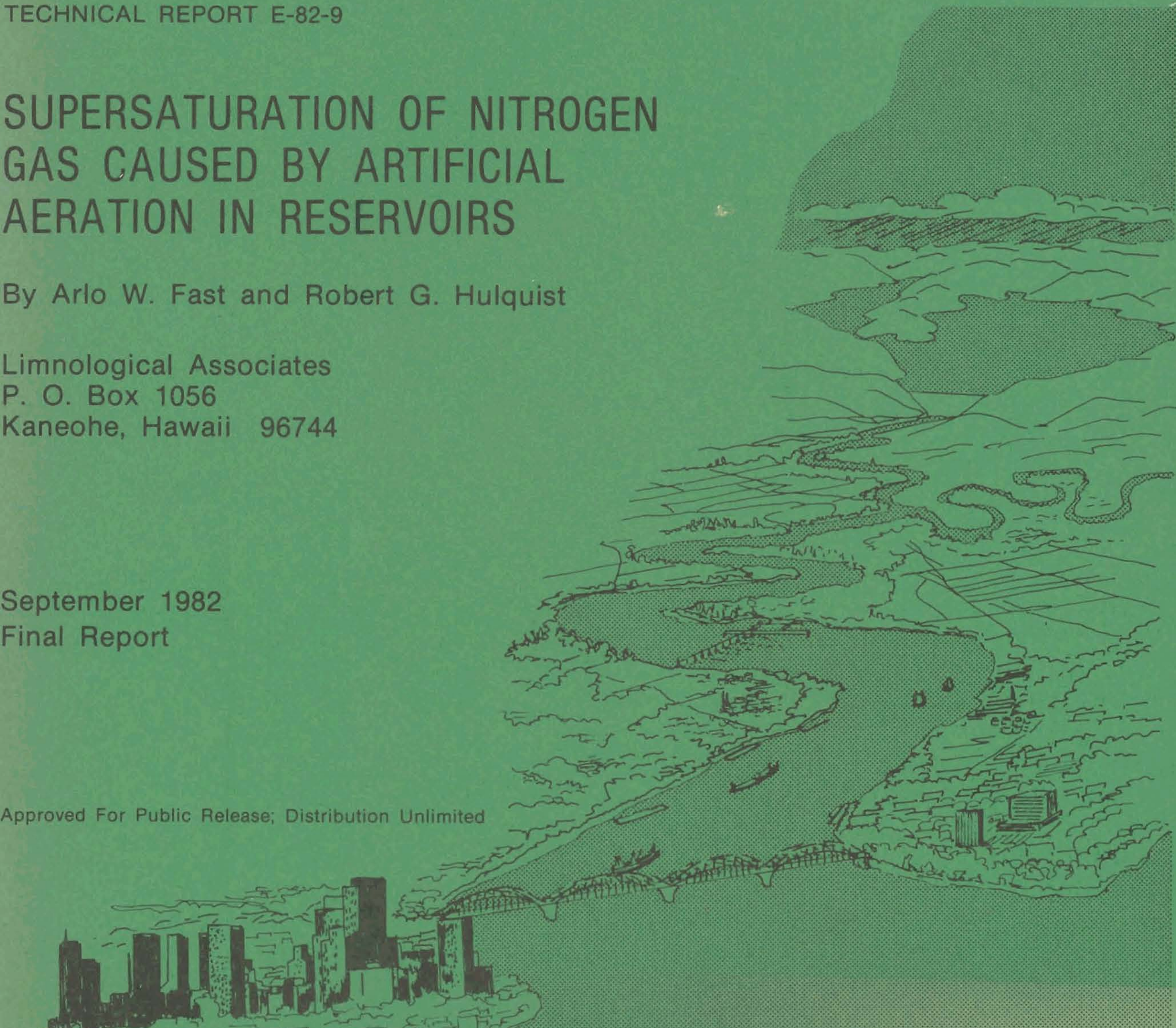

September 1982
Final Report

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Contract No. DACW39-79-M-2666
(EWQOS Work Units IIIB.1 and IIIB.4)

Monitored by Hydraulics Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report E-82-9	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SUPERSATURATION OF NITROGEN GAS CAUSED BY ARTIFICIAL AERATION IN RESERVOIRS		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Arlo W. Fast Robert G. Hulquist		8. CONTRACT OR GRANT NUMBER(s) DACW39-79-M-2666
9. PERFORMING ORGANIZATION NAME AND ADDRESS Limnological Associates P. O. Box 1056 Kaneohe, Hawaii 96744		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS EWQOS Work Units IIIB.1 and IIIB.4
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE September 1982 13. NUMBER OF PAGES 134
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Hydraulics Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aeration
Nitrogen
Reservoir stratification
Reservoirs

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Dissolved nitrogen gas (N_2) contents of 12 southern California reservoirs were assessed during the summer of 1979. Eleven of the reservoirs were artificially destratified by compressed air injection at depths, while one reservoir was not artificially aerated. Destratification ranged from nearly complete to quite incomplete.

The artificially aerated reservoirs could be categorized into four types
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20. ABSTRACT (Continued).

of conditions based on their degrees of destratification and their dissolved N_2 depth profiles.

a. Type I reservoir conditions were characterized by nearly uniform oxygen and temperature conditions at all depths and N_2 saturations between 100 and 110 percent.

b. In Type II reservoirs, the air diffuser was not placed at the deepest depth. Consequently, a thorough mix occurred above the diffuser resulting in N_2 saturations which were 100 to 110 percent; however, strong thermal and chemical stratification persisted below the diffuser where N_2 saturations could exceed 140 percent.

c. Type III reservoir conditions occurred when insufficient air was injected to cause a thorough mix; consequently, there was a shallow thermocline near the lake's surface below which were uniform temperatures. Under Type III conditions, N_2 saturations normally ranged from 106 to 120 percent below the thermocline.

d. Type IV reservoirs had a combination of Type II and III conditions where the air diffuser was placed above the bottom and insufficient air was injected to cause a thorough mix above the diffuser depth. Under Type IV conditions, N_2 saturations also represented a combination of Type II and III conditions.

With all types, N_2 saturations often increased even though absolute N_2 concentrations decreased. This was caused by an incomplete degassing of the deep waters as it was warmed during destratification.

Although there is a general relationship between the types of conditions and N_2 saturations, there are no general procedures for predicting N_2 saturations.

SUMMARY

1. During June through October 1979 we surveyed 11 southern California reservoirs for their dissolved nitrogen gas (N_2) content. Ten of these eleven reservoirs were artificially destratified by air injection. In addition, we obtained 1978 and 1979 N_2 measurements for Lake Casitas, California. Lake Casitas was artificially destratified by air injection both years.

2. We observed N_2 saturations of 110 percent or more in 10 of the 11 aerated reservoirs. N_2 saturations in the only nonaerated reservoir did not exceed 104 percent. N_2 saturations in 5 of the aerated reservoirs exceeded 115 percent.

3. Nitrogen gas saturations were not excessively elevated in situ in any of the reservoirs because hydrostatic pressure reduced the "absolute" saturation values to acceptable levels, although deepwater N_2 was excessively supersaturated relative to surface pressures in certain aerated reservoirs.

4. We did not observe, nor do we expect problems with N_2 supersaturations within a reservoir. However, in some cases, downstream releases from intermediate or deep waters could possibly cause fish mortalities in the receiving stream.

5. None of the reservoirs that we surveyed had significant amounts of intermediate or deepwater releases. Based on N_2 saturations only, had such releases occurred without adequate degassing through the release structure, we would have expected gas bubble disease mortalities in the receiving streams of at least 5 of the 11 aerated reservoirs. In these cases, N_2 saturations could have ranged between 120 and 140 percent. However, in most of the cases where N_2 saturations exceeded 120 percent, dissolved oxygen concentrations were also very low and possibly would have been lethal as well.

6. Artificially destratified lakes typically exhibit one of four general types of conditions in regard to their thermal stratification. The resultant type of condition is related primarily to the amount of air injected per unit water volume and the diffuser depth relative to maximum depth. The type of condition seems to exert an important

influence on N_2 saturations and the depth distribution of N_2 gas.

7. We observed the highest N_2 saturations in aerated reservoirs where the diffuser was not placed in the deepest location, and consequently a volume of water existed below the diffuser which was not apparently circulated upwards or mixed with shallower water. N_2 saturations in these deep waters sometimes exceeded 140 percent.

8. Nitrogen gas supersaturations below the diffuser depth were probably caused by the injected air. However, nitrate (NO_3) denitrification or the inflow of groundwater supersaturated with N_2 could also account at least in part for the N_2 supersaturations.

9. Several reservoirs exhibited decreased subsurface N_2 concentrations during destratification, yet N_2 saturations increased. This was apparently due to N_2 absorption from the injected air without a thorough degassing at the lake's surface. However, penetration of solar irradiance into deeper water, and the consequent warming of this water, could have also contributed to N_2 saturation increases.

10. A very thorough mix, with a temperature difference between the surface and bottom of 1Π C or less, usually results in N_2 saturations of 110 percent or less.

11. The most important factors causing excessive N_2 saturations during artificial aeration, seem to be:

- a. Degree of thermal destratification. A weak mix is associated with higher N_2 saturations.
- b. Absolute depth of air injection. Deeper air injection has a greater potential for N_2 supersaturation than shallow air injection.
- c. Air injection at intermediate depth. Air injection at an intermediate depth creates a substantial risk of N_2 saturations below the diffuser depth that are in excess of the N_2 saturations at or above the diffuser depth.
- d. Air density in the bubble plume. Low air density creates a lower vertical velocity in the upwell plume, which increases the contact time between the air bubbles and the water. More importantly, it may prevent the plume from reaching the lake's surface. Instead, the air bubbles uncouple from the upwell plume and continue their rise to the surface, while the deep water flows out below the thermal gradient and does not surface.

PREFACE

The study reported herein was sponsored by the Office, Chief of Engineers, U. S. Army, as part of the Civil Works General Investigations, Environmental and Water Quality Operational Studies (EWQOS) Program. The work units entitled "Evaluate the Effectiveness of Existing Reservoir Mixing/Destratification Techniques" (IIIB.1) and "Evaluate the Effectiveness of Reservoir Aeration/ Oxygenation Techniques" (IIIB.4) supported the subject study.

The study was conducted during the period April 1979 to April 1980 under contract by Limnological Associates. Messrs. J. P. Holland, D. H. Merritt, and M. S. Dortch of the Reservoir Water Quality Branch (RWQB), Hydraulic Structures Division, Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), and Dr. D. R. Smith, Chief, RWQB, monitored the effort. This report was written by Dr. Arlo W. Fast and Mr. Robert G. Hulquist (Dr. Fast's present affiliation is with the Hawaii Institute of Marine Biology, University of Hawaii at Manoa). Program Manager of EWQOS was Dr. J. L. Mahloch.

Directors of WES during this study and the preparation of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Fred R. Brown.

This report should be cited as follows:

> Fast, A. W. and Hulquist, R. G. 1982. "Supersaturation of Nitrogen Gas Caused by Artificial Aeration in Reservoirs." Technical Report E-82-9, prepared by Limnological Associates, Kaneohe, Hawaii, for U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

The inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	40.46873	hectares
acre feet (AF)	1233.489	cubic metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
horsepower (electric)(3)	746.0	watts
miles (U. S. statute)	1.609347	kilometres
standard cubic feet per minute (SCFM)	0.0004719474	standard cubic metres per second
square feet	0.09290304	square metres
torr (mmHg, 0°C)	133.322	pascals

SUPERSATURATION OF NITROGEN GAS CAUSED BY ARTIFICIAL AERATION IN RESERVOIRS

PART I: INTRODUCTION

1. Excessive dissolved gas saturation can cause substantial fish mortality. Juvenile salmonid mortalities in the Snake and Columbia Rivers have ranged between 40 and 95 percent due to excessive nitrogen gas (N_2) saturation which was caused by spillway releases into deep tailwaters (Ebel and Raymond 1979). These mortalities were especially important since the Columbia River drainage produces about 42 and 73 percent, respectively, of the entire U. S. commercial chinook salmon and steelhead trout catches.

2. Biological problems caused by excessive gas saturations are collectively called "gas bubble disease." Bouck (1980) defines gas bubble disease as "...a noninfectious, physically induced process caused by uncompensated hyperbaric pressure of total dissolved gases." Although total dissolved gases are the important determination, N_2 saturation is the principal factor in most cases.

3. Bouck (1980) also discusses the difficulties associated with defining "safe" N_2 saturation levels. In some cases, 115 percent or more is safe; however in other situations 105 percent or less is not. Definition of a safe level requires a case-by-case evaluation, even though the U. S. Environmental Protection Agency (1976) recommends that total dissolved gas pressure in water "...should not exceed 110 percent." Weitkamp and Katz (1980) have conducted a thorough review of one biological problem associated with gas supersaturation. Their review documents the causes and extent of this problem.

4. Both barometric pressure (pressure of atmosphere) and hydrostatic pressure (pressure of overlying water column) dictate gas saturation levels. For example, the total pressure on gases at the 10-m depth (33 ft) is twice that of gases at the lake's surface. Consequently, the water at the 10-m depth can hold twice as much gas without absolute supersaturation (supersaturation at depth) compared with surface waters.

However, if water which is 100 percent absolute saturated at the 10-m depth is brought to the surface without degassing, it would be 200 percent saturated with respect to absolute saturation at the surface. Throughout this report we will refer to gas saturation values relative to surface pressures rather than absolute saturation at depth. That is, we will refer to gas saturation as if the water were brought to the lake's surface with no degassing. This concept is most important since N_2 is seldom highly supersaturated in situ in a lake, although it is often supersaturated relative to surface pressures.

5. Artificial aeration of lakes and reservoirs is a potential source of nitrogen gas supersaturation. These impoundments are often injected with compressed air to reduce or eliminate oxygen depletions and other undersirable conditions associated with eutrophication (American Water Works Assoc. 1971). Eutrophication is caused by excessive plant nutrients such as phosphorus, and it can lead to excessive algal growth and anaerobic bottom waters. Hydroelectric facilities usually have intake levels that are deep in the pool and therefore may release water that is low in dissolved oxygen (DO). Unpleasant odors and fish kills downstream have resulted from such discharges. Therefore, artificial aeration is a possible solution to this low oxygen discharge problem. This approach, however, inherently introduces N_2 into the impoundment which, for intermediate or lower depth releases that undergo inadequate degassing, may result in elevated levels of N_2 downstream.

6. The effects of air injection on N_2 saturation in reservoirs has been poorly documented. We know of only two such studies. Fast et al. (1975) measured N_2 saturations during hypolimnetic aeration at Lake Waccabuc, New York, and Fast (1980, 1979a, b) measured N_2 saturations during the artificial destratification of Lake Casitas, California. Hypolimnetic aeration by air injection caused 150 percent N_2 saturations in the hypolimnion of Lake Waccabuc after 80 days of aeration (Figure 1). The lake was aerated with a submerged aerator, and the authors speculated that even greater N_2 supersaturations were likely with deeper lakes or with longer aeration periods. Significant N_2 supersaturation did not occur in situ within Lake Waccabuc due to hydrostatic pressures, nor were there any observed problems with gas bubble disease in the biota.

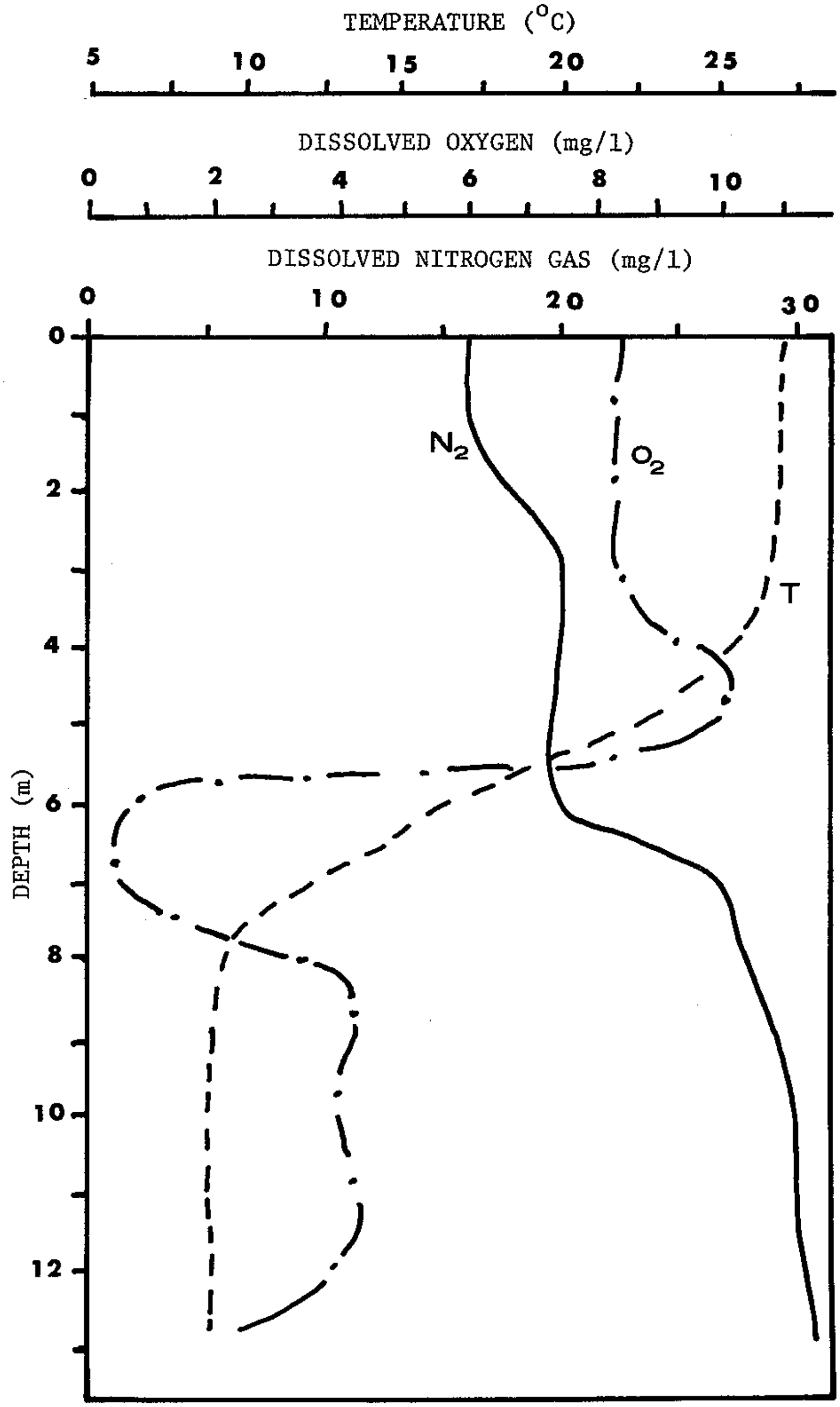

Figure 1. Temperature, oxygen, and dissolved nitrogen gas values at Lake Waccabuc, New York, during 1973 (Fast et al. 1975)

7. At Lake Casitas, N_2 saturations in excess of 140 percent occurred below the diffuser depth during destratification by air injection. Again, significent N_2 supersaturation did not occur in situ, nor were any fish mortalities observed.

8. Allatoona Reservoir, Georgia, is the only reservoir that we know of which has both bottom releases into a receiving stream and is being destratified by air injection (Raynes 1979). Although large quantities of water are released through the hydroelectric facility at Allatoona, no gas bubble disease symptoms have been observed in the tailwater trout fishery (Raynes, personal communication). Although N_2 saturation was not measured either in the reservoir or discharges, this lack of observed fish mortalities seems to indicate that at least in some cases artificial aeration can be used without causing fish deaths in the receiving stream.

9. During our study, we surveyed 11 southern California reservoirs that were aerated by air injection. We also surveyed one nonaerated reservoir. These reservoirs varied greatly in volume, air injection rates, air injection depths, degrees of destratification and eutrophic conditions. We wished to (a) determine the extent of N_2 supersaturation in aerated reservoirs and (b) identify the most important parameters associated with N_2 supersaturation. Our primary goal was to provide further insight into the N_2/aeration problem, and by so doing help the development of predictive methods and suitable aeration techniques.

PART II: METHODS

10. Nitrogen gas was measured in situ with a new tensiometer described by D'Aoust et al. (1975) and Fickeisen et al. (1975). A special probe (Figures 2 and 3) was lowered to the desired depth and allowed to equilibrate with the total dissolved gases. Other gases were measured directly or indirectly and subtracted from the tensiometer reading to yield concentrations of nitrogen gas (N_2) plus argon gas (Ar) by difference.

11. We allowed the tensiometer probe to equilibrate for at least 10 minutes at each depth before total gas pressure was measured. Temperature was measured with a Yellow Springs Instrument (YSI) dissolved oxygen meter, while dissolved oxygen was measured using a modified Winkler technique. Fast (1971) describes the oxygen measurement techniques in more detail.

12. Some temperatures during the June survey were measured with the tensiometer thermister. However, this thermister was later found to be inaccurate, and temperatures were thereafter measured only with the YSI thermister. A correction curve between the YSI and tensiometer readings was constructed, and the tensiometer temperature readings were corrected.

13. Barometric pressure was measured at each reservoir with the tensiometer (out of water) and compared with either theoretical values (average sea level pressure adjusted for elevation at the reservoir) or observations from a nearby weather station. If the tensiometer values were substantially different from the theoretical or the weather station's, we then used the theoretical or weather station values. We also corrected the observed tensiometer readings at depth by the difference between the barometric value used and the tensiometer value out of water. We used a constant correction value for all measurements at a given reservoir on a given date. Theoretical barometric pressure was calculated based on an average sea level pressure of 760 mmHg, and a pressure

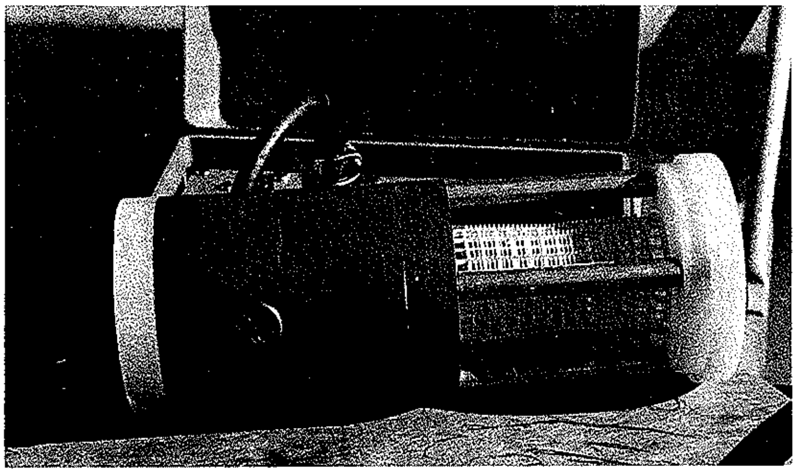

Figure 2. Submersible tensiometer probe used to measure total gas pressure in situ

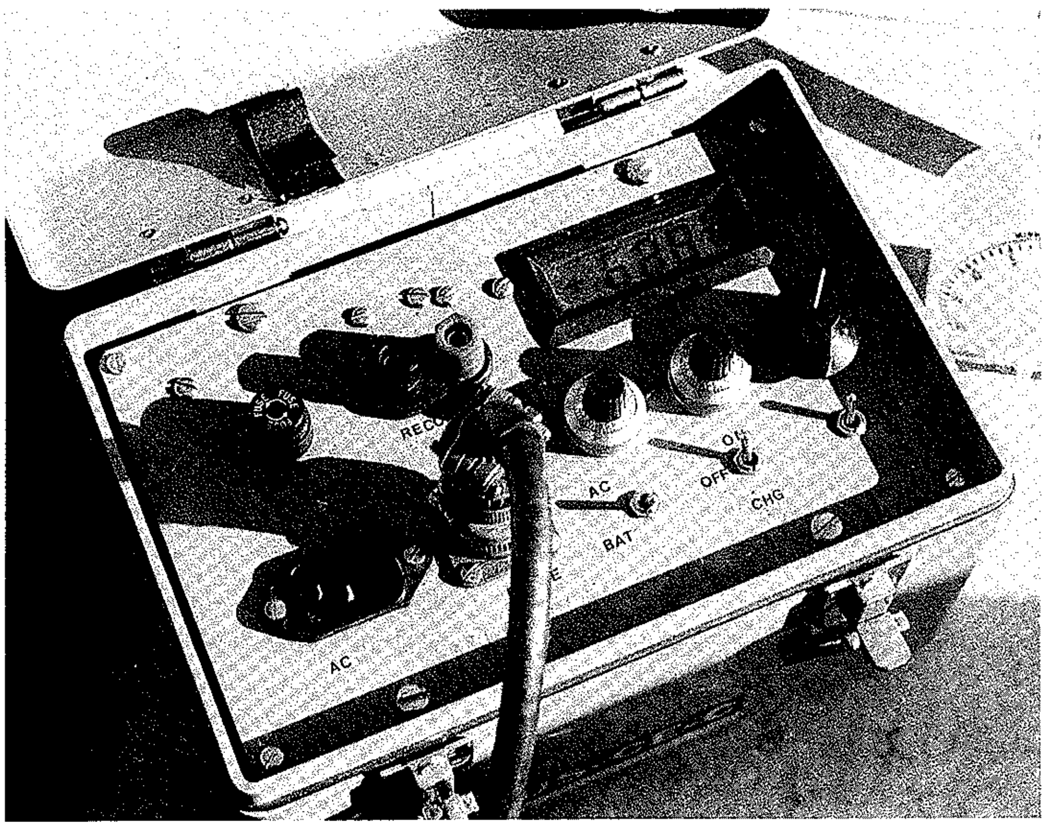

Figure 3. Digital readout meter used to measure total gas pressure from the submerged tensiometer probe

reduction of 2.7 mmHg per 100-ft* (30.5-m) increase in elevation. The elevations and theoretical barometric pressures are shown in Table 1. A tensiometer barometric value was considered substantially different from the expected if it differed by 2 percent or more from the theoretical, which is about ±14 mmHg or more from the theoretical.

14. Nine reservoirs were sampled three times each, Lake Murray was sampled twice, and Lake Cachuma was sampled once all during 1979 (Table 1). All reservoirs were located in southern California (Figure 4). Lake Cachuma was the only reservoir that was not artificially aerated or circulated. Lake Casitas was sampled six times during 1978 and five times during 1979 by the Casitas Municipal Water District (CMWD) using techniques similar to ours. CMWD used a D'Aoust tensiometer to measure total gas pressure and a Hydrolab multiprobe survey instrument to measure oxygen and temperature.

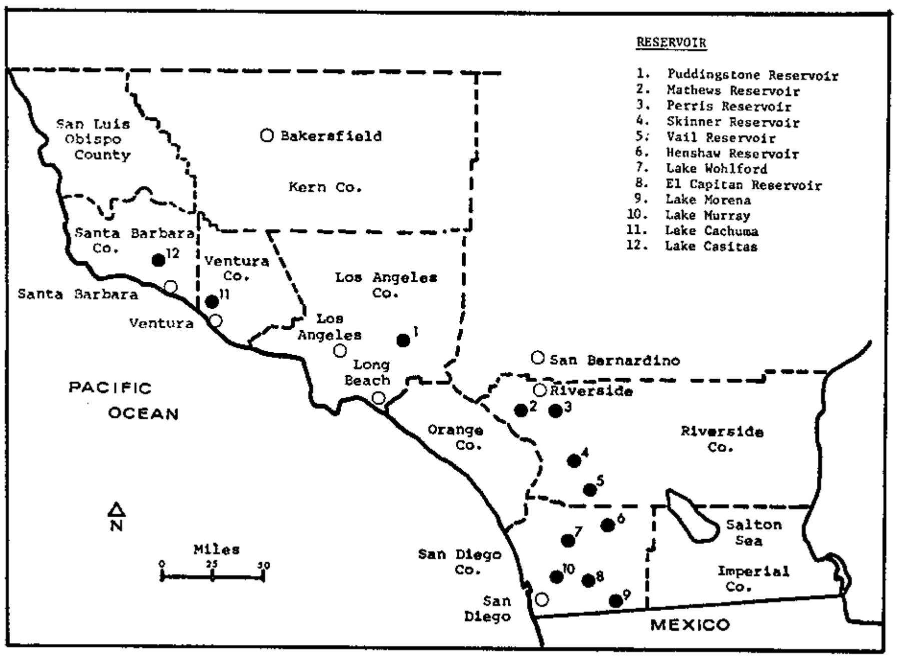

Figure 4. Map of southern California showing the locations of the 12 reservoirs surveyed during this study

* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 10.

15. All field data were sent to the U. S. Army Corps of Engineers Waterways Experiment Station (WES) for analysis. They calculated nitrogen gas concentrations using the procedure described by D'Aoust et al. (1975) and Fickeisen et al. (1975).

16. Nitrogen gas saturation values as a function of temperature at a pressure of 1 atmosphere are shown in Table 2 (Rucker 1972). These values are in mℓ of N_2 per ℓ of water. These values should be multiplied by 1.25 to convert to mg N_2/ℓ.

17. All dissolved "N_2" values shown here are actually nitrogen plus argon. Since we measured N_2 by difference, we did not distinguish between these two gases. However, dissolved argon has been shown to constitute only about 1.2 percent of the dissolved nitrogen values (Rucker and Kangas 1974). Other dissolved atmospheric gases are less than 0.02 percent of the N_2 values. Atmospheric compositions are 78.08 percent for N_2, 20.95 percent for O_2, and 0.93 percent for Ar.

18. Nitrogen, oxygen, and temperature values were always measured at the same location at each reservoir, but the distance from the sampling point to the air injection area varied greatly among reservoirs. In some cases we made our measurements within 100 ft of the bubble plume, while in other cases we were more than 1/2 mile from the plume. In no case did we measure directly in the plume. Fast (1980) observed essentially no difference between N_2 depth profiles measured at the plume and 2,600 ft (800 m) from the plume in Lake Casitas (Figure 5). We therefore conclude that our measurements are representative of the reservoirs as a whole, although we measured only at one location.

19. In this report we use the terms "lake" and "reservoir" interchangeably. All of the lakes that we surveyed are artificial impoundments or reservoirs. They all have a dam, and receive at least some of their water from a stream or river. They are all lakes as well, even by the definition that most limnologist would ascribe. They are either large and/or deep enough to stratify thermally if allowed to do so.

20. In this report, we usually use the terms aeration and destratification synonymously. What we normally mean is <u>artificial destratification by air injection</u>. Common usage of these terms has led

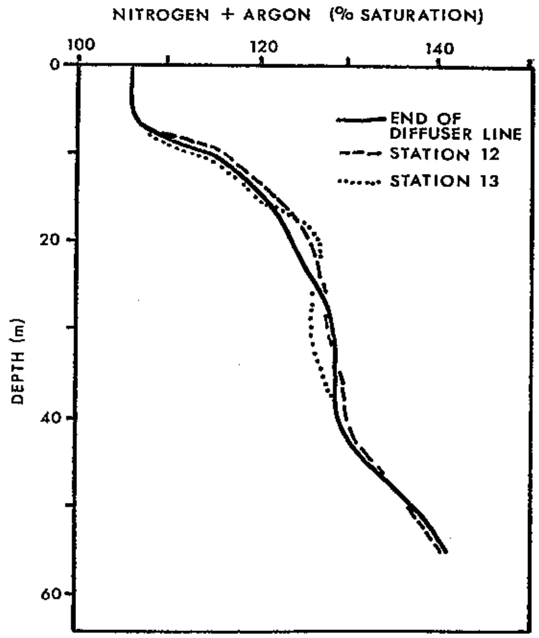

Figure 5. Dissolved nitrogen and argon gas concentrations at three locations in Lake Casitas, California, during October 1977 (Fast 1980)

to the abbreviated terms "aeration" and "destratification," when in fact the longer phrase is intended. When we are referring to some other situation we will use more specific terminology.

21. As previously stated, unless otherwise noted we refer to saturation values relative to surface pressures at the given reservoir. This is different from in situ saturation which takes hydrostatic pressure into consideration.

PART III: RESULTS

22. Dissolved nitrogen gas, dissolved oxygen, temperature, barometric pressure and other numerical data on each reservoir are presented in Appendix A. Graphs of these data are presented in this section along with the results for each reservoir.

23. Each reservoir's aeration system is described in Appendix B.

Puddingstone Reservoir

24. Artificial aeration began at Puddingstone after our June survey. The compressor operated continuously for six weeks and terminated operation about the time we conducted our August survey.

25. Temperature and oxygen stratification during June represented the undisturbed state. Strong thermal and chemical (oxygen) stratification was present, with a thermocline extending between the 2- and 10-m depths and with no oxygen below 6 m (Figure 6).

26. Artificial aeration caused a thorough mix from the surface down to 14 m, with less than 0.5° C difference between those depths on August 28 (Figure 6). A sharp thermocline existed below 14 m, with a temperature decrease from 26.0° C at 14 m to 15.9° C at 16 m. Oxygen concentrations were relatively uniform above 14 m, but decreased rapidly to zero at 16 m. Oxygen was undersaturated at all depths below the surface layer.

27. Although Puddingstone was not artificially aerated during September or October, the reservoir was nearly isothermal at 23° C from the surface to the 15-m depth on October 9 (Figure 6). Below 15 m, temperatures decreased to 19.3° C at 17 m. Oxygen concentrations showed a similar pattern with nearly uniform oxygen from the surface to 15 m and zero oxygen at maximum depth. Again, oxygen was undersaturated at all depths. Oxygen saturations ranged between 49 percent and 62 percent between the surface and 15 m.

28. Nitrogen gas concentrations on June 13 ranged from 11.1 mℓ/ℓ at the surface to 15.5 mℓ/ℓ at the bottom (Figure 7). This represents saturation values of 105 percent at the surface to 117 percent at the

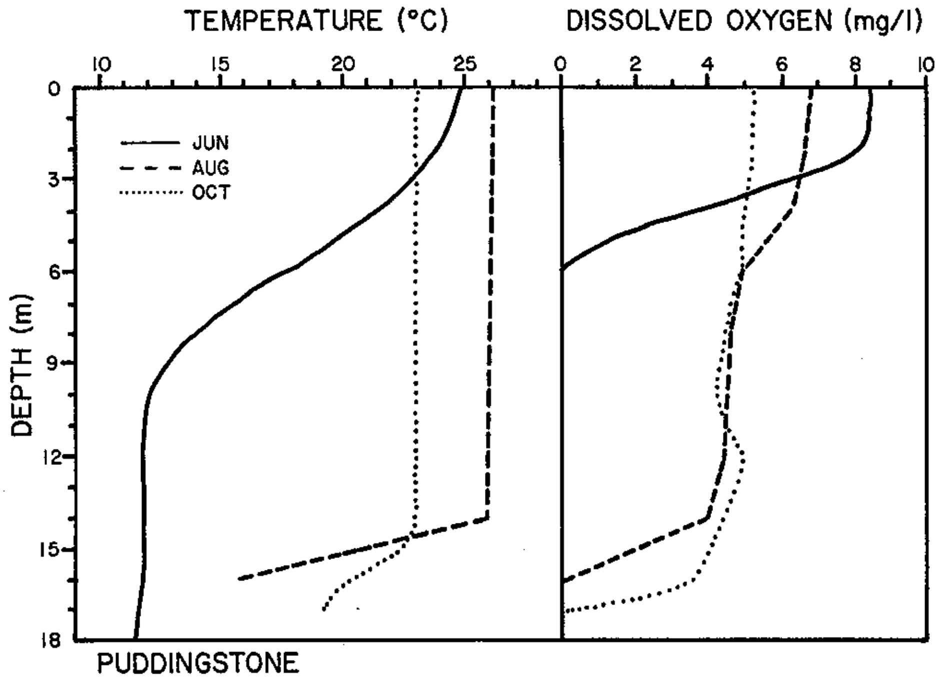

Figure 6. Oxygen and temperature values at Puddingstone Reservoir during 1979

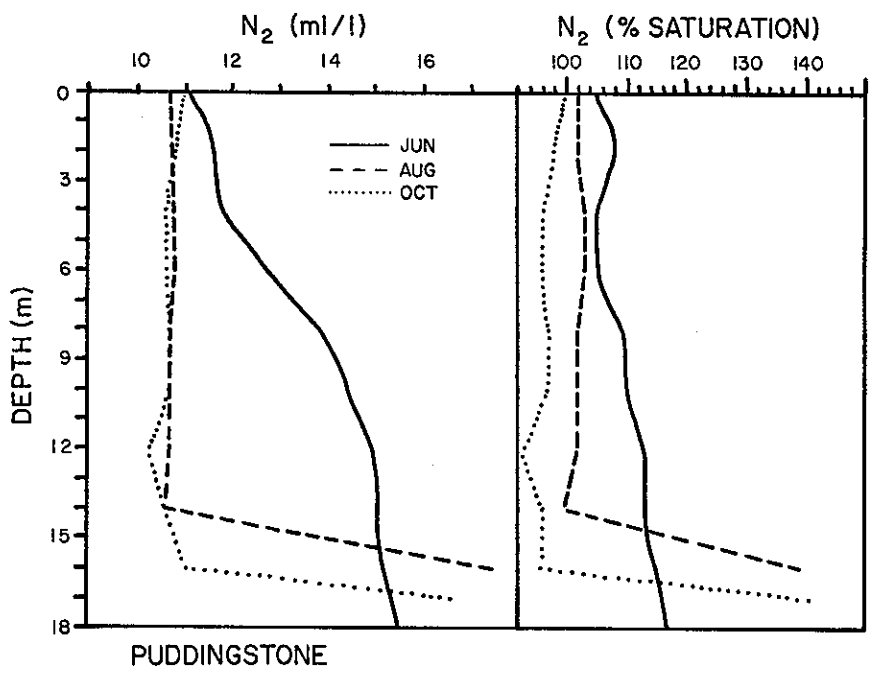

Figure 7. Dissolved nitrogen gas concentration and saturation at Puddingstone Reservoir during 1979

bottom. There was a steady increase in N_2 saturation from 6 m with 105 percent to 18 m with 117 percent.

29. Nitrogen gas concentrations decreased in the mixed zone during aeration. N_2 concentrations during August 28 ranged from 10.6 to 10.8 mℓ/ℓ between the surface and 14 m, but increased sharply below the mixed depth to 17.5 mℓ/ℓ at 16 m (Figure 7). N_2 saturations in the mixed zone were about 100 percent to 103 percent, but increased to 139 percent at the bottom.

30. Nitrogen gas concentrations during October 9 were nearly identical to the August concentrations. N_2 ranged between 10.3 and 11.0 mℓ/ℓ down to the 14-m depth, but increased to 16.6 mℓ/ℓ at 17 m (Figure 7). N_2 saturation was 100 percent or less from the surface to 16 m, but increased to 141 percent at 17 m.

Lake Mathews

31. Artificial aeration began at Mathews on June 1 with one electric compressor in operation. A second compressor, a diesel, began operation on June 4. Aeration continued through our October sample date.

32. Temperature stratification during June was partially disrupted by the air injection, but strong thermal stratification existed between the surface and the air injection depth on June 14. The temperature ranged from 24.5° C at the surface to 12.0° C at 32 m (Figure 8). Temperatures decreased only slightly below 32 m to 11.7° C at 52 m. Oxygen concentrations on this date were highest near the surface with a gradual decrease to 2.4 mg/ℓ near the bottom.

33. During August 29, Mathews was well mixed by the aerator down to 25 m, but it was not well mixed below that depth (Figure 8). A well-defined thermal gradient existed between 25 and 40 m, with temperatures decreasing from 23.9 to 12.9° C. Oxygen concentrations also reflect this condition with the largest decrease occurring between 25 and 30 m. Oxygen concentrations were 0.3 mg/ℓ or less below 30 m.

34. Temperatures during October were nearly identical to those in August, except that the temperatures were more uniform from the surface to 30 m (Figure 8). A well-developed thermocline existed between 30 and

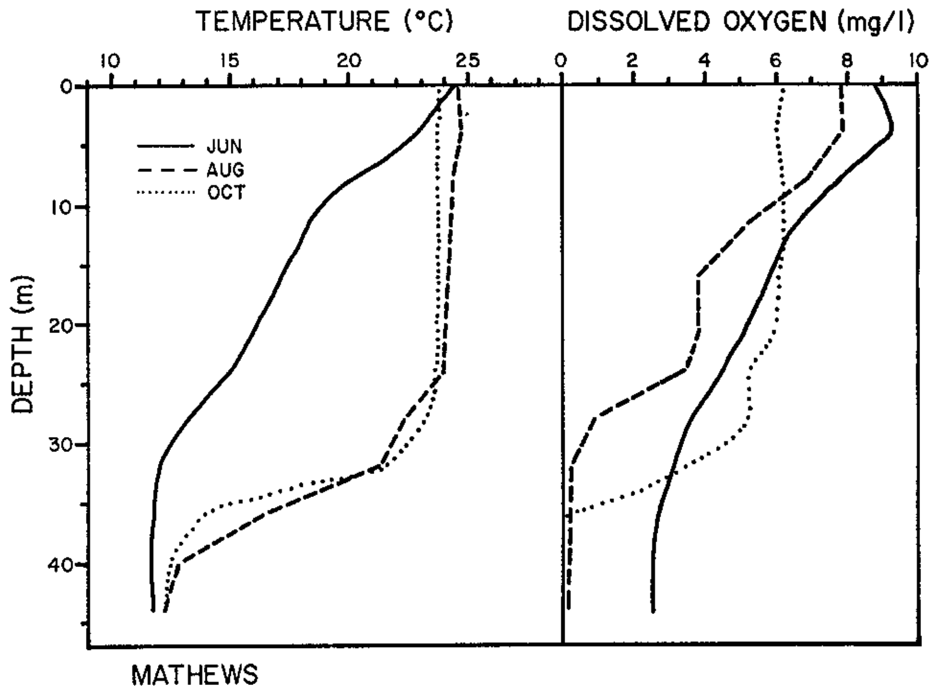

Figure 8. Oxygen and temperature values at Lake Mathews during 1979

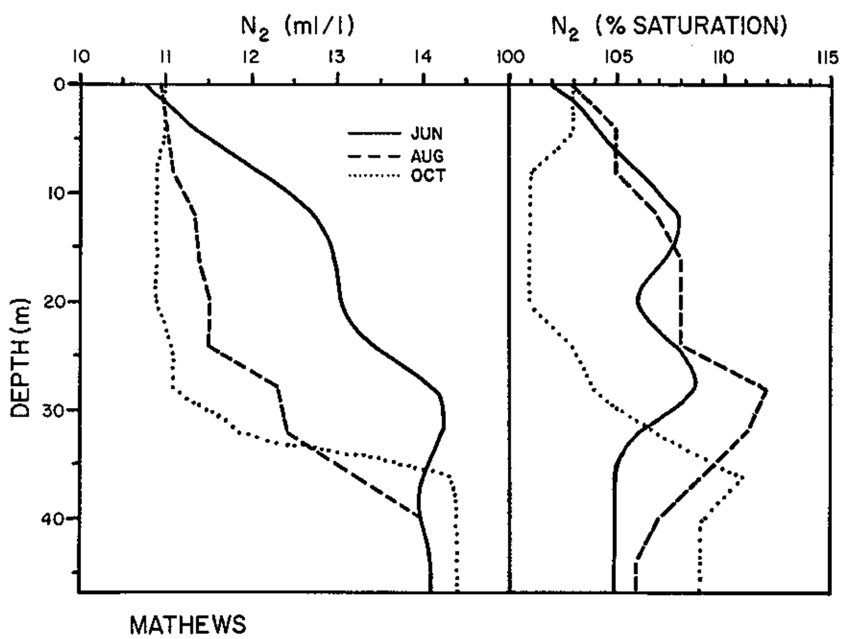

Figure 9. Dissolved nitrogen gas concentrations and saturations at Lake Mathews during 1979

35 m, and bottom temperatures were nearly identical to August. Oxygen concentrations were more uniform between 0 and 30 m as well. This represents a decrease in surface concentrations, but an increase in concentrations below 10 m. Oxygen was 0.0 below 40 m.

35. Nitrogen gas concentrations during June increased from 10.8 mℓ/ℓ at the surface to 14.2 mℓ/ℓ at 28 m (Figure 9). They decreased slightly to 14.0 and 14.1 mℓ/ℓ below 32 m. These values produced an unusual N_2 saturation profile, with a maximum value of 109 percent at 28 m, a 102 percent minimum at the surface, and 105 percent below 36 m.

36. Nitrogen gas concentrations decreased greatly at all depths above 40 m (except at the surface) during August (Figure 9). This reduction in concentration was not reflected in a similar decrease in percent saturation. For example, the concentration at 28 m decreased from 14.2 to 12.3 mℓ/ℓ during the two dates, but the percent saturation increased from 109 percent to a maximum of 112 percent. N_2 saturation at the bottom increased by 1 percent, although the concentrations were identical during June and August. Their increases in percent saturation were associated with temperature increases at the respective depths.

37. There was a further decrease in N_2 concentrations during October at depths less than 32 m, but an increase below 35 m (Figure 9). This time, percent saturation values reflected these relative changes.

38. Nitrogen gas concentration below the diffuser depths did not change greatly during more than 4 months of continuous aeration. This is in contrast to some of the other reservoirs surveyed, where both N_2 concentrations and saturations increased greatly in the unmixed zone below the diffusers.

Perris Reservoir

39. Artificial aeration began at Perris on May 9. The aeration system operated continuously through our October sampling date.

40. Temperature stratification on June 15 was well established, although the temperature profile indicates that substantial mixing had occurred (Figure 10). Surface temperatures were uniform at 23° C

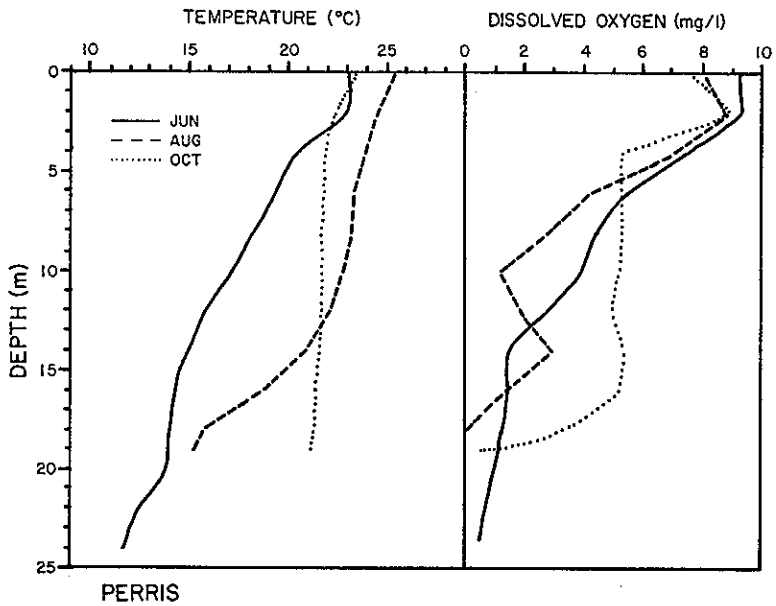

Figure 10. Oxygen and temperature values at Perris Reservoir during 1979

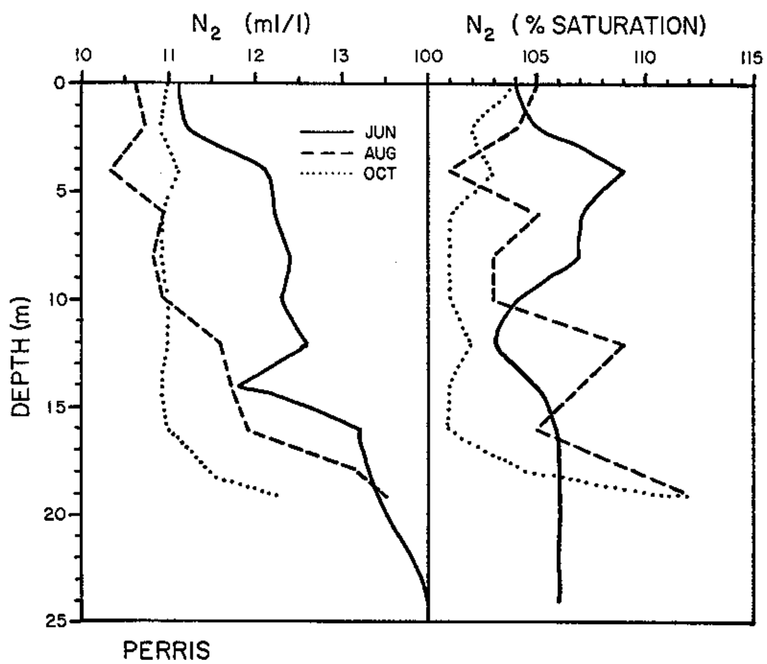

Figure 11. Dissolved nitrogen gas concentrations and saturations at Perris Reservoir during 1979

between the surface and 2 m, but decreased gradually to 11.6° C at 24 m. Oxygen concentrations were uniform in the upper 2 m and decreased uniformly between 2 and 14 m. Below 14 m, the rate of oxygen decrease was much smaller.

41. Temperatures on August 31 were more uniform, especially in the upper 12 m (Figure 10). They decreased from 25.4° C at the surface to 22.1 at 12 m and to 15.3 at 19 m. The aeration system was mixing the waters more thoroughly above 12 m than below. Oxygen concentrations were supersaturated at the surface (114 percent) probably due to algal photosynthesis, but decreased to 1.2 mg/ℓ at 10 m. Oxygen increased to 3.0 mg/ℓ at 14 m and then decreased to 0.0 at 18 and 19 m.

42. Temperatures on October 13 were very uniform due to the artificial mixing and fall cooling (Figure 10). There was only a 2.3° C difference between the surface and the bottom and only a 0.7° C difference between 4 m and the bottom (19 m). Oxygen concentrations reflect this well-mixed condition. Oxygen was 5.0 mg/ℓ or more above 16 m, but it decreased to 0.6 mg/ℓ at 19 m.

43. Nitrogen gas concentrations during June increased from 11.1 mℓ/ℓ at the surface to 14.0 mℓ/ℓ at 24 m (Figure 11). There was an anomolous decrease at 14 m. N_2 saturations varied from 103 percent to 109 percent, with the maximum at 4 m and the minimum at 12 m.

44. Nitrogen gas concentrations decreased at all depths during August, except at the bottom (Figure 11). The greatest decrease occurred between 4 and 12 m. N_2 saturations were about the same as during June, except for an increase to 112 percent at the bottom and a change in the depth profile configuration.

45. Nitrogen gas concentrations were much more uniform between the surface and 16 m during October, with variations between 10.9 and 11.1 mℓ/ℓ (Figure 11). They increased to 12.2 mℓ/ℓ at 19 m, but this was lower than during either June or August. N_2 saturations were quite low at all depths during October, except at the bottom where they increased from 101 percent at 16 m to 112 percent at 19 m.

Skinner Reservoir

46. Artificial aeration began on May 2 at Skinner. The aeration system operated continuously through our October sampling date. About 300 SCFM of air was injected between May 2 and July 30, but 600 SCFM was injected thereafter.

47. A large volume of water was flushed through Skinner. Between June 15 and August 4, 53,821 acre ft (AF) of water were discharged to Skinner (at the surface), while 51,461 AF were withdrawn (at 24- to 52-ft depths). Between August 4 and October 11, 59,946 AF were discharged to Skinner (at the surface), while 59,695 AF were withdrawn (at 24- to 27-ft depths). The volume maintained in the reservoir was only about 40,000 AF, which means that more than 125 and 149 percent of the water was "replaced" during each of these periods, respectively.

48. Temperatures on June 15 were quite uniform, indicating a good mix (Figure 12). The greatest temperature difference was between the surface (22.8° C) and 6 m (19.9° C). From 6 m to 18 m temperatures decreased only 0.9° C. They decreased further to 16.9° C at 23 m. Oxygen concentrations decreased gradually from about 9.0 mg/ℓ near the surface to 0.2 mg/ℓ at the bottom (23 m).

49. Temperatures on August 4 were very uniform with only a 3.2° C difference between the surface and the bottom (Figure 12). Oxygen concentrations decreased very evenly from 8.6 mg/ℓ at the surface to only 0.1 mg/ℓ at the bottom. Oxygen was less at almost all depths compared with June.

50. Temperatures during October 11 were nearly isothermal, with only a 0.2° C difference between the surface and 23 m (Figure 12). Oxygen concentrations were also very uniform, although they were undersaturated at all depths.

51. Nitrogen gas concentrations during June 15 ranged from 11.2 mℓ/ℓ at the surface to 12.9 mℓ/ℓ at the bottom (Figure 13). These represent saturation values of 104 to 111 percent.

52. Nitrogen gas concentrations had decreased at all depths by August 4 (Figure 13). The decreases ranged from 0.5 to 1.3 mℓ/ℓ.

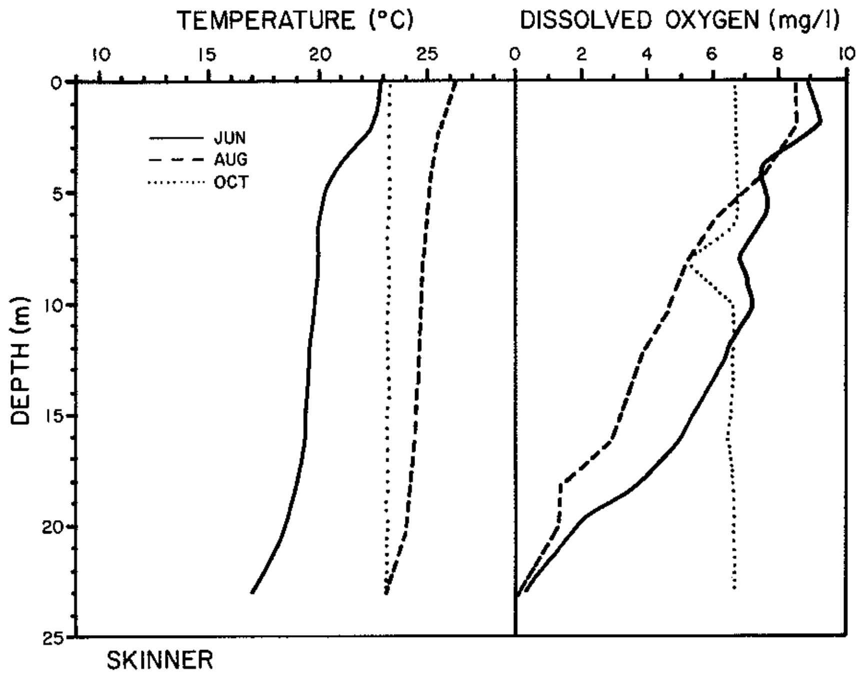

Figure 12. Oxygen and temperature values at Skinner Reservoir during 1979

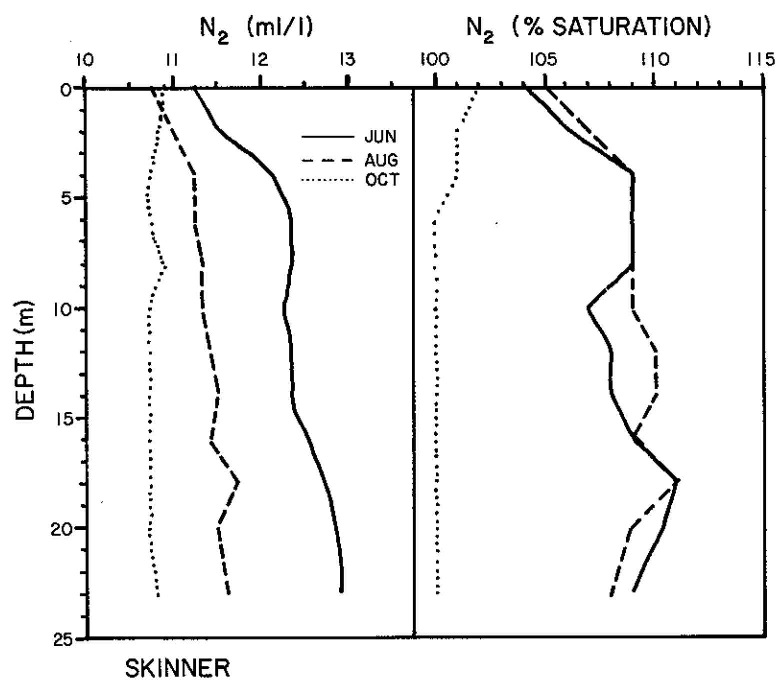

Figure 13. Dissolved nitrogen gas concentrations and saturations at Skinner Reservoir during 1979

Although the concentrations decreased, the percent saturations were nearly identical during June and August. N_2 saturations ranged from 105 percent to 111 percent during August.

53. Nitrogen gas concentrations during October were lowest of all (Figure 13). The greatest decreases occurred in deep water, which had as much as 2.3 mℓ/ℓ less N_2 compared with June. Percent saturations were also lower in October, with 102 percent at the surface and 100 percent at 6 m and deeper.

Vail Lake

54. We were not able to obtain information on the Vail aeration system design or operation from the reservoir operators. However, we did observe the system in operation during three visits. The injected air was rising all along the face of the dam (Appendix B), which suggests that the air line was broken and that the air was not issuing from a diffuser.

55. Temperature profiles on all three dates are typical of reservoirs in this area that are not aerated (Figure 14). On June 11, for example, surface temperatures were 22.8° C, and a classical thermocline existed between 6 and 12 m. Hypolimnetic temperatures were approximately 9.8° C. Temperatures during August and October again showed no signs of destratification. The thermocline was intact and existed between 6 and 12 m. Hypolimnetic temperatures warmed only 0.2° C between June and August and 0.8° C between August and October.

56. Oxygen concentrations also show no indication that artificial aeration was occurring (Figure 14). During June, oxygen concentrations were slightly supersaturated at the surface, but decreased to 0.2 mg/ℓ at 9 m, and 0.0 mg/ℓ at 12 m. A similar oxygen profile existed on August 5, with 0.0 mg/ℓ at 9 m. The October 11 oxygen profile shows some deepening of the mixed depth associated with the fall overturn. The oxygen depletion depth was again at 12 m. On all dates, there was a strong odor of hydrogen sulfide in the anaerobic hypolimnion water.

57. Nitrogen gas concentrations during June were 11.1 mℓ/ℓ at the surface and 15.3 mℓ/ℓ at the bottom (Figure 15). These concentrations correspond to 102 and 108 percent saturation, respectively. By August,

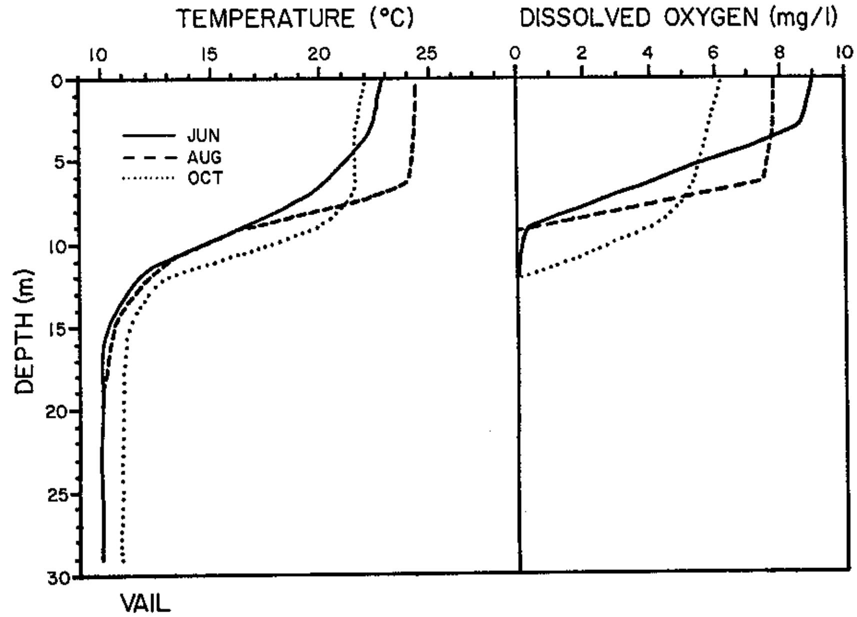

Figure 14. Oxygen and temperature values at Vail Lake during 1979 (The lake was artificially aerated, but the depth of air injection was probably above the thermocline)

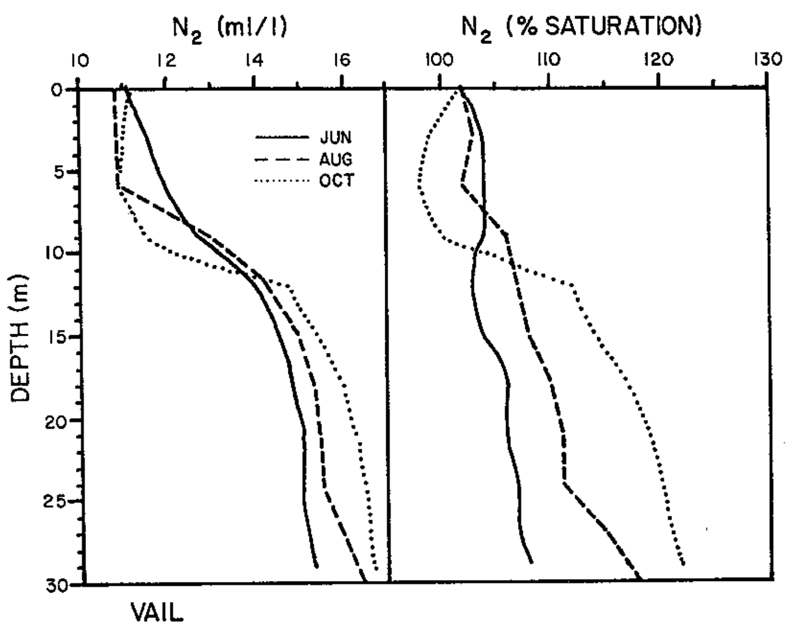

Figure 15. Dissolved nitrogen gas concentrations and saturations at Vail Lake during 1979 (The lake was artificially aerated, but the depth of air injection was probably above the thermocline)

N_2 concentrations below the thermocline had increased by 0.5 to 1.1 mℓ/ℓ, and saturation values had increased by 4 to 10 percent. Saturation at 30 m had increased to 118 percent. By October, N_2 concentrations and saturation values below the thermocline had increased further. The highest values were at maximum depth with 16.7 mℓ/ℓ and 122 percent saturation. Saturation values above the thermocline ranged between 98 and 104 percent.

Lake Henshaw

58. The aeration system at Henshaw began operation during May. It operated continuously until about October 1.

59. Lake Henshaw has one of the largest maximum capacities of all reservoirs in southern California. When full, it contains more than 194,000 acre ft and has an area of 5,675 acres. At the time of this study the water volume was maintained at a very low level. Consequently, water that would otherwise be stored and used was discharged downstream. During our study, water volumes in storage at Henshaw average only 6,548 AF, or 3.4 percent of capacity (Table 1).

60. Temperatures at Lake Henshaw were nearly isothermal on all sample dates (Figure 16). During June they ranged from 19.8° C at the bottom to 20.8° C at the surface. Similar profiles existed during August and October, although the lake was almost 4° C warmer in August and 3° C cooler in October.

61. Oxygen concentrations at Henshaw were very uniform from surface to bottom (Figure 16). Oxygen concentrations seldom varied by more than about 1 mg/ℓ from surface to bottom, but it was always undersaturated. Saturation on all dates ranged from 40 to 69 percent. This undoubtedly was due to the water drawdown. This drawdown increased concentrations of sediments with their corresponding high oxygen demands.

62. Nitrogen gas concentrations were also very uniform from surface to bottom on a given sampling date (Figure 17). On June 16, for example, N_2 ranged from 10.8 to 11.1 mℓ/ℓ and from 99 to 103 percent saturation. Concentrations varied on the other sample dates, mostly as a function of temperature changes, and saturation values never exceeded 104 percent. N_2 saturation was usually less than 100 percent during August and October.

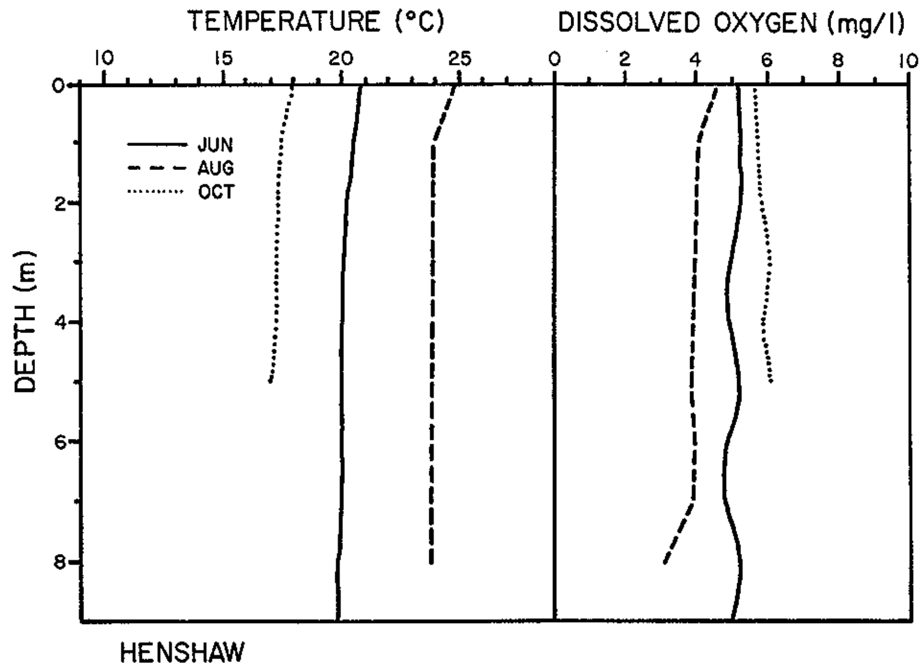

Figure 16. Oxygen and temperature values at Lake Henshaw during 1979

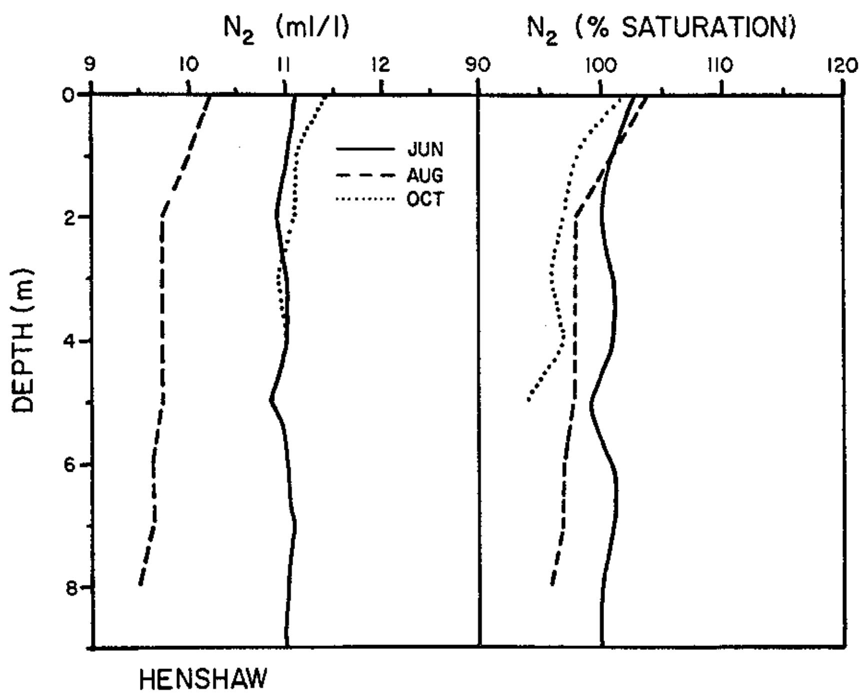

Figure 17. Dissolved nitrogen gas concentrations and saturations at Lake Henshaw during 1979

Lake Wohlford

63. Artificial aeration began at Lake Wohlford on April 10 and continued on an intermittent basis through September. The aerator generally operated 4 days per week, 24 hours each day of operation. It was sometimes operated during the other months on an "as needed" basis.

64. The aeration system at Lake Wohlford is one of the pioneers in lake aeration for southern California. It began operation during 1962 and clearly demonstrated the benefits of aeration for domestic water quality purposes (Koberg and Ford 1965).

65. Temperatures at Lake Wohlford were very uniform from surface to bottom on each sampling date as a result of artificial aeration (Figure 18). Temperature differences between surface and bottom never varied by more than 1.3° C, and they were usually less than 1.0° C. This indicates a very thorough mix by the aeration system.

66. Oxygen concentrations were always greater than 1.0 mg/ℓ (Figure 18). They were most uniform when the compressor was in operation, but even a few days of inoperation could result in oxygen depletions in the deep water. This lake has always had dense algal concentrations which sometimes cause oxygen supersaturations in shallow water (due to photosynthesis) and oxygen depletions in deeper water (due to respiration and decay).

67. Nitrogen gas concentrations were likewise quite uniform on a given date (Figure 19). During June for example, N_2 ranged from 12.0 mℓ/ℓ at the surface to 11.9 mℓ/ℓ at the bottom. These concentrations corresponded to N_2 saturations between 106 and 110 percent.

68. Nitrogen gas concentrations were smaller during August than during June, i.e. 10.9 mℓ/ℓ to 11.5 mℓ/ℓ, but saturation values were slightly greater below 3 m (Figure 19). N_2 saturation below 3 m averaged 106.8 percent during June and 108.5 percent during August.

69. Both N_2 concentrations and saturations were further reduced during October (Figure 19). N_2 concentrations ranged from 10.8 to 11.0, and saturations averaged 100.6 percent. The reduction in percent saturation during October is more noticeable than the reduction in

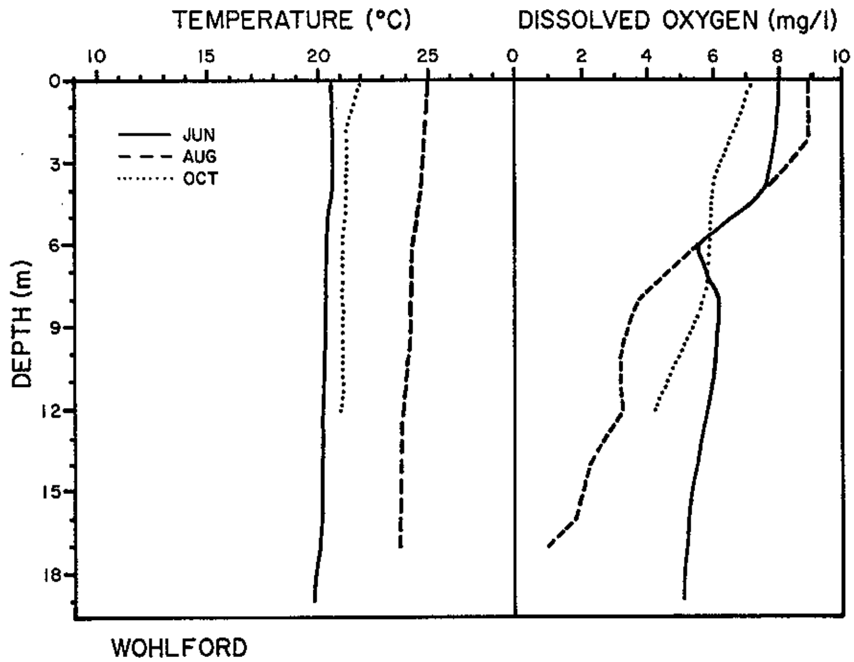

Figure 18. Oxygen and temperature values at Lake Wohlford during 1979

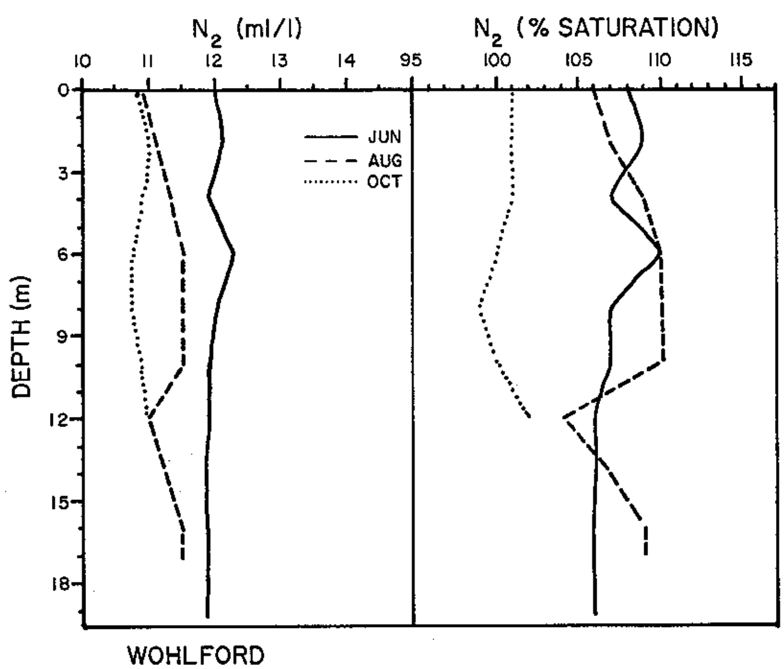

Figure 19. Dissolved nitrogen gas concentrations and saturations at Lake Wohlford during 1979

concentration. This is caused primarily by the lower temperatures during October and degassing caused by advective cooling and mixing.

70. Water volumes decreased during sampling. In August and October they were 80 and 51 percent, respectively, of the June volumes (Table 1).

El Capitan Reservoir

71. Artificial aeration began at El Capitan on June 1 and was continued through December 1, except for brief servicing periods.

72. Temperatures at El Capitan on June 17 indicate considerable alteration of the thermal profile, but the reservoir was far from destratified (Figure 20). Temperatures ranged from 19.7° C at the surface to 11.7° C at the bottom. Oxygen concentrations were near saturation at the surface, but decreased to 1.4 mg/ℓ near the bottom.

73. By August 30, a more thorough mix was achieved (Figure 20). Temperatures ranged from 23.0 at the surface to 18.9° C at the bottom, or a 7.2° C increase in bottom temperatures due to artificial destratification. Although the reservoir was well mixed thermally, oxygen concentrations were quite low below 9 m. They decreased from 2.9 mg/ℓ at 9 m to 1.0 mg/ℓ at 24 m, and to 0.0 mg/ℓ at 42 m. Without aeration, oxygen concentration could have been 0.0 mg/ℓ at 9 m and below.

74. Temperatures were higher at depth during October, and more uniform (Figure 20). Temperature differences between the surface and the bottom were only 0.5° C. The reservoir was most likely being mixed by advective cooling from the surface at this time. Oxygen concentrations also suggest convective cooling, or at least a very well-mixed condition. Oxygen concentrations were very uniform from top to bottom (4.3 and 3.8 mg/ℓ, respectively). Oxygen saturations were between 43 and 51 percent, which represents a substantial reduction at the surface and an increase in the bottom waters.

75. Nitrogen gas concentrations were greater in June, but decreased during August and October due to reservoir heating (Figure 21). During June, N_2 concentrations ranged from 12.1 mℓ/ℓ at the surface to 14.3 mℓ/ℓ at the bottom. Saturation values ranged between 104 and 108 percent. By August, N_2 concentrations had decreased to 11.7 mℓ/ℓ

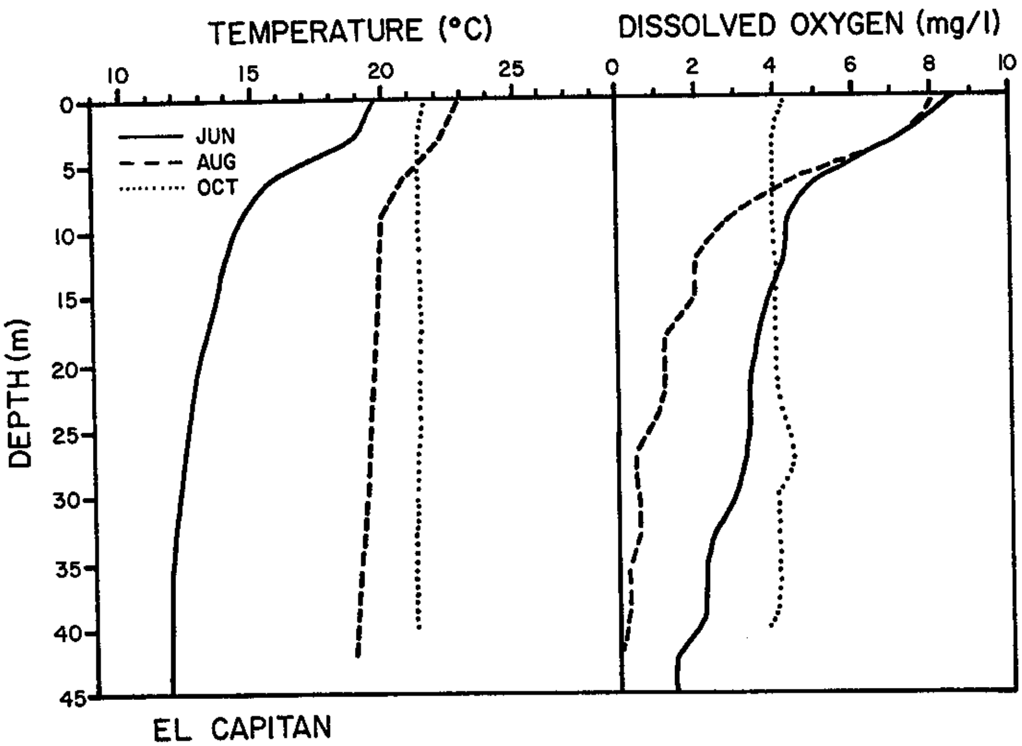

Figure 20. Oxygen and temperature values at El Capitan Reservoir during 1979

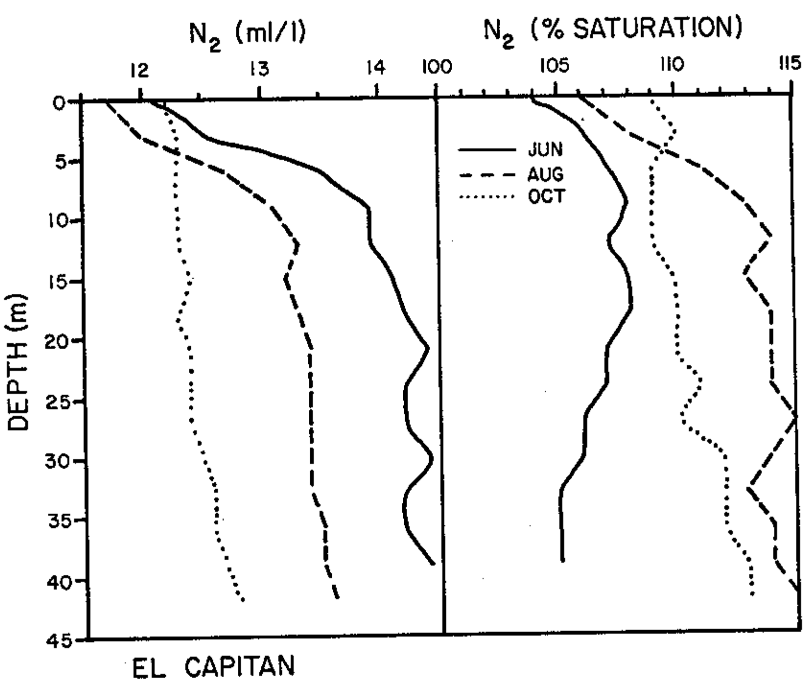

Figure 21. Dissolved nitrogen gas concentrations and saturations at El Capitan Reservoir during 1979

at the surface and 13.6 mℓ/ℓ at the bottom. However, N_2 saturation had increased substantially and averaged 114 percent below 9 m. By October, N_2 concentrations had decreased even further and ranged between 12.2 and 12.8 mℓ/ℓ. N_2 saturations had decreased from their August maximums, but still averaged greater than 110 percent below 9 m.

Lake Morena

76. Artificial aeration began at Lake Morena on April 18 and continued through our October sample date. Aeration was continuous.

77. Temperatures on June 18 were nearly isothermal, with only a 2.2° C difference between the surface and bottom (Figure 22). Between 2 m and the bottom the difference was only 1.1° C. This indicates a rather thorough mix by the aeration system. Although the lake was well mixed, oxygen concentrations varied greatly between the surface and bottom. Surface oxygen was 8.4 mg/ℓ, but decreased sharply to 4 mg/ℓ at 2 m and 0.0 mg/ℓ at 22 and 24 m. The bottom samples had an odor characteristic of decomposing algae. There were dense algal concentrations in the water and windrows of bluegreen algal scum on the lee shores and coves.

78. Temperatures increased about 6° C between June and August (Figure 22). The lake was very well mixed below 2 m, with only a 1.6° C difference between 2 and 25 m. The greatest temperature change (2.9° C) occurred between the surface and 2 m. Again, although the lake was well mixed, oxygen concentrations at depth were very low. Surface oxygen was only 6.4 mg/ℓ (89 percent saturation), but quickly dropped to 3.0 mg/ℓ at 2 m and 0.0 mg/ℓ at 4 to 25 m. There was a pronounced hydrogen sulfide odor even 600 ft (183 m) downwind from the aeration plume. Algal densities were again very high, and the Secchi disc depth measured 0.9 m.

79. Temperatures during October had cooled to between 20.8° C at the surface and 20.5° C at the bottom (Figure 22). The lake was almost certainly mixed diurnally by advective cooling. Oxygen concentrations were uniform and low (0.4 and 0.8 mg/ℓ). The well-mixed condition associated with the fall overturn contributed to this condition. Conditions had been even worse about a week earlier, when the lake

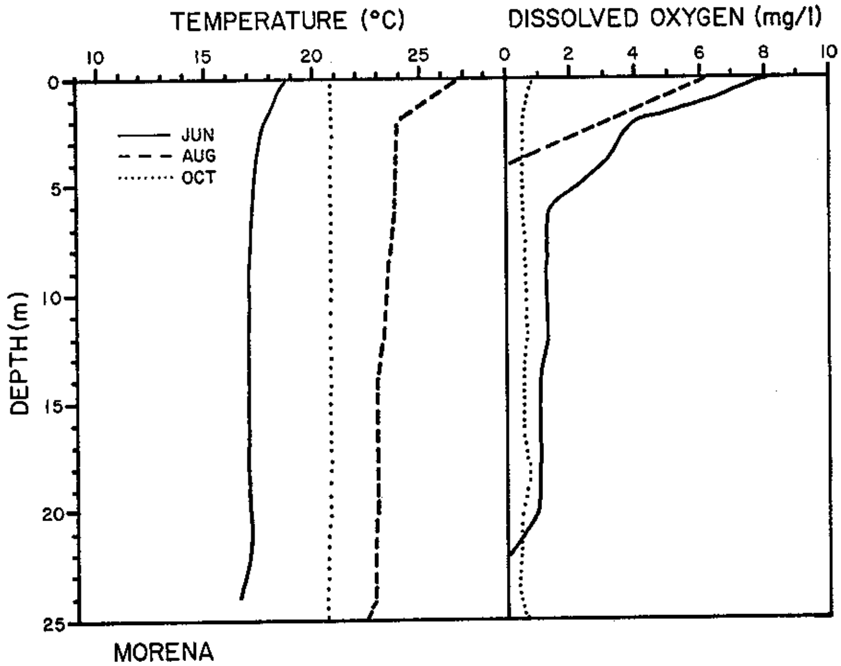

Figure 22. Oxygen and temperature values at Lake Morena during 1979

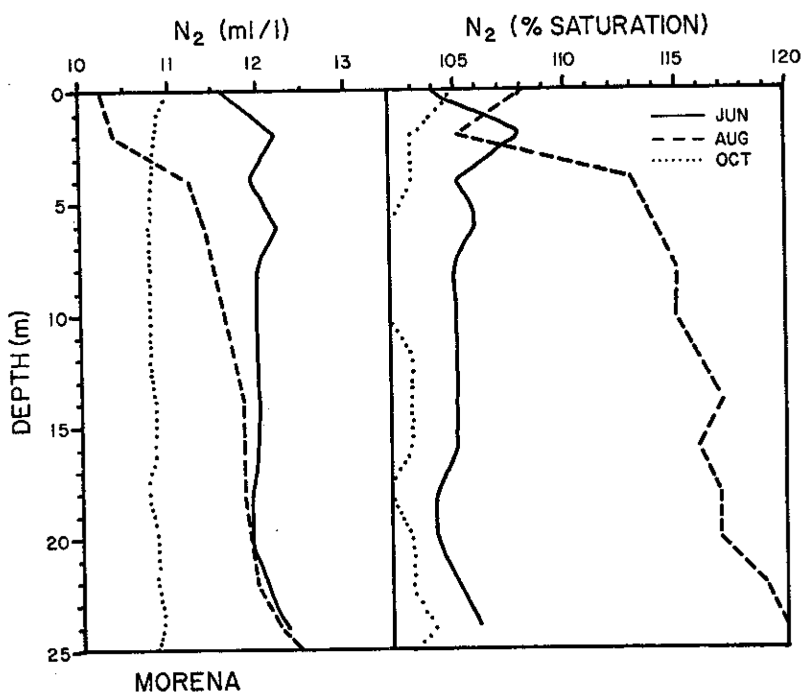

Figure 23. Dissolved nitrogen gas concentrations and saturations at Lake Morena during 1979

experienced a fish kill. Overcast skies and algal die-off contributed to the oxygen depletions.

80. Nitrogen gas concentrations were relatively uniform during June and only slightly supersaturated (Figure 23). Concentrations ranged between 11.6 and 12.3 mℓ/ℓ (104 to 108 percent saturation, respectively).

81. Nitrogen gas concentrations decreased somewhat during August, but the decrease occurred mostly in shallow water (Figure 23). The greatest decrease was above 6 m, and there was very little reduction below 12 m. This is in marked contrast to El Capitan where a substantial decrease occurred at all depths during both August and October (Figure 21). Morena's N_2 saturation increased greatly--to 120 percent at the bottom (Figure 23). There was an almost constant increase from 113 percent saturation at 4 m to 120 percent at 24 m.

82. Both N_2 concentrations and saturations decreased greatly during October (Figure 23). They were also very uniform with depth, indicating a thorough mix was occurring. On October 14, N_2 ranged between 10.7 and 11.0 mℓ/ℓ, and saturations did not exceed 105 percent. The lowest saturation was 102 percent.

Lake Murray

83. Aeration began at Lake Murray in June 1 and ran continuously through our August sampling. Although a large amount of air was injected, the diffuser line was well off the deepest part of the lake and consequently the lake was only partly mixed. On June 19 for example, the diffuser was at the 7-m depth, but maximum depth was more than 17 m.

84. Temperatures during June and August indicate at least partial mixing down to the 12-m depth (Figure 24). Below 12 m, temperatures decreased rapidly to about 12° C. Oxygen concentrations show this same pattern, although the 12-m break is more pronounced in August. On both dates, oxygen was 0.0 mg/ℓ at 14 m and below.

85. Nitrogen gas concentrations were quite uniform from the surface to 12 m during both June and August, but increased linearly from 12 m to 17 m (Figure 25). The August profile was almost identical to

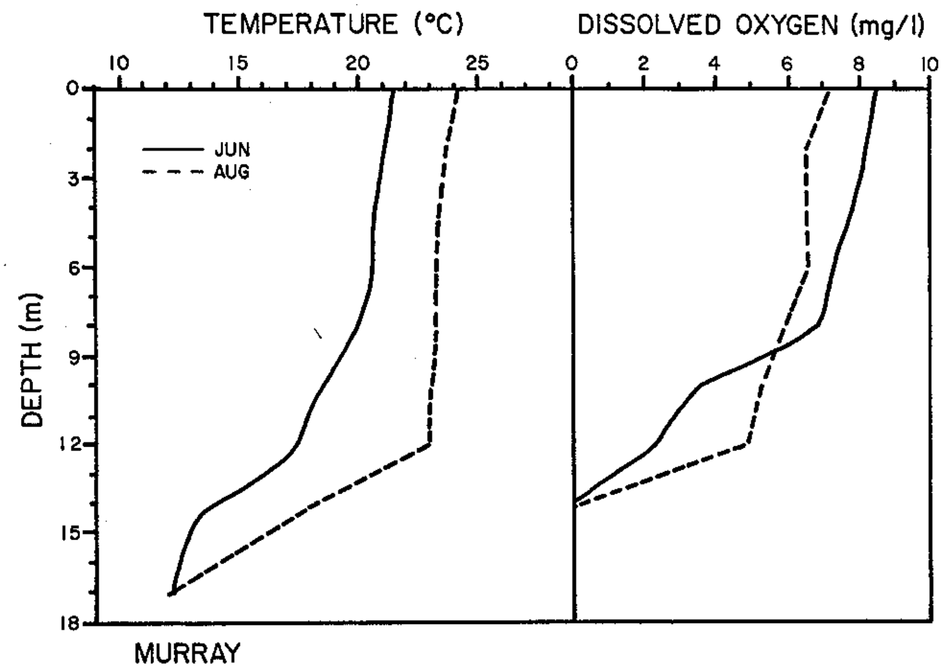

Figure 24. Oxygen and temperature values at Lake Murray during 1979

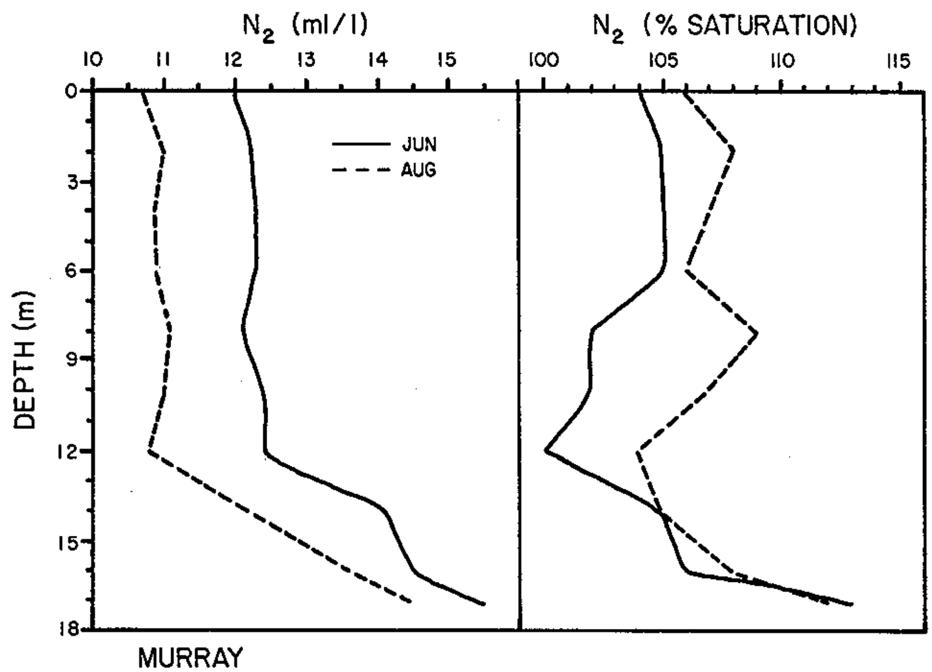

Figure 25. Dissolved nitrogen gas concentrations and saturations at Lake Murray during 1979

the June profile except that N_2 concentrations were about 1.0 to 1.3 mℓ/ℓ smaller at all depths in August. These concentrations produced saturation profiles which were high near the surface, had a minimum value on each date at 12 m, and were highest at the bottom (17 m). N_2 saturations ranged between 100 and 113 percent. The highest values occurred below the diffuser depth and below the zone which was apparently mixed by the aeration system.

86. We did not sample Lake Murray during October because of its very low water level. Water volumes decreased from a high of 4,142 AF in August to 1,329 AF in October (Table 1).

Lake Cachuma

87. Lake Cachuma was not aerated during 1979. It served as our control lake and presumably is representative of conditions without artificial aeration.

88. Lake Cachuma was still strongly stratified during October 28 (Figure 26). Temperatures were nearly uniform at about 19° C down to 15 m, a thermocline existed between 15 and 18 m, and the hypolimnion existed from 18 m (at 14.4° C) to 44 m (at 12.7° C). Oxygen concentrations reflect this condition. Oxygen was between 7 and 8 mg/ℓ from the surface to 15 m, but decreased sharply within the thermocline to 0.1 mg/ℓ at 18 m. Oxygen concentrations ranged between 0.0 and 0.4 mg/ℓ from 18 to 44 m. However, hydrogen sulfide was not detected even at 21 m where we measured 0.0 mg/ℓ of oxygen.

89. Nitrogen gas concentrations at Lake Cachuma were uniform from the surface to 15 m at about 11.7 mℓ/ℓ; then they increased sharply to 13.4 mℓ/ℓ at 18 m (Figure 27). N_2 was relatively uniform throughout the hypolimnion where it ranged between 13.2 and 13.5 mℓ/ℓ. N_2 was mostly undersaturated within the epilimnion where it averaged 99 percent. Its highest value was 104 percent saturation at 18 m. Below 18 m, N_2 saturation ranged between 100 and 101 percent.

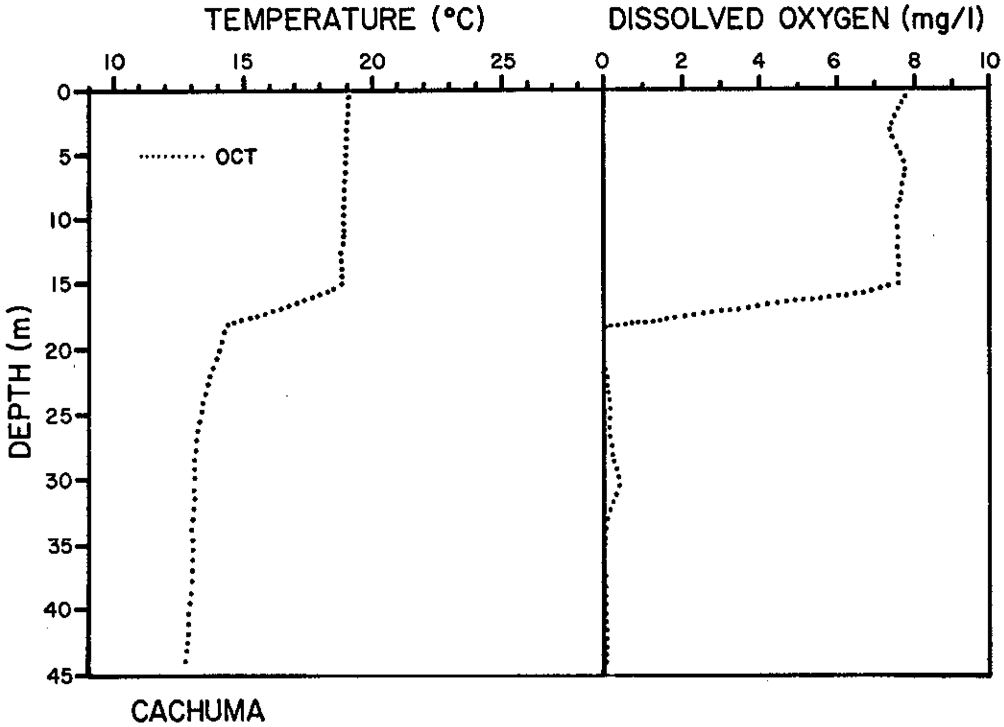

Figure 26. Oxygen and temperature values at Lake Cachuma during October 1979 (Lake Cachuma was not artificially aerated)

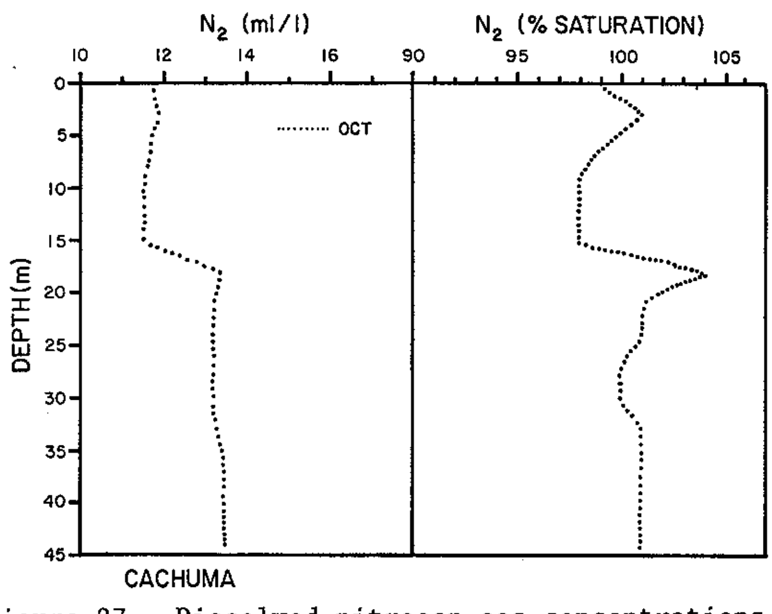

Figure 27. Dissolved nitrogen gas concentrations and saturations at Lake Cachuma during October 1979 (Lake Cachuma was not artificially aerated)

Lake Casitas: 1977

90. Artificial aeration began at Lake Casitas on April 11, 1977, and continued through October. The aeration system operated continuously, 24 hr a day, 7 days a week. During most of the aeration period, only one compressor operated and 315 SCFM of air was injected. Later in the season both compressors were operated with a total air input of 630 SCFM. The air was evenly injected along 700 ft of diffuser line.

91. Only two sets of N_2 data were collected during 1977. These data were collected in September and October and showed some amazing results (Fast 1979a, b, and 1980).

92. The lake was not well mixed by the aeration system, even above the diffuser depths. Two thermoclines were present, one below the diffuser depth (46 m) and another in the 5- to 12-m depth (Figure 28). The water volume below the diffuser depth was apparently not mixed very much by the air injection and had little temperature increase from April through October. Oxygen values followed the same patterns as temperatures: near saturation at the surface, a sharp decrease between 5 and 12 m, uniform between 12 and 45 m, and decreasing to near zero below 45 m.

93. Nitrogen gas values showed an inverse pattern compared with oxygen and temperature (Figure 28). Saturation was lowest at the surface, but increased to more than 120 percent between 12 and 45 m. Between 45 and 60 m, N_2 saturation increased to more than 140 percent. These latter observations were most perplexing since this deep water did not seem to be mixed by the aeration system.

94. Prior to these observations, most workers in the field did not anticipate significant N_2 saturation. The general feeling was that the excess N_2 would degas at the lake's surface, with a resultant N_2 saturation of slightly more than 100 percent. Such high values below the diffuser depth had not been anticipated.

Lake Casitas: 1978

95. Artificial aeration began at Lake Casitas during April 17, 1978. The aeration system operated 12 hr a day with both compressors

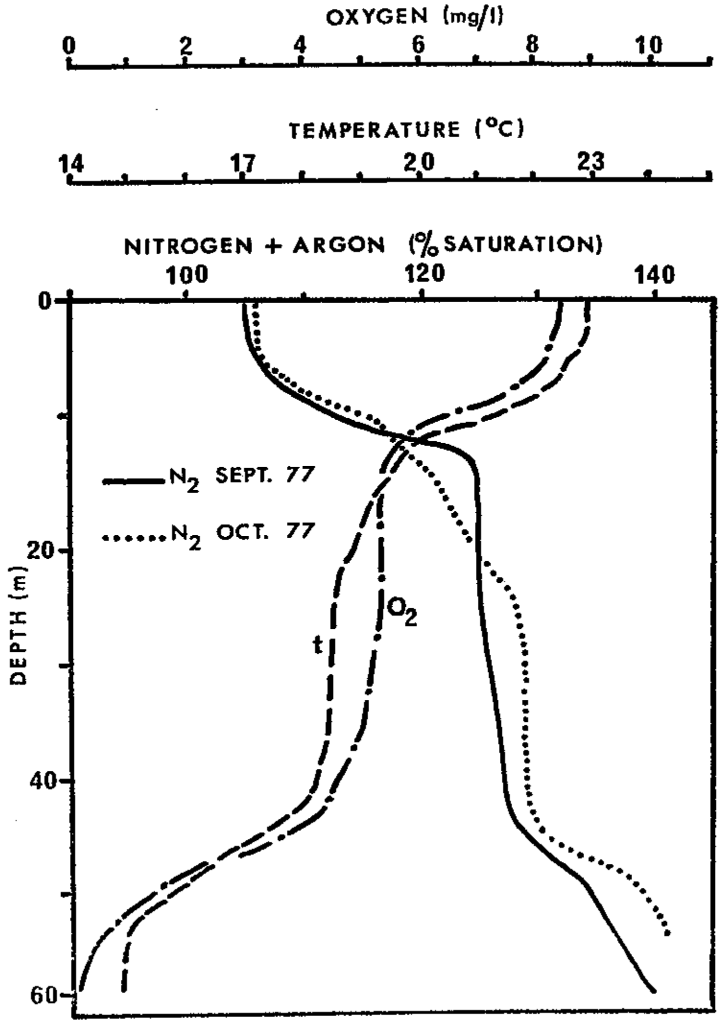

Figure 28. Nitrogen gas plus argon, oxygen, and temperature values at Lake Casitas, California, during artificial destratification (Fast 1980)

in operation. On August 4, 1978, both compressors began continuous operation for 24 hr each day until aeration was discontinued on October 30. Air was injected evenly through 700 ft (213 m) of diffuser set at the 150-ft (46-m) depth.

96. Temperatures on June 9 were not greatly altered by the air injection even though the system had been in operation almost two months (Figure 29). Surface temperatures were 22° C, with a strong thermal gradient down to 20 m, at 15.1° C. Temperatures decreased further to

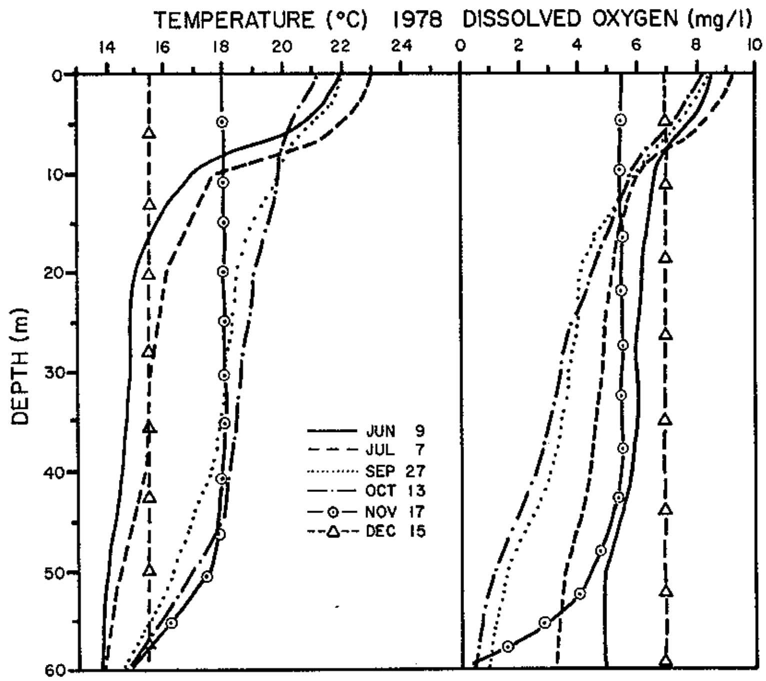

Figure 29. Oxygen and temperature values at Lake Casitas during 1978 (Lake Casitas was artificially aerated from April 17 through October 30)

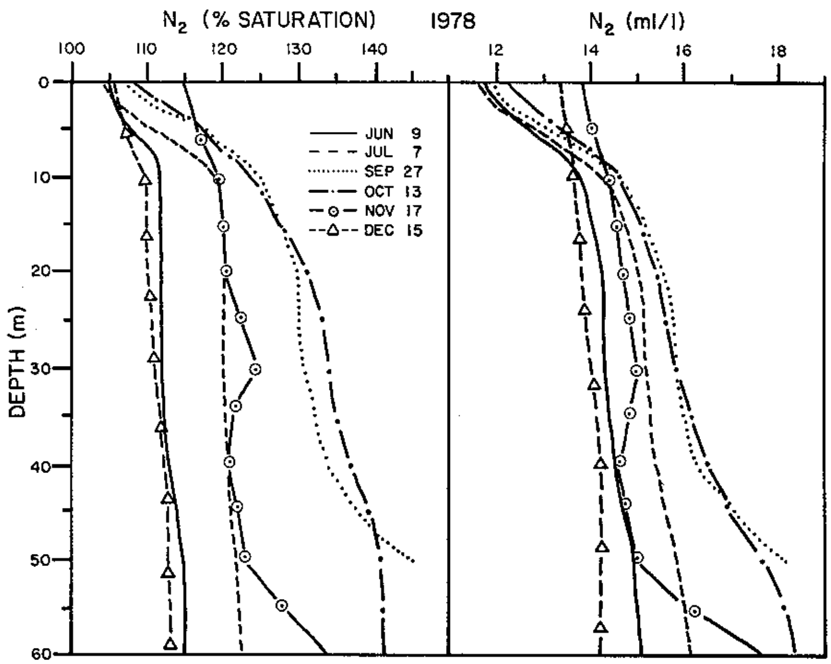

Figure 30. Dissolved nitrogen gas concentrations and saturations at Lake Casitas during 1978 (Lake Casitas was artificially aerated from April 17 through October 30)

13.9° C at 60 m. Oxygen concentrations on June 9, which were saturated at the surface (8.6 mg/ℓ), showed a break at 10 m and another break at 50 m. Between 20 and 40 m oxygen concentrations were nearly uniform.

97. A month later, on July 7, the temperatures had warmed at all depths (Figure 29). The greatest heat increase occurred at the surface down to 50 m with a 1° C increase. The increase at 60 m was only 0.1° C. Oxygen concentrations decreased at all depths other than the surface. Decreases averaged 1.2 mg/ℓ.

98. Temperatures on September 27 increased further, except at the surface which was 1° C cooler (Figure 29). The greatest temperature increases occurred at middepth and were as much as 2.4° C. However, temperatures also increased below the diffuser depth: 1.7° C at 50 m and 0.6° C at 60 m. The 20- to 40-m-depth interval had a fairly uniform temperature, but sharp temperature gradients did not occur above or below this interval. Oxygen concentrations decreased at all depths compared with June and July, but were still above zero. The lowest oxygen concentration occurred at 60 m and was 0.9 mg/ℓ.

99. Surface temperatures cooled slightly by October 13, but strong thermal stratification persisted (Figure 29). Temperatures between 10 and 50 m had increased slightly since September 27, and oxygen concentration continued to decline below 20 m. The lowest oxygen concentration of 0.4 mg/ℓ occurred at 60 m.

100. By November 27, advective cooling was well established and the lake was mixed down to 50 m (Figure 29). It was isothermal at 18° C between the surface and 40 m, with 17.4° C at 50 m and 14.6° C at 60 m. The 60-m temperature was unchanged since September 27 and only 0.7° C warmer than during June 9. Oxygen concentrations were also well mixed down to 50 m although they were only 46 to 59 percent saturated between the surface and 50 m. Oxygen at 60 m was 0.0 mg/ℓ.

101. The lake was completely mixed by advective cooling during December 15 (Figure 29). It was isothermal at 15.5° C. Oxygen concentrations were also uniform at 6.8 to 6.9 mg/ℓ from the surface to 60 m.

102. Nitrogen gas concentrations during June 9 were 11.8 mℓ/ℓ at the surface, with a sharp increase to 13.8 mℓ/ℓ at 10 m and then a more

gradual increase to 15.1 mℓ/ℓ at 60 m (Figure 30). These concentrations correspond to saturation values of 105 percent at the surface, 112 percent at 10 m, and 115 percent at 60 m.

103. Nitrogen gas concentrations increased further during July at all depths except the surface (Figure 30). Increased concentrations averaged slightly less than 1 mℓ/ℓ. N_2 saturations also increased at all depths except the surface. N_2 saturation at 10 m was 118 percent, while at 60 m it was 124 percent.

104. Nitrogen gas concentrations continued to increase during September and October, and they were nearly the same on both dates (Figure 30). During September, N_2 concentrations ranged from 12.0 mℓ/ℓ at the surface to 18.2 mℓ/ℓ at 50 m (deepest sample on that date). This 50-m concentration produced the highest saturation value of the year, 146 percent. Saturation values during October were nearly as high, with 141 percent at 50 m and 142 percent at 60 m. The 60-m N_2 concentration of 18.4 mℓ/ℓ was the highest concentration recorded during 1978.

105. As the lake cooled and advective cooling took place, N_2 concentrations decreased (Figure 30). By November 17, N_2 concentrations were 15 mℓ/ℓ or less at all depths except 60 m. N_2 saturation also decreased to between 119 and 123 percent at middepth, compared with 131 to 141 percent a month earlier.

106. Nitrogen concentrations were lowest of all during December (Figure 30). They were nearly uniform from the surface to bottom. Although N_2 was still substantially supersaturated at 110 percent to 113 percent below 10 m, concentrations ranged from 13.4 to 14.4 mℓ/ℓ.

107. Casitas is especially interesting because both N_2 concentrations and N_2 saturations continued to increase at depth from June through October. At most of the other aerated reservoirs, saturation values increased but concentrations decreased. Casitas also had: (a) the deepest injection depth, (b) the lowest air density along its diffuser line, and (c) one of the lowest air volume/total water volume ratios.

Lake Casitas: 1979

108. Aeration began at Lake Casitas during April 3, 1979. Both

compressors operated continuously (24 hr/day) until October 29, except from April 23 through May 23 when one compressor failed and was replaced. Air was injected evenly through 400 ft (122 m) of diffuser line set at the 150-ft (46-m) depth.

109. Temperatures during March 15, 1979, show the onset of thermal stratification (Figure 31). Suface temperatures were 15.7° C, with a decrease to 13.1° C at 10 m. The temperatures from 20 to 60 m were nearly isothermal at 12.5 to 12.7° C. Oxygen concentrations were high at all depths and ranged from 10.0 mg/ℓ at the surface to 7.8 mg/ℓ at 60 m.

110. Temperatures 2 months later, on May 11, were higher at all depths (Figure 31). The highest increases of 2.4° C occurred at the surface, but temperatures at 60 m increased by 0.5° C between these dates. The aeration system had been in operation for more than a month by this time and undoubtedly caused the increased temperatures in the deeper water. Oxygen concentrations on May 11 had decreased by 0.9 mg/ℓ or more at all depths. The greatest decrease of 2.0 mg/ℓ occurred at 60 m.

111. Temperatures on June 29 continued to increase compared with May (Figure 31). Surface temperatures were at 23.0° C, and the greatest thermal gradient occurred between 0 and 10 m. Oxygen concentrations continued to decline at all depths except the surface. Again, the greatest decrease of 1.6 mg/ℓ occurred at 60 m, which now had 4.2 mg of oxygen per litre.

112. Temperatures continued to increase through July and August with the greatest increases occurring at middepths (Figure 31). Between June 29 and August 29, surface and bottom temperatures increased 0.4° and 1.4° C, respectively. However, middepth temperatures (20 to 40 m) increased an average of 2.3° C. Oxygen concentrations continued to decline, especially at the deeper depths. Oxygen concentrations at 10 m decreased from 7.1 to 6.1 mg/ℓ between June 29 and August 29, while at 55 m the decrease was from 4.6 to 3.0 mg/ℓ.

113. Nitrogen gas concentrations ranged from 13.6 mℓ/ℓ at the surface to 14.7 mℓ/ℓ at 60 m on March 15, 1979 (Figure 32). This was the preaeration condition. Even though aeration had not yet occurred

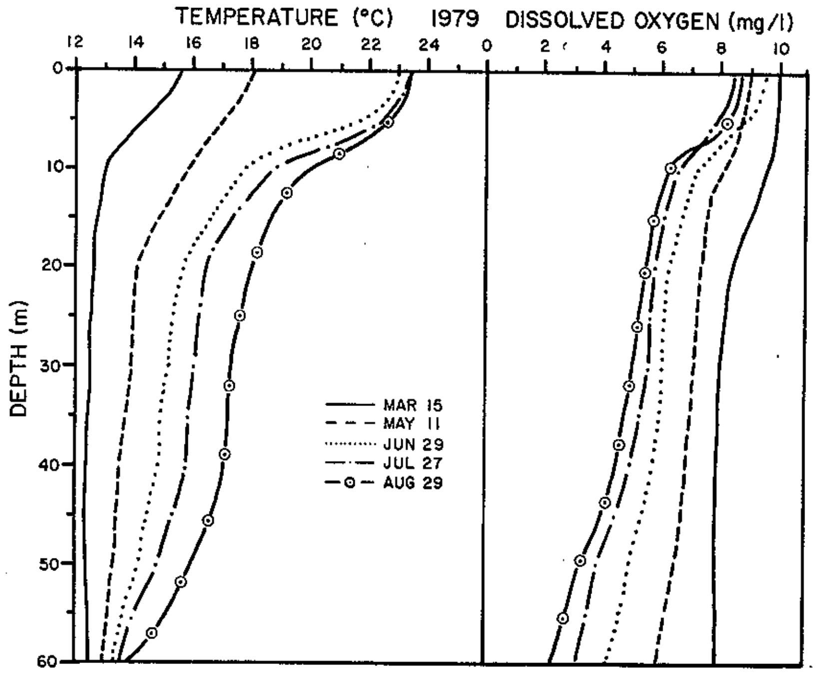

Figure 31. Oxygen and temperature values at Lake Casitas during 1979 (Lake Casitas was artificially aerated from April 3 through October 29)

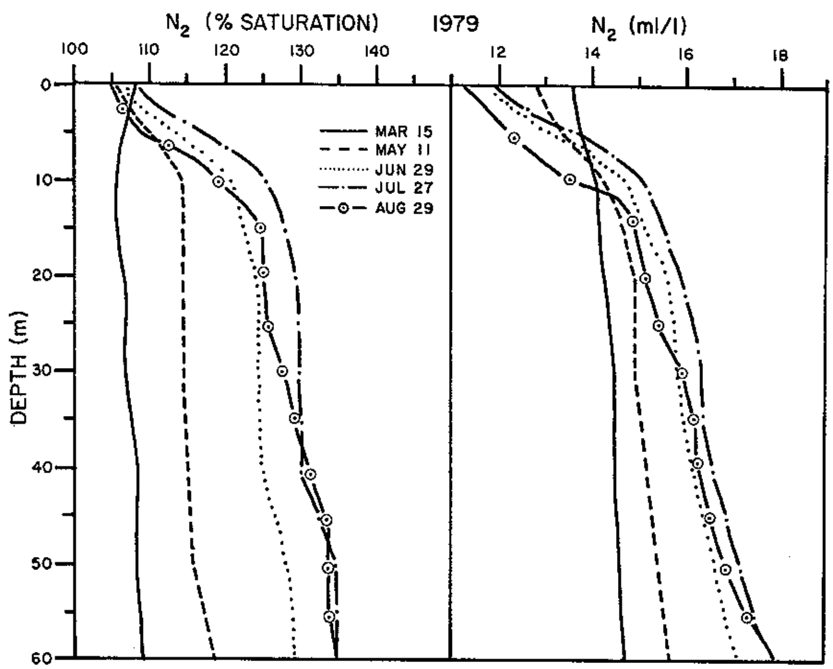

Figure 32. Dissolved nitrogen gas concentrations and saturations at Lake Casitas during 1979

during 1979, these concentrations represent saturation values of 106 to 109 percent.

114. After a month of aeration, N_2 concentrations and saturations increased at all depths except the surface (Figure 32). Concentrations increased only 0.6 mℓ/ℓ at 20 m, but the increase at 60 m was 1.0 mℓ/ℓ. N_2 saturations increased from 107 to 114 percent at 20 m and from 109 to 118 percent at 60 m.

115. Nitrogen gas concentrations and saturations continued to increase through June and July (Figure 32). By July 27, N_2 concentrations reached their highest values in deep water. Concentrations were 15.1 mℓ/ℓ at 10 m and increased to 17.8 mℓ/ℓ at 60 m. These concentrations represent saturations of 126 and 135 percent, respectively.

116. Nitrogen gas concentrations decreased at all depths on August 29, relative to July 27 (Figure 32). The greatest decreases were in shallow water. N_2 saturations also decreased between the surface and 30 m, but below 30 m saturations were about the same on these two dates.

PART IV: DISCUSSION AND CONCLUSIONS

117. Clearly, artificial destratification by air injection can cause substantial N_2 supersaturation. Destratification can cause N_2 supersaturation under a variety of conditions that are not intuitively obvious. In certain instances N_2 saturations increased during aeration even though the N_2 concentrations decreased. These N_2 saturation increases were due to temperature increases. Modest N_2 absorption from injected air and/or a modest temperature increase without degassing can result in N_2 saturation increases. Other times both N_2 saturation and concentrations increased during aeration. These changes can occur in that portion of the lake which is "mixed" by the aeration system as well as below the diffuser depth in the apparently unmixed portion of the lake.

118. Lakes which are being destratified exhibit several thermal conditions. We recognize at least four general types of conditions which exist during destratification (Figure 33). The type of condition which exists will affect both N_2 concentrations and saturations. For this reason, we will discuss the four conditions and relate our survey findings to these conditions.

119. Although a given lake at a given time may occupy a thermal configuration intermediate between one of these types, most lakes will fit into one of these categories once a nearly steady-state condition is reached. Such a state normally exists after the destratification system has been in operation for several weeks. At that point, the rate of destratification is usually reduced, or even nearly balanced, by solar influx which is working toward a more stratified condition. A purely steady-state condition is probably never (or seldom) achieved since heat fluxes are so dynamic. A given lake can also exhibit different types of conditions during the year.

Type I Conditions

120. Type I conditions are characterized by a thorough mix throughout the lake, nearly uniform temperature and oxygen conditions at all depths, and relatively frequent contact between water (from all

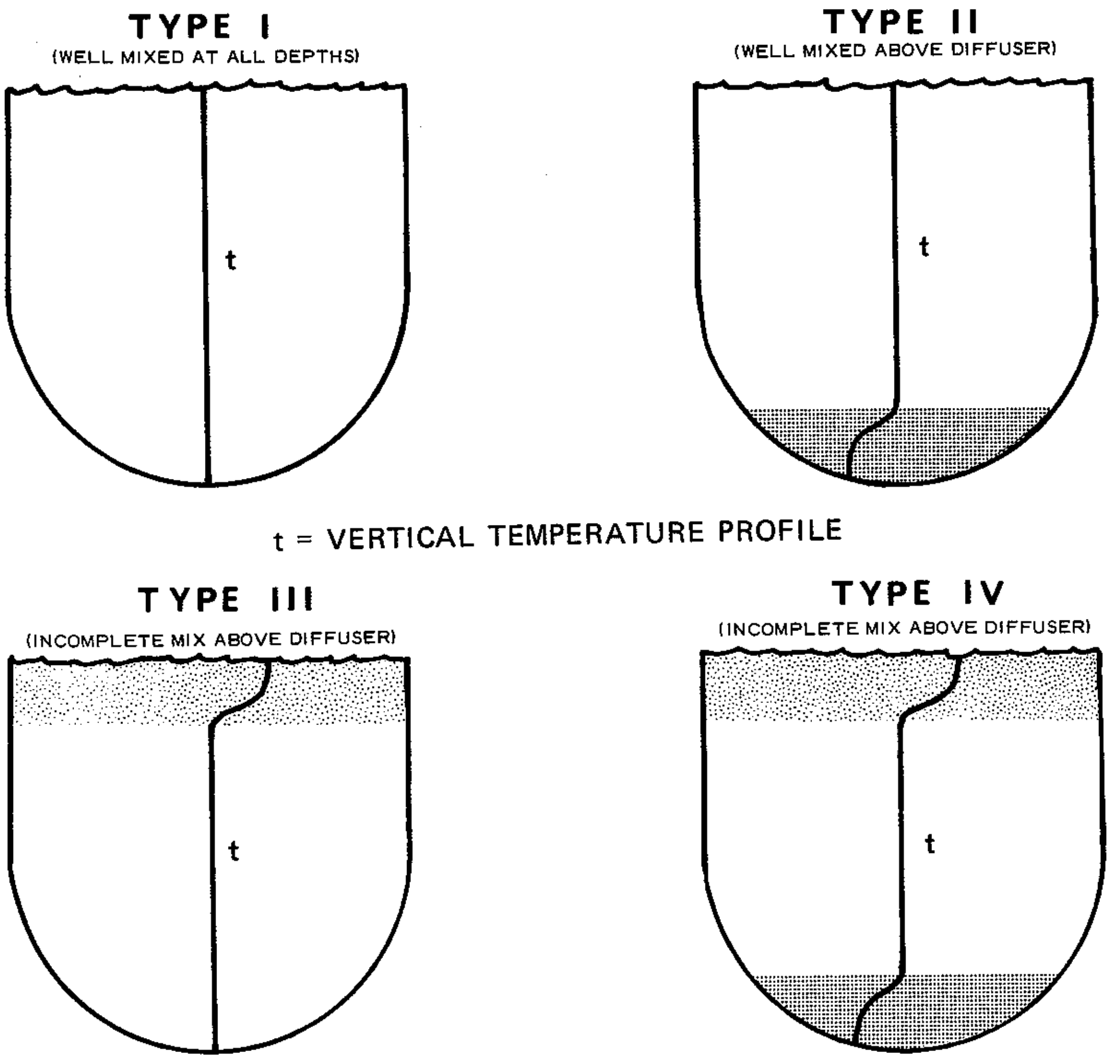

Figure 33. Four types of conditions, with respect to degree of mixing, that usually exist during artificial destratification

depths) and the atmosphere at the air/water interface. All of the survey lakes should exhibit these characteristics during the winter when advective cooling causes the lake to circulate freely. Several of the lakes even showed these characteristics during October; i.e., Skinner, Henshaw, Wohlford, El Capitan, and Morena. Without aeration these lakes would still have been stratified (with respect to temperature and oxygen) during October. However, artificial destratification caused a warming of the bottom waters and an increased heat budget. Consequently, when advective cooling set in the entire lake was mixed from 2 to 3 months earlier than normal.

121. During June and August only Lakes Henshaw and Wohlford exhibited Type I characteristics. Henshaw would probably have been well mixed, even without the aeration system, because of its shallow depth. Lake Wohlford, on the other hand, exhibited these characteristics because its aeration system was adequately sized to create a thorough mix and because the diffusers were at or near the deepest point. Continuous operation of the Wohlford aerator would probably have created an even more uniform condition during the summer.

122. Nitrogen gas saturations during Type I conditions are usually near 100 percent saturation. The reason for this is that there is a rapid exchange of N_2 at the lake's surface between the atmosphere and the individual water parcels. This allows for both the rapid exchange of N_2 and a trend towards 100 percent saturation at all depths (relative to the surface). On all three sampling dates, N_2 saturation at Henshaw never exceeded 104 percent. At Lake Wohlford, N_2 saturations were highest in June and August, but were still less than 110 percent on all three dates. N_2 conditions during October at Wohlford were clearly Type I.

123. Of the other lakes which exhibited Type 1 thermal and N_2 conditions during October, these conditions were most clearly present at Lakes Skinner and Morena; El Capitan was still intermediate between Types I and III. At Skinner and Morena, N_2 concentrations and saturations were the lowest of the year, and saturations did not exceed 105 percent. N_2 concentrations at El Capitan during October were the lowest of the year, but N_2 saturation in the deep water still exceeded 110 percent.

124. If Type I conditions can be achieved by an artificial destratification system using air injection, then we do not expect N_2 saturations greater than 110 percent at any depth in the lake.

Type II Conditions

125. Type II conditions are nearly the same as Type I, at least down to the diffuser depth. Below the diffuser depth the water is not appreciably mixed with shallower water, nor is it greatly heated. Above the diffuser depth, thermal, oxygen, and N_2 values are the same as we have discussed for the whole lake with Type I conditions.

126. Puddingstone during August and October, Mathews during October, Murray during June and August, and Casitas during November 1978 are examples of Type II conditions. Vail is probably another example, although we do not know the diffuser depth, and assume that the air was injected above the thermocline.

127. In all of these Type II examples, the highest N_2 concentrations and saturation values on a given date were always found below the diffuser depth. Except at Lake Casitas, N_2 saturations above the diffuser are very uniform and seldom exceed 110 percent. In most cases they are below 105 percent. However, we observed N_2 saturations below the diffusers of 141, 111, 113, 135, and 122 percent, respectively, for Puddingstone, Mathews, Murray, Casitas, and Vail reservoirs. These values at Puddingstone, Casitas, and Vail are clearly excessive and could cause fish mortalities if they were present downstream. Fast (1979a) first reported these high N_2 saturations below the diffuser at Lake Casitas during 1977.

128. We are perplexed by the high N_2 concentrations and saturations which are often observed below the diffuser depth with Types II and IV conditions (discussed later). These N_2 concentrations and saturations are some of the highest found during artificial aeration and can exceed 140 percent of saturation. The perplexing aspect is that often the water below the diffuser is apparently not circulated upwards by the air, nor warmed significantly; yet the N_2 content of this water increases greatly during aeration.

129. Fast (1979a, b, 1980) first reported this phenomenon from Lake Casitas during 1977, but we observed it in our survey at Puddingstone (August, October), Mathews (October), Vail (August, October), Murray (June, August), and Casitas (1978, 1979). In some cases, the saturation increase below the diffuser was modest (less than 15 percent), but saturation in this region exceeded 140 percent at two of these reservoirs.

130. There are three likely sources of high N_2 saturations below the diffuser depth: (a) denitrification of nitrate, (b) N_2 from the injected air, and (c) N_2 from supersaturated groundwater.

131. Denitrification is an anaerobic bacterial process whereby nitrate is reduced to nitrogen gas. It takes place in several steps, but can be shown as a single step for glucose metabolism (Keeney 1972).

$$C_2 H_{12} O_6 + 4 NO_3 \rightarrow 6 CO_2 + 6 H_2O + 2 N_2$$

132. It requires 2.3 mg of nitrate (NO_3) to produce 1.0 mg of N_2. N_2 increases at the bottom of Lake Casitas during 1978 and 1979 were equivalent to 4.1 and 7.4 mg/ℓ of NO_3, respectively. Nitrate concentrations were not observed at these levels at any time, although we would not have expected them to if continuous denitrification had occurred. Further, the Casitas hypolimnion was not anaerobic until the fall of each year. However, the subsurface sediments were anaerobic year round. Migration of NO_3 into the sediments, subsequent denitrification, and the movement of N_2 out into the water might account for the high N_2 concentration.

133. At Vail, hypolimnetic N_2 increased by 1.8 mg/ℓ between June and August. This would require 4.1 mg/ℓ of NO_3. At Puddingstone, the subdiffuser N_2 concentrations increased by 2.5 mg/ℓ from June to August (5.7 mg/ℓ of NO_3), but the temperature also increased by 2.0° C, indicating some mixing by the diffuser.

134. Another explanation for the high N_2 saturation is that groundwater supersaturated with N_2 flowed into the lakes. Matsue et al. (1953) found up to 160 percent N_2 saturations in artesian waters, while

Sugawara and Tochikubo (1955) also found substantial N_2 supersaturations in groundwater. These supersaturations apparently occur by two processes: (a) denitrification of NO_3 within the ground and (b) dissolution of air bubbles carried into the ground by the groundwater. In the first case only N_2 is produced, and the water is deficient in argon. In the latter case, both N_2 and Ar are dissolved in the same proportions as are found in air-saturated waters.

135. Hutchinson (1957) presents some unpublished data of Birge and Juday's from Otter Lake, Wisconsin, which indicate an N_2 saturation of 134 percent within the thermocline. N_2 saturation within the hypolimnion dropped to 115 percent. The most likely explanation for these values is N_2 saturation of the groundwater inflows.

136. At Puddingstone Reservoir, we observed hypolimnetic N_2 saturations of 113 to 117 percent in June, before aeration began. These could have been caused by either NO_3 reduction or N_2 saturated groundwater inflow.

137. Although groundwater N_2 supersaturation undoubtedly can account for some hypolimnetic N_2 supersaturations, we favor the explanation that compressed air is the primary source of the N_2 below the diffuser depth. However, we cannot readily explain how the N_2 is dissolved in this water without causing a greater temperature increase. Although the air itself should not add much heat, we would intuitively expect some shallow (warmer) water to be mixed into the deeper water, thus raising its temperature. Possibly a subdiffuser water circulation pattern is established which allows the absorption of the air without mixing it with shallower water.

138. Although the water volume below the diffusers is a relatively small portion of the total volume, it accounts for a disproportionate portion of the total increase in N_2. During 1979 at Lake Casitas, for example, about 30×10^6 m^3 of water was found below the diffuser depth. This amounted to 14 percent of the volume below 10 m, or 9 percent of the total lake volume. The N_2 increase below the diffusers from March 15 through August 27 was 3.2 mg/ℓ, or 96×10^3 kg. This amounts to 24 percent of the total N_2 increase below the 10-m depth between these two dates

(Table 4), or 4 percent of the total N_2 injected in the compressed air.

139. The probable individual or combined source of this N_2 supersaturation is the compressed air, nitrate reduction and/or groundwater inflows. Analyses of these waters for N_2 and Ar could determine the source. If a low N_2/Ar ratio is found, then the N_2 is from NO_3 reduction since this process does not produce Ar. If the N_2/Ar ratio is normal for air saturation, then the source of the excess N_2 is most likely the compressed air.

140. With Type II conditions, we do not expect N_2 saturations of more than 110 percent above the diffuser depth, although N_2 saturations below the diffuser depth can exceed 140 percent.

Type III Conditions

141. Type III conditions are probably the most common during artificial destratification. Type III conditions are characterized by a relatively small temperature change near the surface (at depths shallower than normally occur during normal thermocline formation) and a more uniform temperature profile below this shallow zone of "microthermal" stratification. The shallow water temperature difference is usually only 2° or 3°C, and the depth interval is normally from 0 to 3 m. However, the temperature and depth ranges can vary. The reason for this thermal stratification is that there is more thermal energy being absorbed at the lake's surface (mostly from solar irradiance) than the destratification system can adequately redistribute (Fast 1973). The destratification system's efficiency greatly decreases as the lake approaches an isothermal condition, and the energy required to cause additional destratification increases logarithmically. Often a nearly steady-state condition exists during most of the summer, and the reservoir is not thoroughly mixed until advective cooling begins in the fall.

142. Type III lakes often have very low oxygen concentrations below the surface zone of thermal stratification. Oxygen concentrations can be especially low near the bottom of the water column. This is most pronounced in eutrophic lakes with dense algal populations. The destratification (incomplete) may even cause increased algal growth compared

with the unaerated condition (Fast 1973).

143. These low oxygen concentrations below the stratified zone indicate that the deep water is not, in general, in contact with the atmosphere, and that oxygen added from the compressed air is insufficient to meet the oxygen demands of the deep water. Consequently, dissolved N_2 and O_2 are not given much opportunity to equilibrate with the atmosphere. Nitrogen gas absorbed by the deep water from injected air does not readily degas, and N_2 supersaturations can result.

144. Lakes with a Type III condition typically have from 105 to 120 percent N_2 saturation below the thermally stratified shallow water. In some cases, N_2 saturation in this zone could exceed 130 percent.

145. Skinner, El Capitan, and Morena during June and August are good examples of the Type III condition. In all three cases, deepwater N_2 concentrations decreased from June to August, but N_2 saturations increased. At El Capitan, for example, deepwater N_2 decreased from about 14.5 mℓ/ℓ in June to about 13.5 mℓ/ℓ in August, but N_2 saturations increased from 106 to 114 percent (Figure 21). At Morena, the decreased N_2 concentrations were much smaller especially near the bottom, but the percent of increase was greater (Figure 23). At 24 m for example, N_2 decreased only 0.1 mℓ/ℓ between June and August, but N_2 saturation increased from 106 to 120 percent.

146. If N_2 is not absorbed from the injected air during the destratification process, and/or if the water below the thermal gradient is not heated by the penetration of solar irradience, then the lake should have 100 percent N_2 saturation at all depths at all times (Figure 34). The N_2 concentration of the deep water should decrease as warm surface water is mixed downward, but N_2 should not exceed 100 percent saturation. This situation seldom exists during Type III conditions, indicating either that N_2 is added to the deep water by the injected air, or the deep water is heated without compensatory degassing, or both.

147. But N_2 saturation changes as temperature does. Even a modest N_2 absorption from the injected air and/or a modest temperature increase without degassing could account for the N_2 saturation increases during Type III conditions. At Lake Morena, for example, the

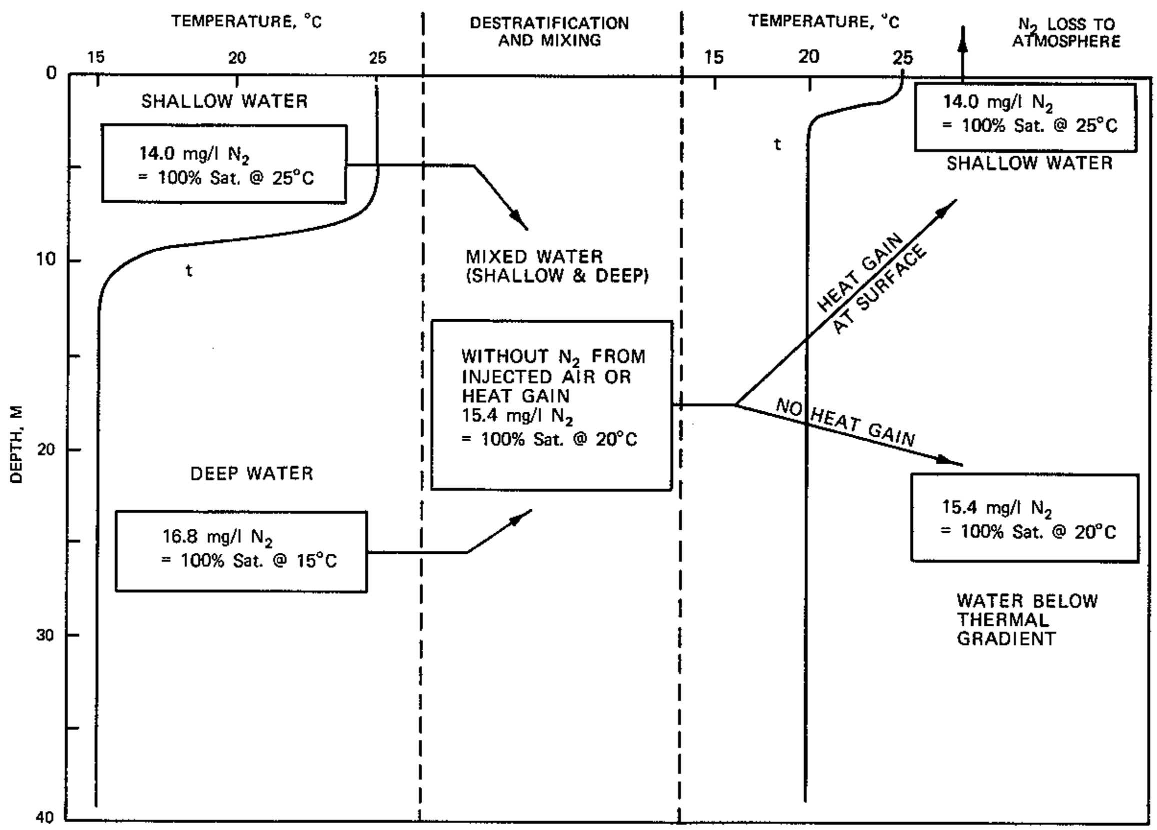

Figure 34. Changes in N_2 concentrations during artificial destratification, assuming no N_2 absorption from the injected air, or heat gain of the mixed water below the thermal gradient, under Type III conditions

total amount of N_2 above 100 percent saturation below the 4-m depth on August 8 was 54.4×10^3 kg (Table 3). From June 18 through August 8, 240 SCFM of air was continuously injected into Lake Morena. This totals 469×10^3 kg of N_2 in the injected air. If only 11.6 percent of the injected N_2 dissolved and remained below the 4-m depth, this would account for the observed concentrations and saturations at Lake Morena. Similar conclusions can be drawn from El Capitan Reservoir. On August 30 there was 97×10^3 kg of N_2 above 100 percent saturation, below the 9-m depth at El Capitan. If 15 percent of the N_2 injected between June 17 and August 30 dissolved and remained below the 9-m depth, the observed N_2 conentrations and saturations could be accounted for.

148. The N_2 supersaturations in the deep water during Type III conditions are probably due at least in part to temperature increases in this zone. Temperature increases in the deep water by two processes: (a) warm surface water moving downward and mixing with colder water below the thermocline, thus increasing the temperature of the bottom water (cold bottom water which moves upward and mixes with surface waters will decrease the surface water temperature, but the temperature soon rises due to solar heat input at the surface) and (b) solar irradiance penetrating the thermal gradient during Type III conditions.

149. The simple mixing of warm and cold waters at 100 percent N_2 saturation will normally cause only a slight N_2 supersaturation. For example, equal volumes of N_2 saturated waters at 15° and 25° C will mix to produce 20° C water with 101 percent N_2 saturation (Table 2, Figure 35). Zero degree and 30° C water mixed equally will produce water with 110 percent N_2 saturation; however we did not observe any conditions at this extreme, nor would we expect more than a 1 percent supersaturation from this source during most artificial destratification.

150. If sufficient solar irradiance penetrates into the deep water, it could cause heating without degassing and thus lead to N_2 supersaturation. Without artificial destratification, the thermocline is usually deep enough to prevent this occurrence. Almost all of the solar irradiance is absorbed above the thermocline. However, when Type III conditions develop during artificial destratification, the

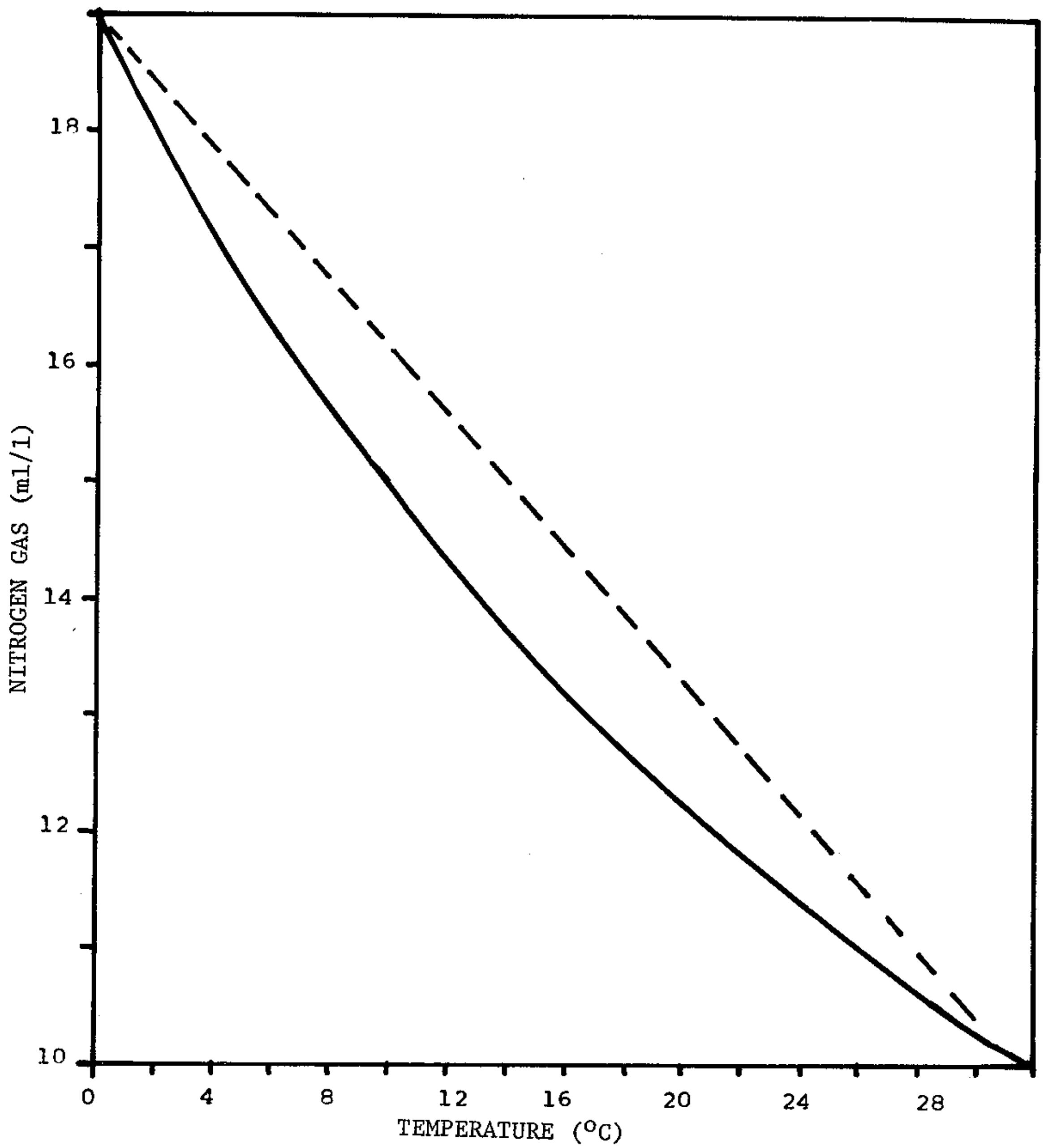

Figure 35. Dissolved atmospheric nitrogen gas saturation values from moist air, at one atmosphere in distilled water, as a function of temperature (Rucker 1972) (The dashed line is a straight line drawn between the extremes)

thermal gradient often shoals from 8 m or more to 3 m or less (Figure 34). If the water is clear, significant solar irradiance may penetrate below the 3-m depth and heat the deep water. This heat could be distributed throughout the depths by the circulation induced by destratification.

151. Solar irradiance penetrating below the thermal gradient would heat the deep water without affecting its gas content and cause saturation increases. For example, if the water is heated from 20° to 22° C by this process, N_2 saturations will be increased more than 3.6 percent (Table 2). A temperature increase from 15° to 25° C would produce a 20 percent increase in N_2 saturation. Although this process undoubtedly occurs and contributes to the observed N_2 saturation increases, we feel that it is not the primary cause of these increases. We feel that they come from the compressed air injected at depth as discussed in paragraph 147.

152. If solar absorption below the surface zone causes much warming, then the amount of N_2 absorbed from the compressed air could be even less than indicated above. This would produce the same percent saturation, with less absorption.

153. The relative contribution of the heating effect to N_2 saturation increases could be checked by observing changes in N_2 concentrations and saturations at lakes that are being incompletely mixed by mechanical pumps which do not use air injection. Destratification systems such as the Garton system (Garton et al. 1977) or those described by Dortch (1980a, b) or Ditmars (1970) do not inject air at depth, but they do cause temperature increases in deep water during artificial destratification.

154. An incomplete mix and its associated Type III conditions can lead to reductions in N_2 concentrations during artificial destratification, but concurrent increases in N_2 saturations in the deep water. N_2 saturations are generally less than 120 percent, but saturations in excess of 130 percent are possible.

Type IV Conditions

155. Type IV conditions are a combination of Type II and Type III

conditions. The diffuser is not set at the deepest point, and consequently water below the diffuser depth is not upwelled. At the same time, the aeration system is not large enough to thoroughly mix the lake above the diffuser depth, and thermal stratification persists near the surface. Type IV does not have any unique characteristics of its own, but simply combines characteristics of the other two types.

156. Lake Casitas and Mathews Reservoir are examples of Type IV conditions. Lake Casitas is particularly interesting because of the large N_2 increases that occurred both within the intermediate depths and below the diffuser.

157. Lake Casitas developed the classical Type IV condition during 1977 (Figure 28). During 1978 and 1979 this condition also appeared, but it was somewhat less pronounced (Figures 29-32). Both N_2 concentrations and saturations increased below the 10-m depth all 3 years during aeration, and the water volume below the diffuser depth always had the highest N_2 concentrations and N_2 saturations.

158. The deepwater average N_2 concentration reached a maximum average value of 20 mg/ℓ during September 1978 (Figure 36). During 1979, the average concentrations increased more rapidly and reached a maximum of 20.2 mg/ℓ by late July. The greater increase in 1979 was probably related to the greater rate of air injection during 1979. During 1978, only 331×10^5 ft^3 of air had been injected by July 1; but during 1979, 653×10^5 ft^3 had been injected by this date.

159. N_2 absorption data at Lake Casitas indicate a very high absorption rate, especially during 1978. N_2 content of the water below the 10-m depth increased by 165×10^3 kg between June 9 and July 7, 1978 (Table 4). During this same period, 338×10^3 kg of N_2 was injected into the lake via the compressed air. This indicates an incredible absorption efficiency of 49 percent, which is far higher than any other reported values for destratification systems which use air injection. Absorption efficiency between July 7 and September 27, 1978, dropped sharply to 6 percent. The rates during 1979 were much lower, decreasing from 28 percent during March/May to 6 percent during June/August. The elevated magnitude of the June 9-July 7, 1978, absorption

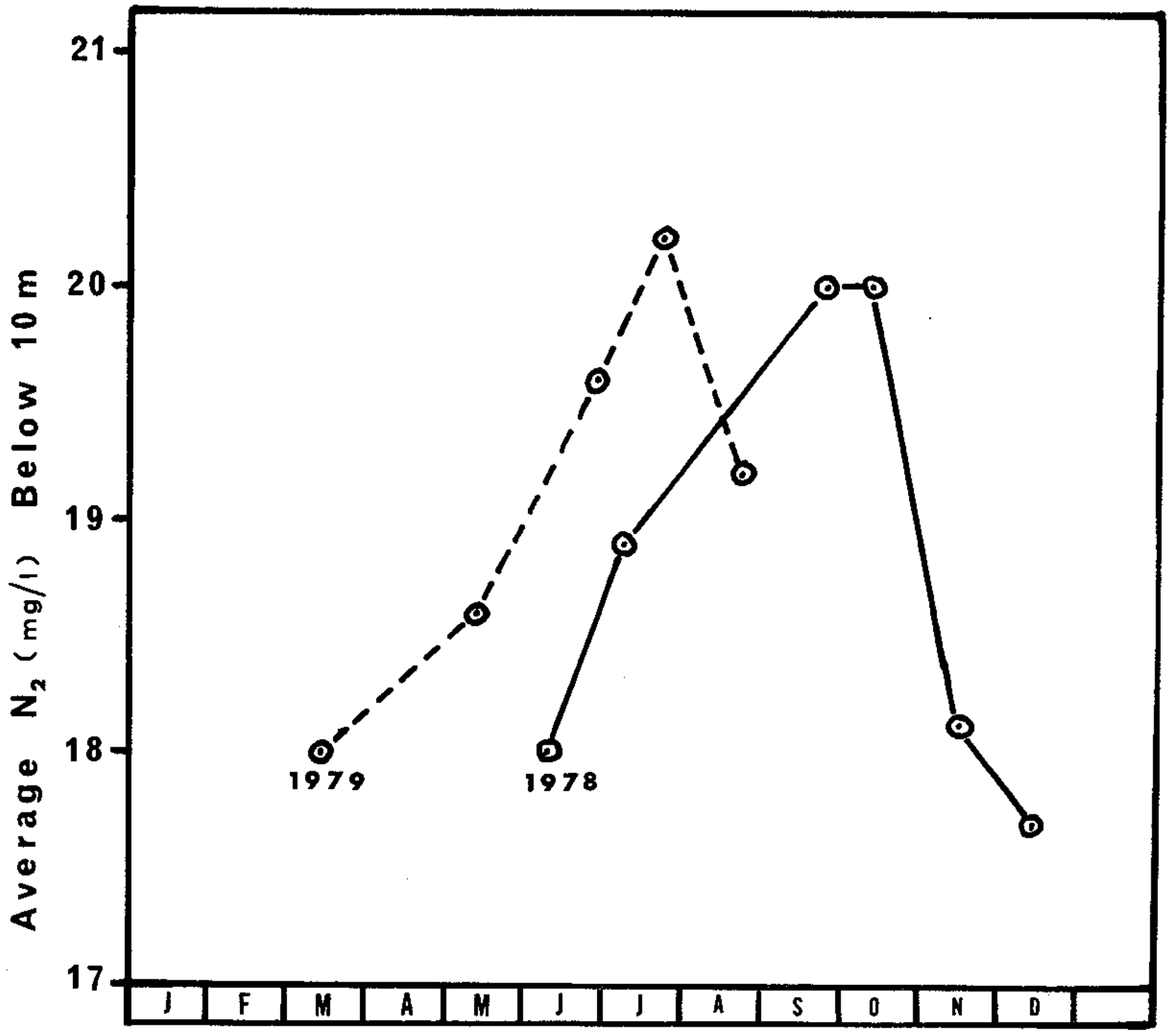

Figure 36. Average dissolved nitrogen gas concentrations below the 10-m depth at Lake Casitas during 1978 and 1979

efficiency above additional observations suggests the incorporation of some error into the N_2 absorption computation. This error may have resulted from incorrect calculation of the N_2 balance in the lake which, due to the addition of N_2 from multiple sources (paragraph 130), could have overestimated the relative absorption of the injected N_2. Inaccurate observation of the in situ N_2 values could have also introduced error into the absorption efficiency computation.

160. The high absorption efficiency and the N_2 concentration

increases at Casitas could be due to the unique diffuser configuration used during 1977, 1978, and 1979. During 1978, 630 SCFM of air was injected through 700 ft of diffuser when the aeration system was in operation. This yields an average air density per foot of diffuser of 0.90 SCFM/ft (Table 5). During early 1977, only one compressor injected 315 SCFM through 700 ft of diffuser for an air density of only 0.45 SCFM/ft. These air densities are much less than used elsewhere. At Wohlford and El Capitan, for example, the densities were 3.50 and 2.15 SCFM/ft, respectively. The low air densities applied at Casitas, combined with deep air injection, led to the high absorption rates for N_2.

161. At the diffuser depth (46 m), the pressure is more than 5-1/2 atmospheres absolute, compared with 1 atmosphere at the surface. Thus, water at this depth can hold 5-1/2 times as much dissolved gas as surface waters. Water saturated at the surface (100 percent) will be only 22 percent saturated at 46 m (Figure 37). Therefore, there is a greater driving force for the dissolution of air when it is injected deep. Casitas has the deepest diffuser depth of all the lakes we surveyed.

162. Low air densities in the bubble plume can lead to a greater N_2 absorption rate by another process. The process begins with the uncoupling of the bubbles from the rising plume when they encounter the thermal gradient near the surface (Figure 38). The bubbles continue to the surface, but the water in the plume spreads out below or within the thermal gradient and may not reach the surface. Thus the opportunity to degas is reduced since the water does not contact the atmosphere. The vertical velocity of the plume is also reduced, and the bubbles have greater contact time.

163. Speece (1975) used this uncoupling principle at Clark Hill Reservoir in South Carolina to artificially oxygenate the hypolimnion. His objective was to prevent the upwelling of the oxygenated hypolimnetic water. He used pure oxygen rather than air.

164. Fast (1979 a, b, 1980) observed this uncoupling phenomenon at Lake Casitas during the summer of 1977, when the diffuser air density was 0.45 SCFM/ft. Surface water temperatures within the bubble plume

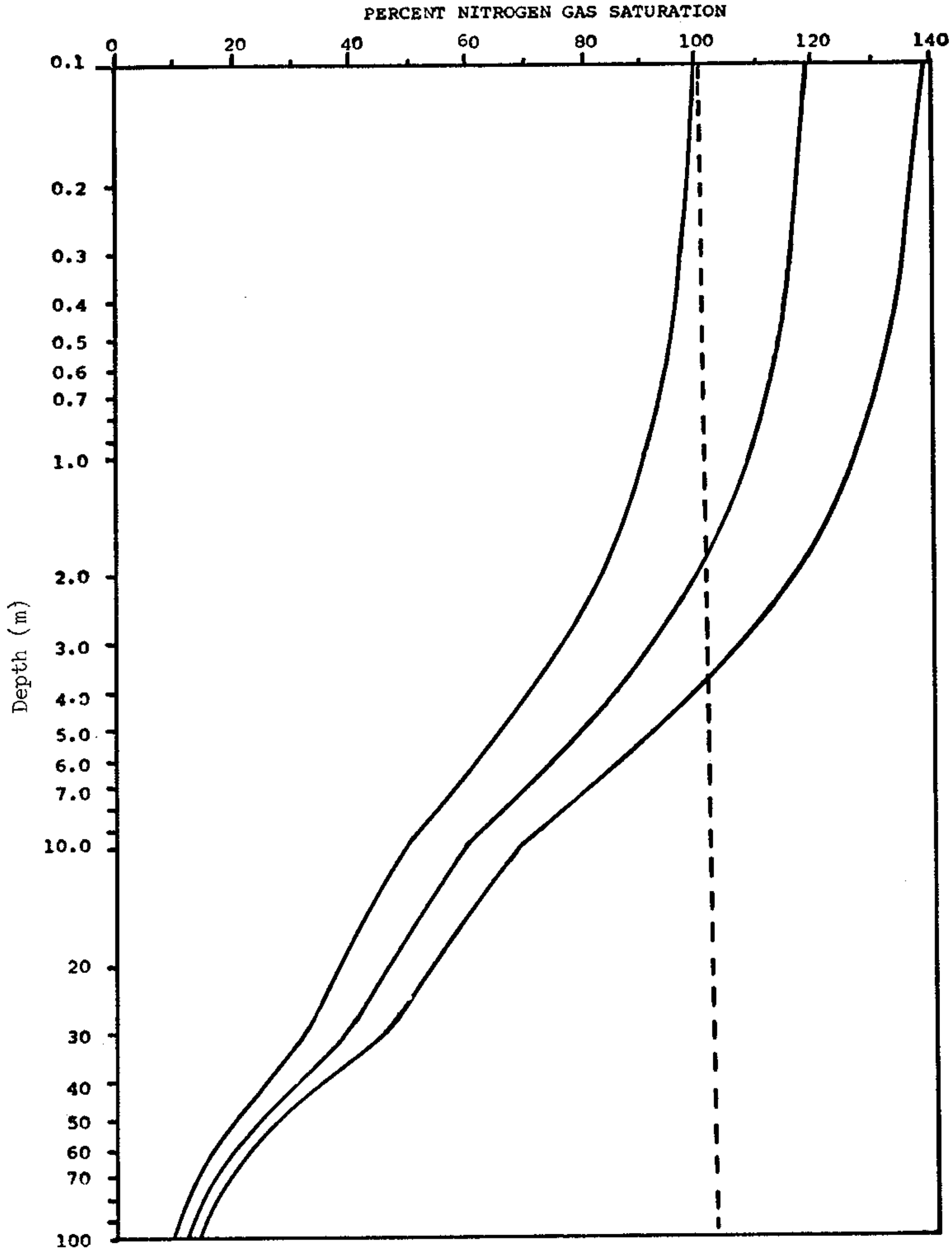

Figure 37. Dissolved nitrogen gas saturation at depth, starting with 100, 120, and 140 percent N_2 saturations at 0-m depth (These are in situ saturations, and are not relative to surface pressures)

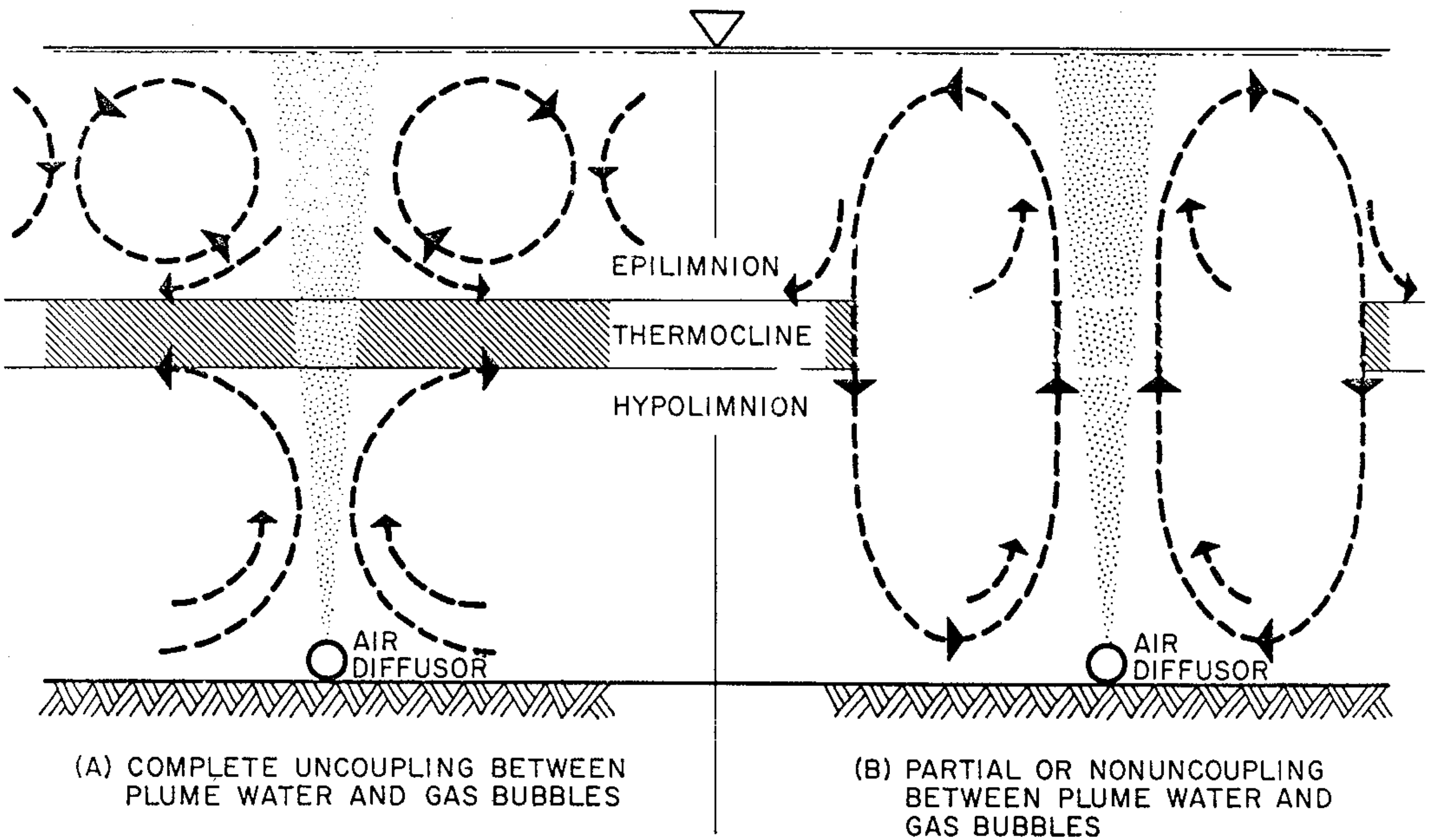

Figure 38. Proposed modes of bubble and water plume interactions during deep oxygen-bubble injection (Speece 1975)

were nearly equal to surrounding surface water temperatures, which indicates that the uncoupling process was nearly complete. The degree of uncoupling during 1978 and 1979 at Casitas, with the higher bubble densities, is unknown.

165. Nitrogen gas saturations during Type IV conditions can exceed 130 percent saturation in the intermediate depths and more than 140 percent below the diffuser depths. Deep air injection and low bubble densities can cause especially high saturation levels and lead to the Type IV conditions. Deep air injection and low bubble density should also cause especially high saturations during Type III conditions.

Summary of Conditions Causing N_2 Supersaturation in Aerated Lakes

166. During the foregoing discussion, we have concentrated our discussion on a few factors affecting N_2 supersaturation. The existing data base is not adequate to describe the relative importance of all factors, nor precisely define the interrelationship between factors. These cause-and-effect relationships must be better defined before we can accurately predict the resultant N_2 saturation in a given reservoir before it is aerated.

167. We believe there are at least nine important factors or conditions affecting N_2 saturation in an aerated reservoir:

a. Degree of thermal destratification. An incomplete or partial destratification such as occurs with Types III and IV conditions is more likely to produce N_2 supersaturation of the water above the diffuser than a thorough mix of this water.

b. Air injection at intermediate depth. This mode of air injection often results in a volume of water below the diffuser depth which is not mixed with overlying water, but which often has very high N_2 saturation values.

c. Depth of air injection. Increased injection depth will increase the potential for N_2 absorption due to the increased hydrostatic pressure.

d. Bubble density in the upwell plume. A very low bubble density will inhibit destratification and enhance N_2 absorption in the deep water. The upwelled water will uncouple from the air below the "thermocline" and will not reach the surface where it can degas.

e. Duration of air injection. A longer period of air injection creates a greater potential for N_2 supersaturation providing that the other conditions are also favorable for N_2 absorption.

f. Air input rate relative to total water volume. Low air input rates should cause an incomplete destratification, but less total N_2 for dissolution. High air input rates should cause a more thorough destratification, but more N_2 for dissolution. Probably the highest N_2 saturations will occur with moderate air input rates where a complete mix is not attained, but relatively large amounts of N_2 are injected in the air. (The highest N_2 saturations that we observed occurred at Lake Casitas even though the lake had the lowest air input to water volume of any that we surveyed. However, Lake Casitas also was the deepest, and had the lowest air bubble density in the upwell plume. Furthermore, the N_2 saturations during 1979 increased more rapidly and reached a greater maximum than during 1978 probably due to the greater air input during 1979.)

g. Oxygen content of the water. A low oxygen content will cause more oxygen to diffuse out of the injected air bubbles and into the water. This will increase the partial pressure of N_2 remaining in the air bubble, and thus increase the potential for the N_2 to dissolve in the water as well.

h. Denitrification. Nitrate reduction to N_2 in the water at the mud/water interface, or within the mud, can contribute N_2 to the lake and cause N_2 supersaturation.

i. Groundwater inflows. Some groundwaters are supersaturated with N_2. If these flows are relatively cold, they could flow into the deep areas of the lake and contribute to N_2 supersaturation within the lake.

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Table 1

Elevations, Theoretical Barometric Pressures, Water Volumes (acre ft), and Areas (acres) of the Reservoirs Sampled for Nitrogen Gas during 1979 (The date that each reservoir was sampled is shown in parentheses below each set of volume and area figures)

Reservoir	Elevation (ft)	Theoretical Barometric Pressure mmHg	June			August			October		
			Volume		Area	Volume		Area	Volume		Area
Puddingston	940	735	6,374	(13)	246	6,119	(28)	238	6,007	(9)	332
Mathews	1300	725	145,470	(14)	2400	146,273	(29)	2400	120,037	(10)	2100
Perris	1590	717	117,131	(15)	2234	78,165	(31)	1919	76,427	(15)	1901
Skinner	1480	720	39,666	(15)	1073	41,785	(4)	1104	39,569	(11)	1071
Vail	1100	730	37,546	(16)	921	34,837	(5)	885	31,290	(15)	838
Henshaw	2740	686	11,426	(16)	1217	6,416	(6)	836	1,802	(12)	303
Wohlford	1500	720	6,728	(17)	220	5,380	(6)	195	3,436	(12)	156
El Capitan	750	740	73,966	(17)	1195	66,837	(30)	1120	59,837	(13)	1041
Morena	2900	682	28,869	(18)	1045	28,435	(8)	1036	26,107	(14)	981
Murray	541	745	3,210	(19)	124	4,142	(7)	151	1,329	(15)	69
Cachuma	650	742	-		-	-		-	-		-
Casitas	550	745	-		-	-		-	-		-

Table 2

Dissolved Atmospheric Nitrogen Gas (N_2) Values from Moist Air at One Atmosphere in Distilled Water, as a Function of Water Temperature*

[Adopted from Weiss' 1970 data]

Temperature °C.	Atmospheric nitrogen as milliliters per liter									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0......	18.92	18.87	18.82	18.77	18.72	18.68	18.63	18.58	18.53	18.48
1......	18.43	18.39	18.34	18.29	18.25	18.20	18.15	18.11	18.06	18.02
2......	17.97	17.92	17.88	17.83	17.79	17.74	17.70	17.66	17.61	17.57
3......	17.52	17.48	17.44	17.40	17.35	17.31	17.27	17.22	17.18	17.14
4......	17.10	17.06	17.02	16.98	16.93	16.89	16.85	16.81	16.77	16.73
5......	16.69	16.65	16.61	16.57	16.53	16.49	16.46	16.42	16.38	16.34
6......	16.30	16.26	16.23	16.19	16.15	16.11	16.08	16.04	16.00	15.96
7......	15.93	15.89	15.85	15.82	15.78	15.75	15.71	15.67	15.64	15.60
8......	15.57	15.53	15.50	15.46	15.43	15.40	15.36	15.33	15.29	15.26
9......	15.22	15.19	15.16	15.12	15.09	15.06	15.03	14.99	14.96	14.93
10......	14.89	14.86	14.83	14.80	14.77	14.73	14.70	14.67	14.64	14.61
11......	14.58	14.55	14.52	14.48	14.45	14.42	14.39	14.36	14.33	14.30
12......	14.27	14.24	14.21	14.18	14.15	14.12	14.10	14.07	14.04	14.01
13......	13.98	13.95	13.92	13.89	13.87	13.84	13.81	13.78	13.75	13.73
14......	13.70	13.67	13.64	13.61	13.59	13.56	13.54	13.51	13.48	13.45
15......	13.43	13.40	13.37	13.35	13.32	13.29	13.27	13.24	13.22	13.19
16......	13.16	13.14	13.11	13.09	13.06	13.04	13.01	12.99	12.96	12.94
17......	12.91	12.89	12.86	12.84	12.81	12.79	12.77	12.74	12.72	12.69
18......	12.67	12.65	12.62	12.60	12.58	12.55	12.53	12.51	12.48	12.46
19......	12.44	12.41	12.39	12.37	12.34	12.32	12.30	12.28	12.25	12.23
20......	12.21	12.19	12.17	12.14	12.12	12.10	12.08	12.06	12.03	12.01
21......	11.99	11.97	11.95	11.93	11.91	11.89	11.86	11.84	11.82	11.80
22......	11.78	11.76	11.74	11.72	11.70	11.68	11.66	11.64	11.62	11.60
23......	11.58	11.56	11.54	11.52	11.50	11.48	11.46	11.44	11.42	11.40
24......	11.38	11.36	11.34	11.32	11.30	11.28	11.26	11.25	11.23	11.21
25......	11.19	11.17	11.15	11.13	11.11	11.10	11.08	11.06	11.04	11.02
26......	11.00	10.99	10.97	10.95	10.93	10.91	10.90	10.88	10.86	10.84
27......	10.83	10.81	10.79	10.77	10.76	10.74	10.72	10.70	10.69	10.67
28......	10.65	10.64	10.62	10.60	10.59	10.57	10.55	10.54	10.52	10.50
29......	10.49	10.47	10.45	10.44	10.42	10.40	10.39	10.37	10.35	10.34
30......	10.32	10.31	10.29	10.27	10.26	10.24	10.23	10.21	10.20	10.18

* Rucker 1972.

Table 3

Dissolved Nitrogen Gas (N_2) in Lake Morena Above 100% Saturation on August 8, 1979 (Between June 18 and August 8, 469 × 10^3 kg of N_2 Was Injected into the Lake by the Lake Aeration System)

Depth Interval (m)	Water Volume (10^6 m^3)	N_2 Concentrations (mg/ℓ)			N_2 (10^3kg)
		Observed	@100% sat.	Difference	
0-2	7.84	12.9	12.1	+ 0.8	6.27
2-4	6.37	13.6	12.4	+ 1.2	7.64
4-6	4.98	14.1	12.4	+ 1.7	8.47
6-8	3.94	14.2	12.5	+ 1.7	6.70
8-10	3.28	14.5	12.6	+ 1.9	6.23
10-12	2.64	14.5	12.6	+ 1.9	5.02
12-14	2.03	14.8	12.6	+ 2.2	4.47
14-16	1.38	14.8	12.7	+ 2.1	2.90
16-18	1.03	14.8	12.7	+ 2.1	2.16
8-20	0.78	14.8	12.7	+ 2.1	1.64
20-22	0.62	15.0	12.7	+ 2.3	1.43
22-24	0.38	15.2	12.7	+ 2.5	0.95
24-25	0.20	15.5	12.9	+ 2.6	0.52

Table 4

Increase in Dissolved N_2 Below the 10-m Depth as a Percentage of the Total N_2 Injected Into Lake Casitas in the Compressed Air

	Total N_2 Injected in Air (10^3 kg)	Dissolved N_2 Increase in Water (10^3 kg)	Absorption Rate (%)
1978			
June 9/July 7	338	165	49
July 7/Sept 27	1,641	94	6
Total or Average =	1,979	259	13
1979			
March 15/May 11	699	199	28
May 11/June 27	1,038	153	15
June 27/Aug 27	676	44	6
Total or Average =	2,416	396	16

Table 5

Average Air Volume to Unit Length of Diffuser for the "Linear" Diffuser Types Surveyed During This Study

Lake	Air Volume (SCFM)	Diffuser Length (feet)	Average (SCFM/ft)
Puddingstone (original)*	260	200	1.30
Henshaw (original)**	125	100	1.25
Wohlford	210	60	3.50
El Capitan	215	100	2.15
Morena	240	190	1.26
Casitas:			
1 compressor	315	700	0.45
2 compressors	630	700	0.90
1 compressor	315	400	0.79
2 compressors	630	400	1.58

* Now replaced by ring diffuser.
** The diffuser is no longer attached to the air line.

APPENDIX A: NITROGEN GAS, TEMPERATURE, OXYGEN, BAROMETRIC PRESSURE, AND SECCHI DISC DATA FROM EACH OF THE 12 RESERVOIRS SURVEYED

RESERVOIR: Puddingstone

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 13 June 1979 Secchi: 1.6m Barometric Pressure: 735							
0	24.9	8.4	104	782	11.1	105	105
2	23.8	8.3	100	780	11.6	108	91
4	21.5	3.6	42	675	11.8	105	76
6	17.5	0.0	0	615	12.7	105	67
8	14.9	0.0	0	634	13.8	109	62
10	13.2	0.0	0	641	14.4	110	57
12	12.9	0.0	0	645	14.9	113	53
14	12.8	0.0	0	659	15.0	113	49
16	12.7	0.0	0	670	15.2	115	46
18	12.5	0.0	0	679	15.5	117	43
Date Collected: 28 August 1979 Secchi: 1.6m Barometric Pressure: 743							
0	26.2	6.8	86	735	10.7	102	102
2	26.2	6.6	84	731	10.7	102	86
4	26.2	6.3	80	729	10.8	103	75
6	26.2	5.0	63	703	10.8	103	66
8	26.1	4.7	59	695	10.7	102	53
10	26.0	4.6	58	692	10.7	102	52
12	26.0	4.4	56	687	10.7	102	48
14	25.8	4.0	50	671	10.6	100	43
16	15.9	0.0	0	817	17.5	139	55
Date Collected: 9 October 1979 Secchi: 1.7m Barometric Pressure: 742							
0	23.1	5.2	62	685	11.0	100	100
2	23.0	5.2	61	671	10.8	98	82
4	23.0	5.0	59	661	10.6	96	70
6	23.0	4.9	58	657	10.6	96	61
8	23.0	4.4	52	655	10.7	97	55
10	23.0	4.2	49	653	10.7	97	50
12	23.0	5.0	59	643	10.3	93	44
14	23.0	4.4	52	647	10.6	96	41
16	20.2	3.6	40	630	11.1	96	38
17	19.3	0.0	0	827	16.6	141	54

RESERVOIR: Mathews

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 14 June 1979 Secchi: 3.6m							
Barometric Pressure:							
0	24.5	8.8	109	757	10.8	102	102
4	22.8	9.3	111	768	11.3	104	76
8	20.0	7.8	87	746	12.1	106	61
12	18.2	6.4	71	727	12.7	108	51
16	17.2	5.8	63	712	12.9	107	43
20	16.2	5.2	69	697	13.0	106	37
24	15.1	4.4	46	689	13.5	108	33
28	13.2	3.6	36	682	14.2	109	30
32	12.0	3.1	30	659	14.2	106	27
36	11.9	2.6	25	645	14.0	105	24
40	11.8	2.6	25	642	14.0	105	22
44	11.7	2.6	25	641	14.0	105	21
48	11.7	2.5	24	641	14.0	105	19
52	11.7	2.4	23	641	14.1	105	18
Date Collected: 29 August 1979 Secchi: 3.0m							
Barometric Pressure: 723							
0	24.7	7.9	98	745	10.9	103	103
4	24.7	7.9	98	753	11.0	105	76
8	24.4	6.8	84	732	11.1	105	60
12	24.2	5.1	63	711	11.3	107	50
16	24.1	3.9	48	694	11.4	108	43
20	24.0	3.8	46	696	11.5	108	38
24	23.9	3.4	41	688	11.5	108	34
28	22.3	1.0	41	665	12.3	112	31
32	21.3	0.3	3	649	12.4	111	28
36	16.5	0.2	2	631	13.2	109	25
40	12.9	0.2	2	621	14.0	107	23
44	12.2	0.2	2	615	14.1	106	21
48	12.0	0.1	1	614	14.1	106	19
52	12.0	0.1	1	613	14.1	106	18

(Continued)

RESERVOIR: Mathews (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 10 October 1979 Secchi: 3.8m							
Barometric Pressure: 728							
0	23.8	6.2	76	711	11.0	103	103
4	23.7	6.0	73	706	11.0	103	75
8	23.7	6.2	76	698	10.8	101	58
12	23.7	6.2	76	698	10.8	101	48
16	23.7	6.1	74	698	10.8	101	41
20	23.6	6.0	73	695	10.8	101	35
24	23.6	5.2	63	694	11.1	103	32
28	23.6	5.2	63	696	11.1	104	29
32	21.8	3.4	40	678	11.8	107	27
36	13.8	0.1	1	643	14.3	111	26
40	12.5	0.0	0	631	14.4	109	23
44	12.2	0.0	0	627	14.4	109	21
48	12.1	0.0	0	626	14.4	109	20
50	12.1	0.0	0	625	14.4	108	19

RESERVOIR: Perris

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 15 June 1979			Secchi: 2.7m				
Barometric Pressure:							
0	23.0	9.2	110	758	11.1	104	104
2	23.0	9.5	113	773	11.2	105	89
4	20.4	7.4	85	746	12.1	109	80
6	19.4	5.4	61	703	12.2	107	69
8	18.2	4.4	49	680	12.4	107	62
10	17.2	3.9	42	655	12.3	104	54
12	15.7	2.7	29	629	12.6	103	49
14	14.8	1.4	15	622	11.8	105	46
16	14.3	1.4	14	620	13.2	105	43
18	14.0	1.2	12	621	13.3	106	40
20	13.0	1.0	10	620	13.5	106	38
22	12.4	0.7	7	614	13.8	106	35
24	11.6	0.5	5	607	14.0	106	33
Date Collected: 31 August 1979			Secchi: 1.7m				
Barometric Pressure:							
0	25.4	8.0	114	740	10.6	105	105
2	24.5	8.7	107	749	10.7	104	88
4	23.9	7.0	85	695	10.4	101	74
6	23.3	4.3	52	666	10.9	105	68
8	23.2	2.8	34	630	10.8	103	60
10	22.7	1.2	14	599	10.9	103	54
12	22.1	1.9	27	646	11.6	109	52
14	20.8	3.0	34	653	11.7	107	47
16	18.8	1.4	16	613	11.9	105	43
18	15.8	0.0	0	619	13.2	110	42
19	15.3	0.0	0	626	13.5	112	41

(Continued)

RESERVOIR: Perris (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 13 October 1979 Secchi: 2.9m							
Barometric Pressure:							
0	23.5	7.6	92	731	11.0	104	104
2	22.4	9.0	107	741	10.9	102	86
4	21.9	5.2	61	674	11.1	103	75
6	21.8	5.3	62	668	10.9	101	66
8	21.7	5.3	62	666	10.9	101	59
10	21.7	5.2	61	666	11.0	101	53
12	21.7	5.0	61	667	11.0	102	49
14	21.6	5.4	64	667	10.9	101	44
16	21.5	5.2	61	663	11.0	101	41
18	21.4	3.2	38	654	11.5	105	40
19	0.6	0.6	7	641	12.2	112	41

RESERVOIR: Skinner

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 15 June 1979			Secchi: 2.1m				
Barometric Pressure: 720							
0	22.8	8.9	109	756	11.2	104	104
2	22.4	9.2	110	772	11.5	106	90
4	20.6	7.4	85	750	12.1	109	80
6	19.9	7.6	86	752	12.3	109	70
8	19.9	6.7	76	738	12.3	109	63
10	19.7	7.2	81	736	12.2	107	56
12	19.5	6.4	72	724	12.3	108	51
14	19.4	5.7	65	714	12.3	108	47
16	19.3	5.0	57	707	12.5	109	44
18	19.0	3.8	43	696	12.7	111	42
20	18.4	1.8	20	658	12.8	110	39
23	16.9	0.2	2	619	12.9	108	35
Date Collected 4 August 1979			Secchi: 2.4m				
Barometric Pressure: 720							
0	26.2	8.6	110	768	10.7	105	105
2	25.6	8.6	109	777	11.0	107	91
4	25.2	7.6	95	765	11.2	109	80
6	25.0	6.2	78	739	11.2	109	70
8	24.8	5.3	66	721	11.3	109	63
10	24.7	4.7	58	711	11.3	109	57
12	24.6	3.9	48	699	11.4	110	52
14	24.5	3.5	43	694	11.5	110	48
16	24.4	3.0	37	681	11.4	109	44
18	24.1	1.4	17	661	11.7	111	42
20	24.0	1.3	16	647	11.5	109	38
23	23.0	0.1	1	621	11.6	108	35

(Continued)

RESERVOIR: Skinner (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 11 October 1979 Secchi: 2.2m							
Barometric Pressure: 722							
0	23.3	6.8	82	709	10.9	102	102
2	23.3	6.8	82	705	10.8	101	85
4	23.3	6.8	82	701	10.7	101	74
6	23.2	6.8	82	697	10.7	100	64
8	23.2	5.3	63	666	10.9	100	57
10	23.2	6.7	80	696	10.7	100	52
12	23.2	6.6	79	696	10.7	100	48
14	23.2	6.6	79	694	10.7	100	44
16	23.2	6.5	77	694	10.7	100	41
18	23.2	6.6	79	695	10.7	100	38
20	23.2	6.6	79	696	10.7	100	35
23	23.1	6.6	79	697	10.8	100	32

RESERVOIR: Vail

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 11 June 1979			Secchi: 3.6m				
Barometric Pressure: 734							
0	22.8	9.0	106	755	11.1	102	102
3	22.3	8.6	101	759	11.5	104	81
6	20.4	4.5	51	684	11.9	104	67
9	16.4	0.2	2	608	12.7	104	56
12	11.6	0.0	0	602	14.0	103	49
15	10.2	0.0	0	606	14.5	104	43
18	10.0	0.0	0	616	14.8	106	40
21	9.9	0.0	0	619	15.0	106	36
24	9.9	0.0	0	622	15.0	107	33
27	9.8	0.0	0	623	15.1	107	30
29	9.8	0.0	0	630	15.3	108	29
Date Collected: 5 August 1979			Secchi: 1.3m				
Barometric Pressure: 730							
0	24.4	7.8	95	736	10.8	102	102
3	24.2	7.7	94	738	10.9	103	80
6	24.0	7.5	90	730	10.9	102	65
9	16.3	0.0	0	614	13.0	106	58
12	12.0	0.0	0	620	14.3	107	51
15	10.5	0.0	0	624	14.9	108	45
18	10.1	0.0	0	635	15.3	110	41
21	10.0	0.0	0	640	15.4	111	38
24	10.0	0.0	0	643	15.5	111	34
27	10.0	0.0	0	663	16.0	115	33
30	10.0	0.0	0	681	16.4	118	31
Date Collected: 11 October 1979			Secchi: 2.2m				
Barometric Pressure: 730							
0	22.1	6.2	73	699	11.2	102	102
3	21.6	5.8	67	675	11.0	99	77
6	21.6	5.4	63	666	10.9	98	63
9	19.7	4.1	46	649	11.5	100	54
12	12.7	0.0	0	647	14.7	112	53
15	11.2	0.0	0	656	15.4	114	47
18	10.9	0.0	0	676	16.0	117	44
21	10.8	0.0	0	686	16.3	119	40
24	10.8	0.0	0	695	16.5	120	37
27	10.8	0.0	0	699	16.6	121	35
29	10.8	0.0	0	702	16.7	122	33

RESERVOIR: Henshaw

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 16 June 1979 Secchi: 0.4m Barometric Pressure: 698							
0	20.8	5.2	63	664	11.1	103	103
1	20.5	5.2	63	652	11.0	101	93
2	20.2	5.2	62	645	10.9	100	85
3	20.1	4.9	58	644	11.0	101	80
4	20.0	5.0	60	644	11.0	101	74
5	20.0	5.2	62	639	10.8	99	69
6	20.0	4.8	57	643	11.0	101	66
7	20.0	4.8	57	645	11.1	101	62
8	19.9	5.2	62	644	11.0	100	59
9	19.8	5.0	60	640	11.0	100	56
Date Collected: 6 August 1979 Secchi: 0.2m Barometric Pressure: 678							
0	24.7	4.6	60	647	10.2	104	104
1	23.9	4.1	53	620	10.0	101	93
2	23.8	4.1	53	606	9.7	98	84
3	23.8	4.0	51	603	9.7	98	78
4	23.8	3.9	50	601	9.7	98	73
5	23.8	3.8	49	598	9.7	98	68
6	23.8	3.9	50	596	9.6	97	64
7	23.8	3.8	49	595	9.6	97	60
8	23.8	3.1	40	575	9.5	96	57
Date Collected: 12 October 1979 Secchi: 0.2m Barometric Pressure: 692							
0	18.0	5.6	64	652	11.4	102	102
1	17.5	5.7	65	630	11.1	98	90
2	17.3	5.8	66	628	11.1	97	83
3	17.2	6.1	69	626	10.9	96	76
4	17.2	5.8	66	625	11.0	97	71
5	17.0	6.1	69	618	10.8	94	65

RESERVOIR: Wohlford

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 17 June 1979 Secchi: 2.0m Barometric Pressure: 720							
0	20.7	8.1	93	756	12.0	108	108
2	20.7	8.0	92	760	12.1	109	92
4	20.7	7.6	87	745	11.9	107	78
6	20.5	5.6	64	725	12.3	110	71
8	20.4	6.2	71	718	12.0	107	62
10	20.4	6.2	71	718	11.9	107	56
12	20.3	5.9	67	709	11.0	106	51
14	20.2	5.6	64	701	11.9	106	46
16	20.2	5.4	61	797	11.9	106	43
18	20.1	5.2	59	694	11.9	106	40
19	20.0	5.2	59	691	11.9	106	38
Date Collected: 6 August 1979 Secchi: 1.4m Barometric Pressure: 720							
0	25.1	9.0	113	774	10.9	106	106
2	24.9	9.0	113	782	11.1	107	91
4	24.7	7.6	94	765	11.3	109	80
6	24.4	5.6	69	732	11.5	110	71
8	24.3	3.8	47	697	11.5	110	63
10	24.2	3.2	40	688	11.5	110	57
12	24.0	3.3	40	658	11.0	104	50
14	24.0	2.3	28	657	11.3	107	47
16	23.8	1.8	22	657	11.5	109	44
17	23.8	1.1	13	642	11.5	109	42
Date Collected: 12 October 1979 Secchi: 0.8m Barometric Pressure: 708							
0	22.1	7.3	87	700	10.8	101	101
2	21.4	6.6	77	688	11.0	101	86
4	21.4	6.1	71	674	10.9	101	74
6	21.2	5.9	69	666	10.8	100	65
8	21.2	5.7	66	658	10.8	99	58
10	21.2	5.1	59	656	10.9	100	53
12	21.2	4.3	50	648	11.0	102	49

RESERVOIR: El Capitan

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 17 June 1979 Secchi: 1.8m							
Barometric Pressure: 740							
0	19.7	8.6	95	758	12.1	104	104
3	19.0	7.2	78	745	12.5	106	83
6	15.8	5.2	53	712	13.5	107	69
9	14.6	4.4	44	700	13.9	108	58
12	14.1	4.3	42	695	13.9	107	50
15	13.7	4.0	39	692	14.1	108	45
18	13.2	3.6	35	685	14.2	108	40
21	12.8	3.4	33	681	14.3	107	36
24	12.6	3.4	33	674	14.2	107	33
27	12.3	3.2	30	668	14.2	106	30
30	12.2	3.0	28	668	14.3	106	28
33	12.1	2.4	23	651	14.2	105	26
36	11.9	2.2	21	648	14.2	105	24
39	11.8	2.2	21	648	14.2	105	22
42	11.8	1.4	13				
44	11.7	1.4	13				
Date Collected: 30 August 1979 Secchi: 2.4m							
Barometric Pressure: 743							
0	23.0	8.1	94	772	11.7	106	106
3	22.2	7.2	84	764	12.0	108	84
6	20.9	4.6	52	734	12.7	111	71
9	20.0	2.9	32	713	13.1	113	61
12	20.0	2.0	22	706	13.3	114	53
15	19.8	2.0	22	698	13.2	113	47
18	19.8	1.2	13	695	13.3	114	42
21	19.7	1.2	13	693	13.4	114	33
24	19.6	1.0	11	689	13.4	114	35
27	19.5	0.4	4	681	13.4	115	32
30	19.4	0.5	5	678	13.4	114	30
33	19.2	0.5	5	674	13.4	113	27
36	19.1	0.2	2	675	13.5	114	26
39	19.1	0.2	2	674	13.5	114	24
42	18.9	0.0	0	674	13.6	115	23

(Continued)

RESERVOIR: El Capitan (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 13 October 1979 Secchi: 2.3m							
Barometric Pressure: 734							
0	21.7	4.3	49	714	12.2	109	109
3	21.4	4.0	45	710	12.3	110	86
6	21.4	4.0	45	707	12.3	109	70
9	21.4	4.0	45	707	12.3	109	59
12	21.4	4.1	47	708	12.3	109	52
15	21.4	4.0	45	711	12.4	110	46
18	21.4	4.1	47	713	12.3	110	41
21	21.4	4.1	47	715	12.4	110	37
24	21.4	4.2	48	719	12.4	111	34
27	21.3	4.5	51	720	12.4	110	31
30	21.3	4.1	47	721	12.5	112	29
33	21.2	4.1	47	723	12.6	112	27
36	21.2	4.1	47	725	12.6	112	26
39	21.2	4.0	45	728	12.7	113	24
40	21.2	3.8	43	727	12.8	113	24

RESERVOIR: Morena

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 18 June 1979 Secchi: 1.1m							
Barometric Pressure: 692							
0	18.7	8.4	101	714	11.6	104	104
2	17.6	4.0	47	657	12.2	108	92
4	17.3	3.0	35	624	11.9	105	78
6	17.2	1.2	14	605	12.2	106	70
8	17.1	1.2	14	598	12.0	105	62
10	17.1	1.2	14	595	12.0	105	56
12	17.1	1.2	14	593	12.0	105	51
14	17.0	1.0	12	592	12.0	105	47
16	17.0	1.0	12	591	12.0	105	43
18	17.0	1.0	12	587	11.9	104	40
20	17.0	0.9	10	584	11.9	104	38
22	16.9	0.0	0	580	12.1	105	36
24	16.5	0.0	0	582	12.3	106	34
Date Collected: 8 August 1979 Secchi: 0.9m							
Barometric Pressure: 682							
0	26.9	6.4	89	708	10.2	108	108
2	24.0	3.0	39	625	10.4	105	89
4	23.9	0.0	0	610	11.2	113	84
6	23.8	0.0	0	618	11.4	114	75
8	23.6	0.0	0	622	11.5	115	68
10	23.5	0.0	0	622	11.6	115	62
12	23.2	0.0	0	625	11.7	116	57
14	23.0	0.0	0	630	11.8	117	53
16	23.0	0.0	0	629	11.8	116	49
18	23.0	0.0	0	631	11.8	117	46
20	22.9	0.0	0	633	11.9	117	43
22	22.8	0.0	0	640	12.0	119	41
24	22.8	0.0	0	646	12.2	120	39
25	22.4	0.0	0	658	12.5	120	38

(Continued)

RESERVOIR: Morena (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 14 October 1979 Secchi: 1.7m							
Barometric Pressure: 677							
0	20.8	0.8	10	580	11.0	105	105
2	20.8	0.5	6	564	10.8	103	88
4	20.8	0.5	6	562	10.7	103	76
6	20.8	0.5	6	560	10.7	102	68
8	20.8	0.6	7	560	10.7	102	61
10	20.8	0.6	7	561	10.7	102	55
12	20.8	0.6	7	564	10.7	103	51
14	20.8	0.5	6	565	10.8	103	47
16	20.7	0.5	6	564	10.8	103	43
18	20.7	0.7	9	564	10.7	102	40
20	20.7	0.5	6	564	10.8	103	38
22	20.6	0.4	5	564	10.8	103	36
24	20.6	0.4	5	565	10.9	104	34
25	20.6	0.6	7	564	10.8	103	33

RESERVOIR: Murray

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 19 June 1979 Secchi: 2.7m							
Barometric Pressure:							
0	21.5	8.5	98	774	12.0	104	104
2	21.1	8.2	93	775	12.2	105	88
4	20.7	7.8	88	768	12.3	105	76
6	20.6	7.3	82	758	12.3	105	66
8	20.0	6.9	77	731	12.1	102	57
10	18.4	3.5	38	670	12.4	102	52
12	17.6	2.4	26	642	12.4	100	46
14	13.7	0.0	0	633	14.1	105	45
16	12.5	0.0	0	636	14.5	106	42
17	12.3	0.0	0	676	15.5	113	43
Date Collected: 7 August 1979 Secchi: 4.0m							
Barometric Pressure: 745							
0	24.2	7.2	87	770	10.7	106	106
2	23.7	6.6	79	770	11.0	108	91
4	23.5	6.6	78	765	10.9	107	78
6	23.4	6.6	78	761	10.9	106	68
8	23.3	6.0	71	760	11.1	109	62
10	23.1	5.3	62	735	11.0	107	55
12	23.0	4.9	57	713	10.8	104	49
14	18.2	0.0	0	619	12.2	105	45
16	14.1	0.0	0	640	13.6	108	41

RESERVOIR: Cachuma

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 28 October 1979 Secchi: 7.1m							
Barometric Pressure: 740							
0	19.1	7.9	86	716	11.7	99	99
3	19.0	7.4	80	718	11.9	101	79
6	19.0	7.8	85	715	11.7	99	63
9	18.9	7.6	89	707	11.6	98	53
12	18.8	7.6	89	706	11.6	98	46
15	18.8	7.6	89	706	11.6	98	41
18	14.4	0.1	1	610	13.4	104	38
21	13.9	0.0	0	595	13.2	101	34
24	13.5	0.2	2	593	13.2	101	31
27	13.2	0.2	2	592	13.2	100	28
30	13.1	0.4	4	592	13.2	100	26
33	13.0	0.1	1	592	13.3	101	24
36	13.0	0.0	0	593	13.4	101	23
39	12.9	0.1	1	593	13.4	101	22
44	12.7	0.1	1	592	13.5	101	20

RESERVOIR: Casitas

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 9 June 1978 Barometric Pressure: 745							
0	22.0	8.6	100	772	11.8	105	105
10	17.1	6.7	70	769	13.8	112	57
20	15.1	6.2	63	758	14.3	112	39
30	14.9	6.0	59	753	14.4	112	29
40	14.5	5.8	58	753	14.6	113	23
50	14.0	4.9	48	751	15.0	115	20
60	13.9	4.8	47	751	15.1	115	17
Date Collected: 7 July 1978 Barometric Pressure: 745							
0	23.0	9.3	108	784	11.5	104	104
10	17.8	6.0	64	792	14.3	118	60
20	16.1	5.1	53	784	15.0	119	41
30	15.6	4.8	49	783	15.2	120	31
40	15.4	4.4	45	782	15.4	121	25
50	14.6	3.6	36	781	15.9	123	21
60	14.0	3.2	31	778	16.2	124	19
Date Collected: 27 September 1978 Barometric Pressure: 745							
0	22.0	8.4	98	782	12.0	107	107
10	19.8	6.0	67	836	14.6	125	64
20	18.5	4.0	43	830	15.6	130	45
30	18.0	3.6	38	832	15.9	131	34
40	17.6	3.0	32	833	16.3	133	28
50	16.3	1.5	15	880	18.2	146	25
Date Collected: 13 October 1978 Barometric Pressure: 745							
0	21.2	8.2	93	780	12.3	108	108
10	19.9	5.8	64	833	14.5	124	64
20	19.0	4.4	48	843	15.5	131	45
30	18.5	3.5	38	848	16.1	134	35
40	18.2	2.6	28	850	16.5	137	29
50	16.6	1.1	11	847	17.5	141	25
60	14.6	0.4	4	842	18.4	142	21

(Continued)

RESERVOIR: Casitas (Continued)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 17 November 1978							
Barometric Pressure: 745							
0	18.0	5.5	59	769	13.9	115	115
10	18.0	5.4	57	784	14.3	118	61
20	18.0	5.4	57	789	14.4	119	41
30	18.0	5.4	57	818	15.0	124	32
40	18.0	5.2	55	799	14.6	121	25
50	17.4	4.4	46	796	15.0	123	21
60	14.6	0.0	0	796	17.5	135	20
Date Collected: 15 December 1978							
Barometric Pressure: 745							
0	15.5	6.9	70	734	13.4	106	106
10	15.5	6.8	69	755	13.9	110	56
20	15.5	6.8	69	756	14.0	110	38
30	15.5	6.8	69	765	14.2	112	29
40	15.5	6.8	69	775	14.4	113	24
50	15.5	6.8	69	776	14.4	113	20
60	15.5	6.8	69	774	14.4	113	17
Date Collected: 15 March 1979							
Barometric Pressure: 745							
0	15.7	10.0	102	795	13.6	108	108
10	13.1	9.6	92	769	14.1	106	54
20	12.7	8.4	81	754	14.3	107	37
30	12.6	8.0	77	752	14.5	107	28
40	12.5	8.0	75	754	14.5	108	22
50	12.5	7.8	74	755	14.6	108	19
60	12.5	7.8	74	758	14.7	109	16
Date Collected: 11 May 1979							
Barometric Pressure: 745							
0	18.1	9.0	97	775	12.8	106	106
10	15.9	8.1	84	798	14.3	114	58
20	14.1	7.3	72	784	14.9	114	39
30	14.0	7.1	70	782	14.9	114	30
40	13.6	6.8	66	783	15.2	115	24
50	13.4	6.5	63	782	15.4	116	20
60	13.0	5.8	56	781	15.7	118	18

(Continued)

RESERVOIR: Casitas (Concluded)

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/ℓ)	Dissolved Oxygen (% sat. rel. surf.)	Tension Pressure (mmHg)	N_2 (mℓ/ℓ)	N_2 (% sat. rel. surf.)	N_2 (% sat. *in situ*)
Date Collected: 29 June 1979							
Barometric Pressure: 745							
0	23.0	9.6	112	806	11.8	107	107
10	17.7	7.1	76	827	14.7	121	62
20	15.8	6.3	64	827	15.6	124	43
30	15.2	6.1	62	826	15.8	124	32
40	14.9	5.7	58	826	16.1	125	26
50	14.3	4.9	49	827	16.6	128	22
60	13.4	4.2	41	823	17.1	129	19
Date Collected: 27 July 1979							
Barometric Pressure: 745							
0	23.4	8.4	99	793	11.9	108	108
10	18.8	6.5	71	852	15.1	126	64
20	16.7	5.8	60	850	15.9	129	44
30	16.1	5.5	57	850	16.3	130	34
40	15.9	5.0	52	849	16.5	131	27
50	15.0	3.8	38	846	17.2	134	23
60	13.5	3.2	31	842	17.8	135	20
Date Collected: 27 August 1979							
Barometric Pressure: 745							
1	23.4	8.8	104	790	11.3	105	--
2	23.4	9.0	106	797	11.5	107	--
4	23.3	9.1	107	793	11.4	106	--
6	22.2	7.8	91	816	12.0	110	--
8	21.1	7.0	80	808	12.8	114	--
10	20.1	6.1	68	809	13.5	118	--
15	18.7	5.7	62	816	14.9	125	--
20	18.1	5.4	58	816	15.0	124	--
25	17.7	5.2	55	821	15.4	126	--
35	17.4	5.0	53	824	16.2	129	--
45	17.1	4.8	51	822	16.4	133	--
55	14.8	3.0	30	818	17.3	134	--

APPENDIX B: AERATION SYSTEM DESCRIPTIONS

Puddingstone Reservoir Aeration System

1. The Puddingstone Reservoir aeration system was installed and began operation during 1968. The system was installed by the Los Angeles County Department of Parks and Recreation in an effort to improve fishing quality. Without artificial aeration, less than 50 percent of the reservoir's volume and bottom area was inhabitable by the fish. Fast and St. Amant (1971) describe the system and its initial operation.

2. The system consists of a single compressor on shore and a single air line running along the bottom to the diffuser reaction. The compressor is a Jaeger rotary compressor, producing 260 SCFM at 100 psi. The compressor is housed in a block building which protects it from visitors and the weather (Figure B1). This building also reduces the noise generated by the compressor. Air is conveyed from the compressor into the lake through a 2-in. steel pipe. The steel pipe is buried underground from the compressor building to the shoreline, and the steel line extends into the lake for another 300 ft (Figure B2). Attached to the end of the steel pipe is another 425 ft of 2-in. PVC (schedule 80) pipe. The original diffuser was attached to the end of this pipe and consisted of another 200 ft of PVC pipe drilled with holes. The diffuser section was attached to the main line at a 45° angle and contained 400 1/16-in. holes.

3. The original diffuser secton broke off from the main line several years ago and has since been replaced by a circular diffuser. The ring diffuser is 24 ft in diameter, of 2-in. black iron pipe, and has an unknown number of holes of unknown size. The ring stands 4 to 6 ft off the bottom in about 45 ft of water. Description of the location of the diffuser system for each reservoir is given in Table B1.

4. The compressor operation is erratic. The first year (1968) that it was in operation, it operated only 12 hr each day from 2100 to 0500 hr. Some years it was not operated at all. During 1979, it began operation during early July and discontinued operation during late August. While in operation during 1979, it operated continuously 24 hr each day.

Figure B1. Compressor building at Puddingstone Reservoir

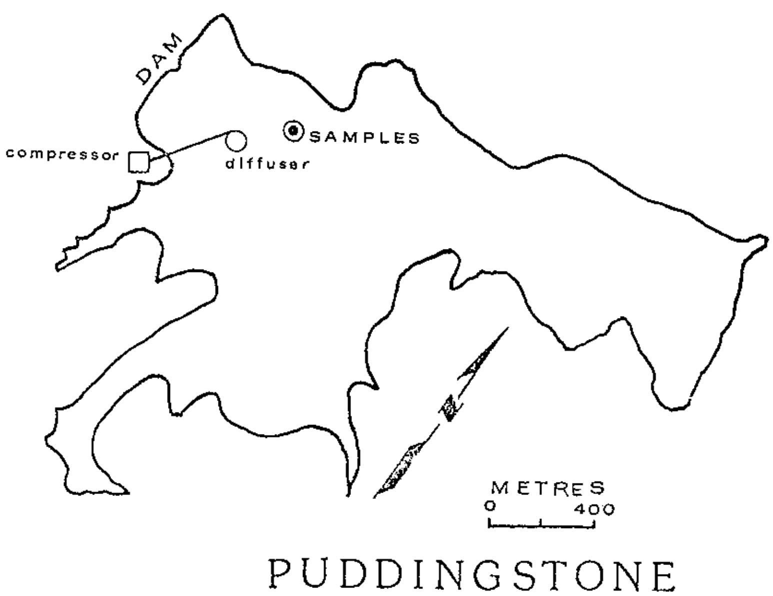


Figure B2. Puddingstone Reservoir, showing the aeration system and our sampling station

Lake Mathews Aeration System

5. The Lake Mathews aeration system is operated by the Metropolitan Water District of Southern California. This aeration system, as well as the one at Skinner Reservoir, was designed by them. It is a unique design, but apparently based at least partially on earlier designs used by the California Department of Water Resources. The system first began operation in 1976, but has been modified since. The aeration system is operated solely for domestic (drinking) water quality purposes. Of the reservoirs that we surveyed, this is the only one not open to public recreation, although there are plans to open it in the future.

6. The Mathews aeration system consists of two compressor installations. The one installation consists of a 450-SCFM Gardner-Denver diesel compressor and fuel tank on the south shore (Figures B3 and B4). This compressor began operating during 1976. The compressor delivers air to a circular diffuser ring, which during our June survey was suspended at the 110-ft depth in 150 ft of water.

7. The second compressor installation consists of two LeRoi 75-hp, rotary screw electric compressors (Figure B5). Each compressor produces about 350 SCFM of air. These compressors were installed during 1978 and 1979. Only one compressor is normally operated at a time. The electric compressors deliver air to a second circular ring diffuser, which during our June survey was suspended at the 115-ft depth in 125 ft of water.

8. When in operation, the system operates 24 hr each day, 7 days a week. The lake is monitored routinely, and the aeration system begins operation when the oxygen concentration in the bottom waters declines to 2.0 mg/ℓ. Aeration is discontinued when thermal destratification is complete, or when there is a significant increase in the oxygen content of the bottom waters. During 1979, the diesel compressor was operated from June 1 through September 17, while an electric compressor was operated from June 12 through October 18. Earlier experience showed that both compressors and both diffuser rings must be

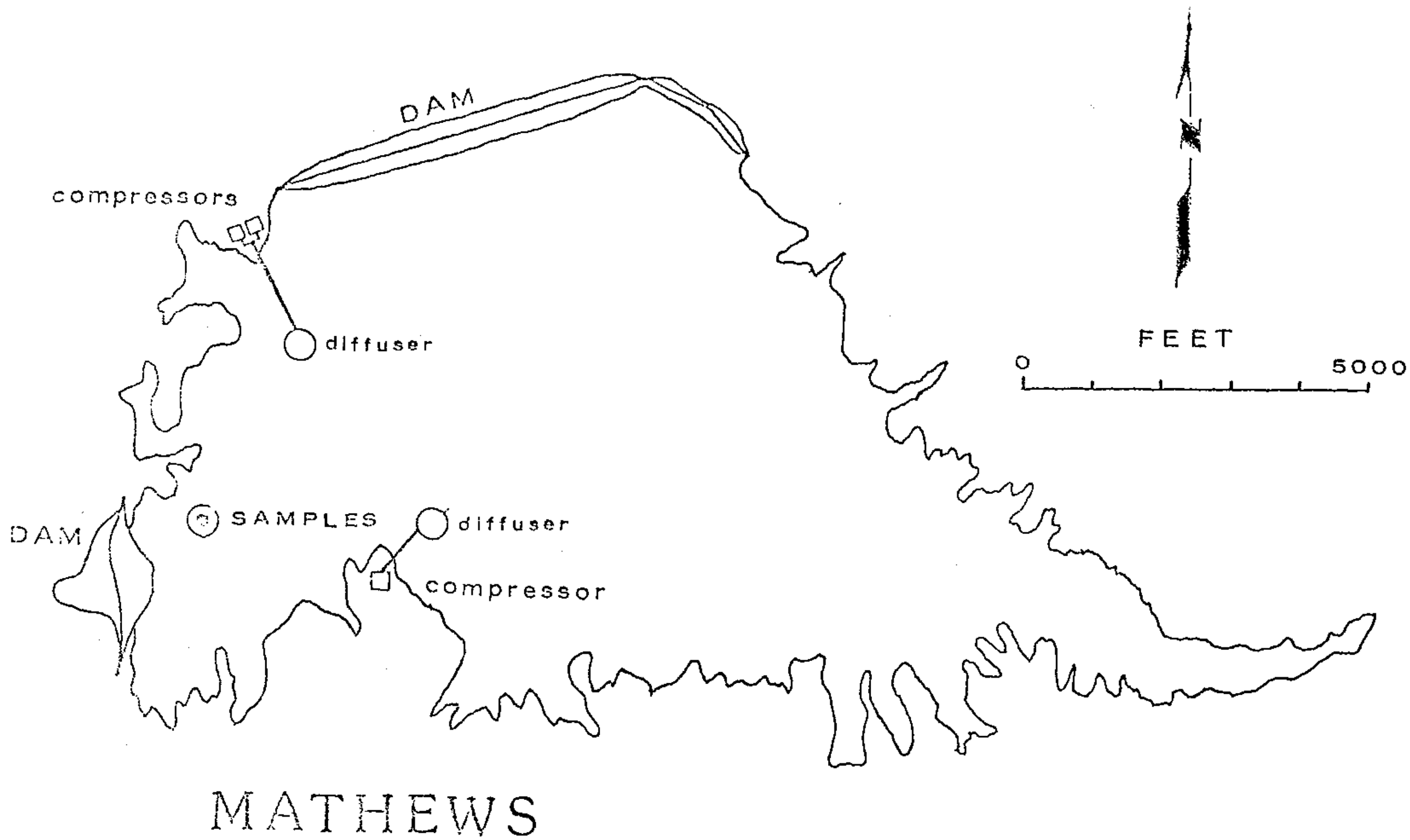


Figure B3. Lake Mathews (The two compressor installations are shown, along with the locations of their respective diffuser rings)

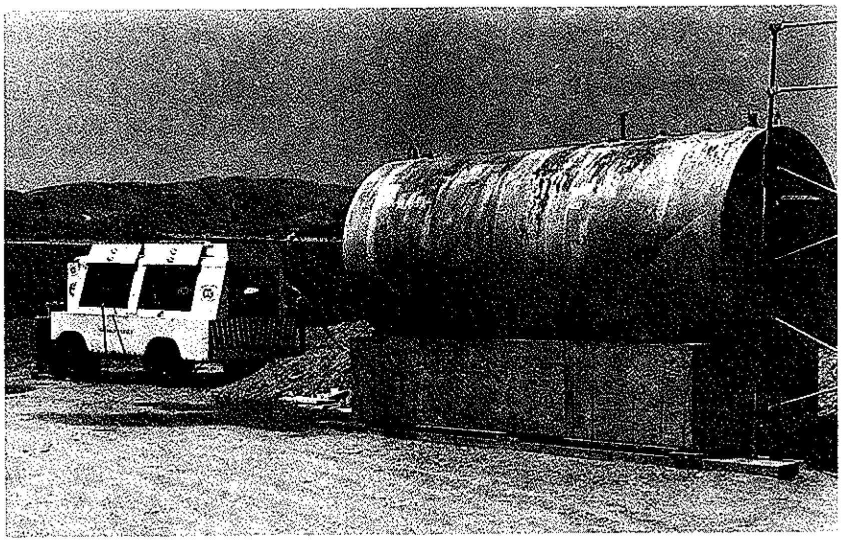


Figure B4. Lake Mathews' diesel air compressor and fuel tank

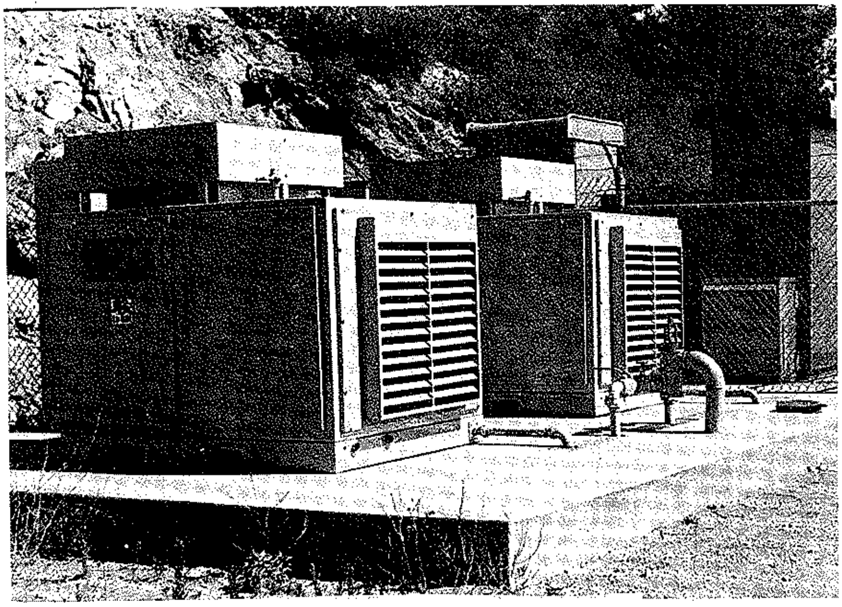


Figure B5. Lake Mathews' electric air compressor installation operated to achieve the described results.

9. The ring diffusers have a unique design. They are 50 ft in diameter and constructed of steel (Figure B6). The outer pipe is 2 in. in diameter and 157 ft in circumference. This pipe is connected to the central hub by four "spokes" of 2-in. steel pipe at 90-deg intervals around the hub. The hub is 8 in. in diameter and 7 ft high. The rim pipe and spokes are drilled and tapped at 1.33-ft centers. Each threaded hole is fitted with a 1/8-in. pipe fitting with a 1/16-in. orifice. Thus there are about 232 1/16-in. orifices through which the air is discharged. These orifices are drilled on alternate sides of the pipe to equalize pressures.

10. An earlier model of the ring diffuser had problems with excessive spinning, but this problem has apparently been solved in this model.

11. The major attributes of the ring diffuser are that it can be (a) easily raised or lowered for maintenance and repair and (b) suspended at any desired depth.

12. The disadvantages of the ring design are: (a) the air is concentrated in a smaller area than with the line design, (b) the ring is more complex to construct, install, and operate than a good linear diffuser design, and (c) the diffuser ring and associated hardware are more expensive.

13. At Lake Mathews, air is conveyed from the compressor to the water through a 4-in. steel pipe and then out to the diffuser-ring raft through a 4-in. plastic pipe (Figure B7). These float at the surface. A steel cable is anchored on shore and connected to the raft. The air is banded to this cable at several points. The diffuser-ring raft has two nylon anchor lines which keep it positioned offshore and which keep tension on the shore cable (Figure B8). The diffuser-ring raft has a pneumatic winch on deck which is used to raise or lower the diffuser ring.

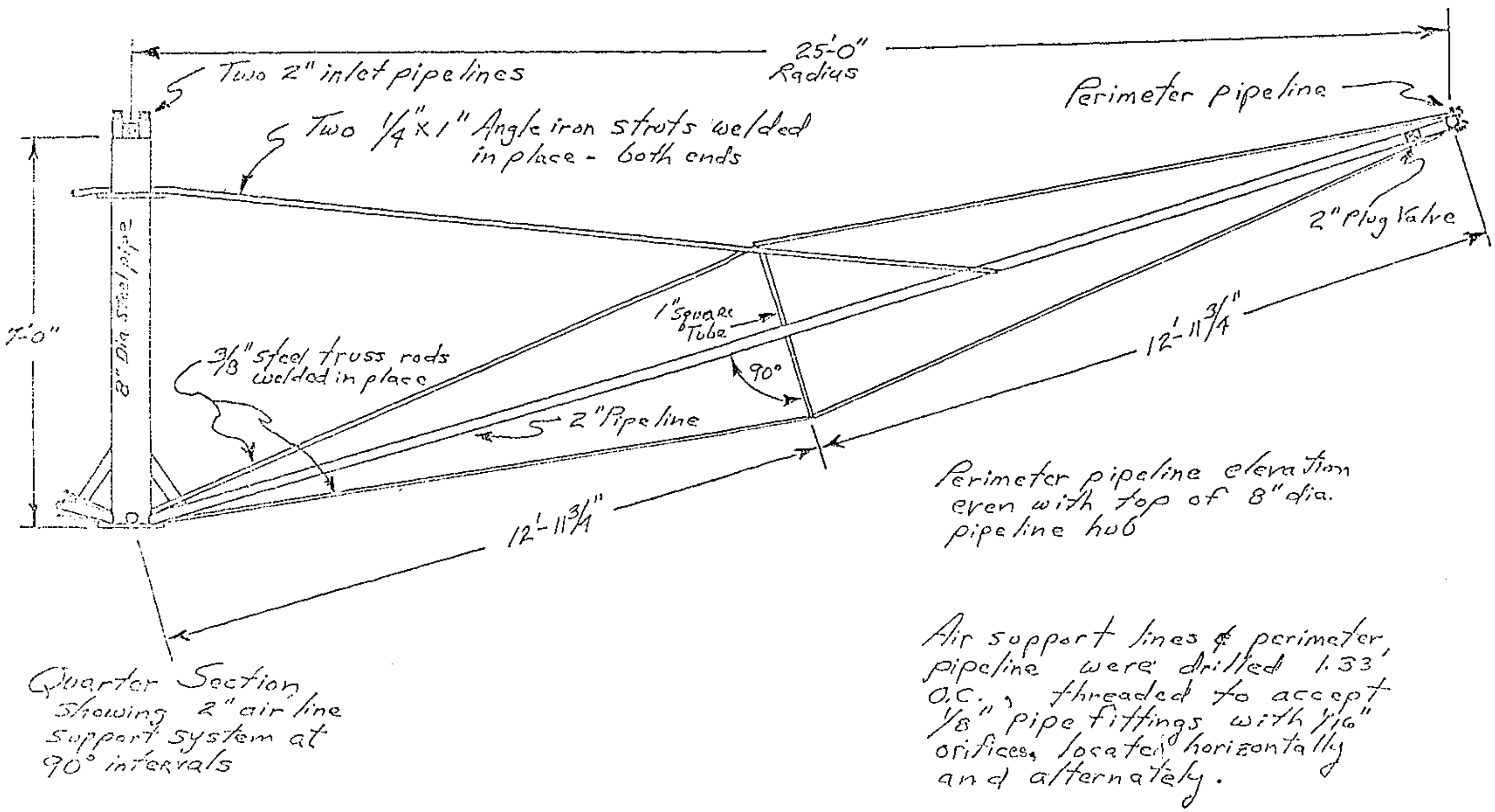


Figure B6. Partial cross section through the diffuser ring used at Lake Mathews
(Some of the cross bracing is not shown)

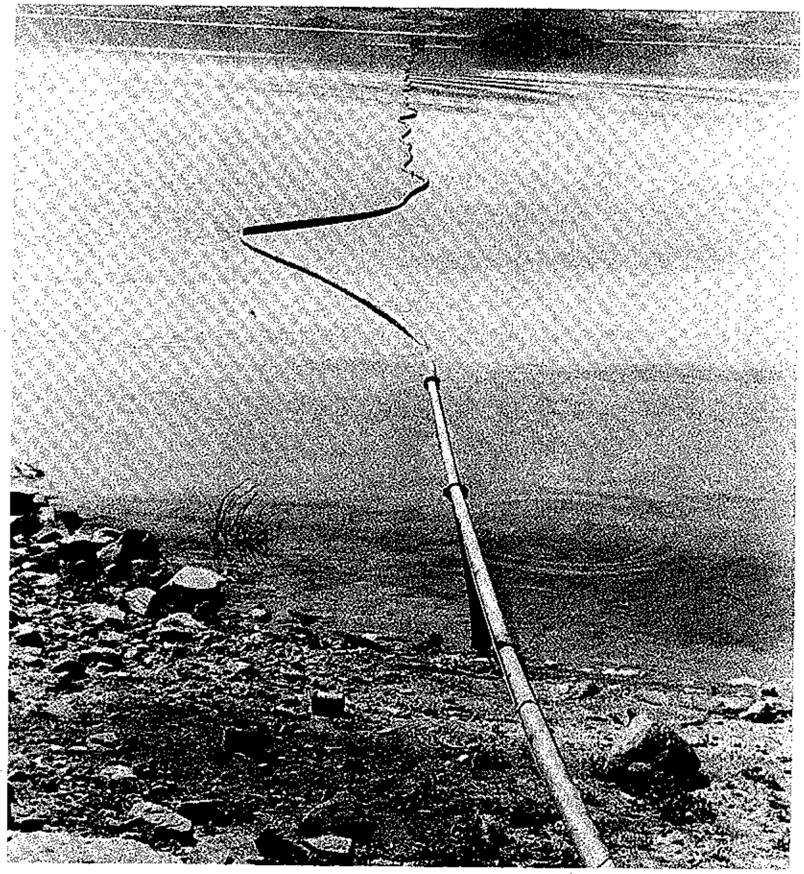


Figure B7. Air line extending from the electric air compressors at Lake Mathews to the diffuser-ring raft

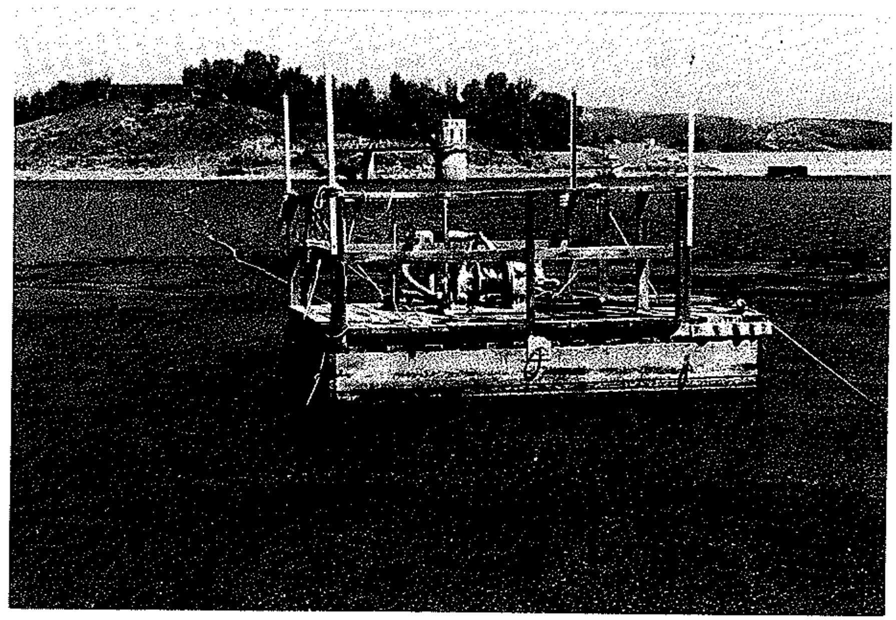


Figure B8. Diffuser-ring raft at Lake Mathews

Perris Reservoir Aeration System

14. The Perris aeration system was designed and operated by the California Department of Water Resources (DWR). It began operation during 1974 and is operated primarily for domestic water quality purposes. Brim et al. (1977) describe the system in detail and some effects of its use.

15. The aeration system includes two Sullair 75-hp, electric rotary screw air compressors (Figure B9). Each compressor delivers about 315 SCFM of air, and normally only one compressor is operated at one time. The system may be modified such that both compressors can be run simultaneously (Figure B10). The compressors are located adjacent to the outlet tower and dam (Figure B11). When in operation, a compressor operates 24 hr each day, 7 days a week. Normally, operation occurs between May and October or November.

16. Air is delivered to the ring support float through a 2-in. galvanized pipe which is suspended 10 ft below the lake surface by floats (Figure B12). A 1-in. rubber hose leads from the galvanized pipe to the ring diffuser.

17. The ring diffuser is suspended by a 3/8-in. steel cable from the support float (Figures B12 and B13a). The diffuser is constructed much like a bicycle wheel (Figure B13b). The outer rim consists of 2-in. galvanized steel pipe formed into a 50-ft-diam ring. Air is released from this ring through 72 3/32-in. holes. The rim is connected to the central hub by 1/4-in. high tensile wires which are threaded and tightened. The hub consists of a 6-ft length of 3-in. galvanized pipe. The support cable passes through the hub, and weight can be added to the end of the cable.

18. During 1979, air was delivered simultaneously to two ring-type diffusers located very close to the outlet tower. One diffuser (as described) was circular and 50 ft in diameter, while the other was octagonal and 40 ft in diameter. The 50-ft-diam diffuser was suspended at the 30-ft depth, while the octagonal diffuser was resting on the bottom (10 ft off bottom) in about 90 ft of water during our June survey. The

deeper diffuser was resting on the side of a channel, so that it was not horizontal. Consequently, much of the air escaped from the high side of the diffuser.

19. During our June survey, the upwelled water was much clearer than the surface waters. Divers with the DWR said that during their dives water below the 30-ft depth had much greater clarity than shallow water.

20. The DWR was constructing a third ring which they planned to suspend about 1000 ft from the outlet tower and off the face of the dam.

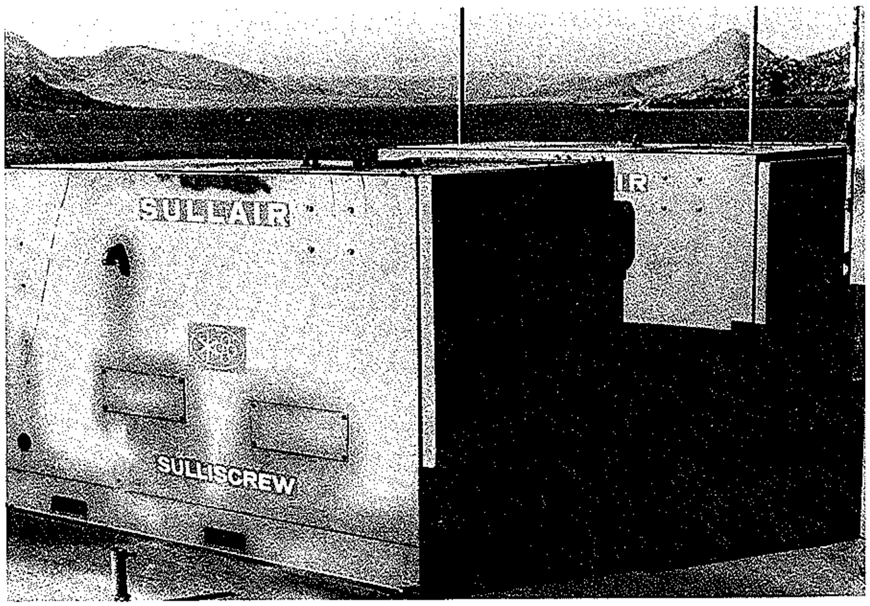


Figure B9. Perris Reservoir air compressors

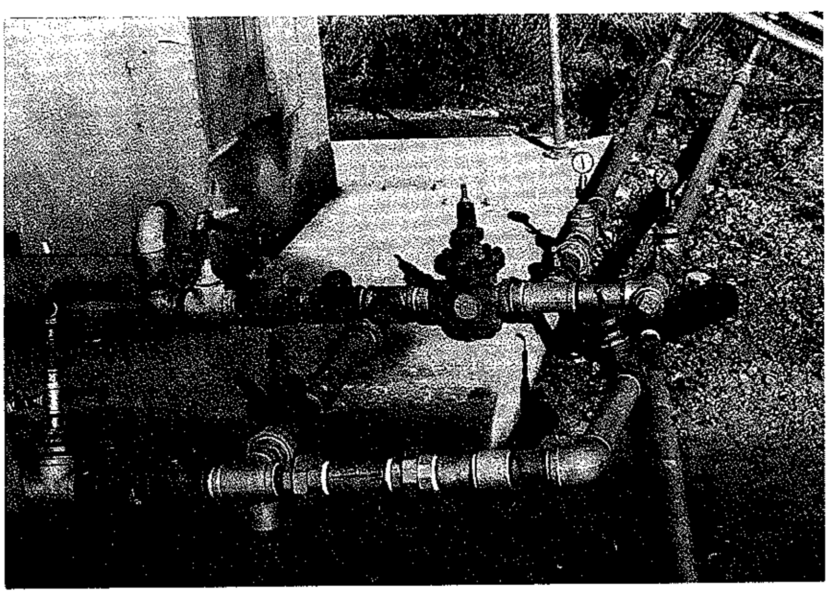


Figure B10. Piping connecting the two air compressors at Perris Reservoir and leading to the ring diffusers in the reservoir

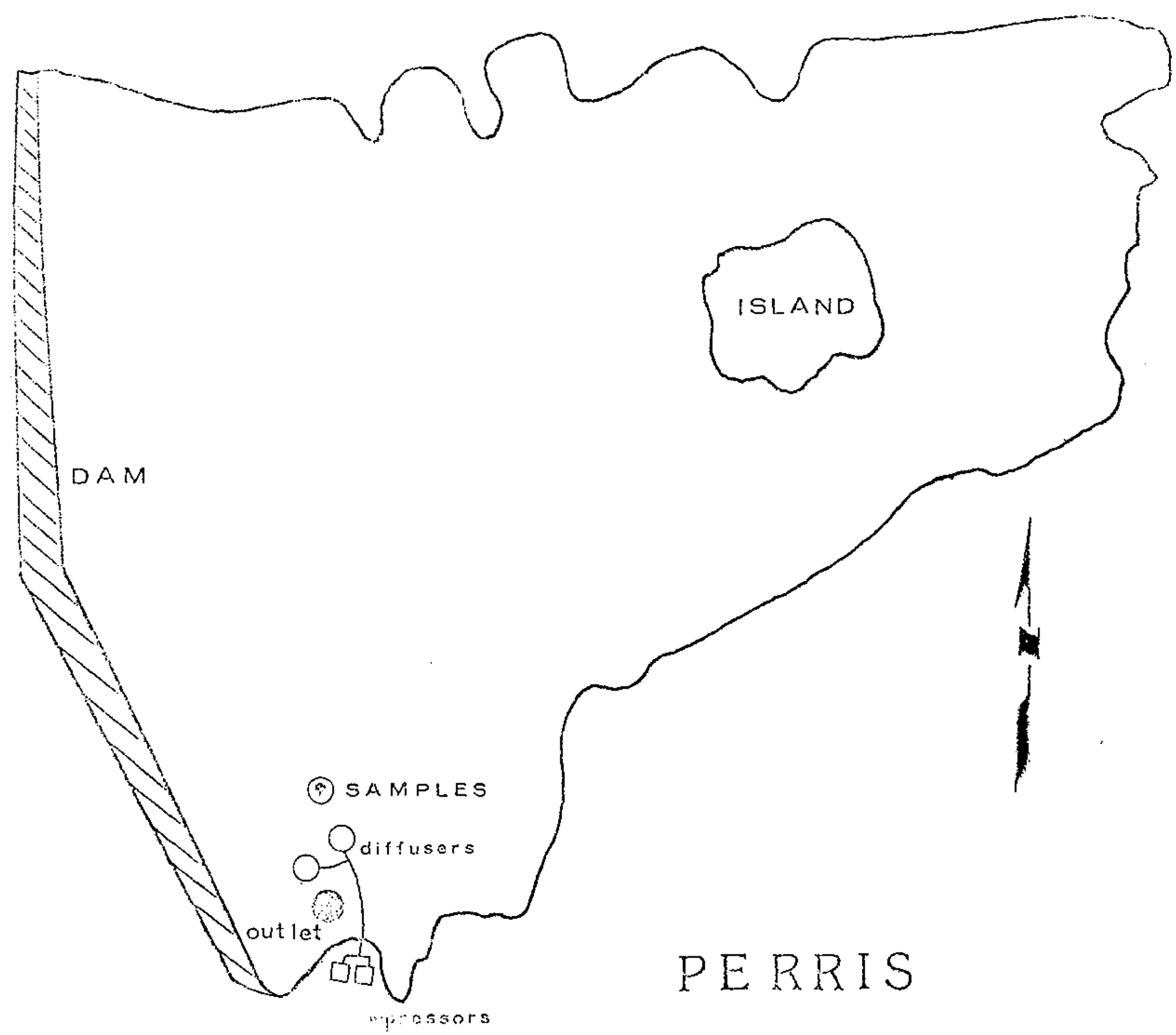


Figure B11. Perris Reservoir showing location of aeration system and outlet tower

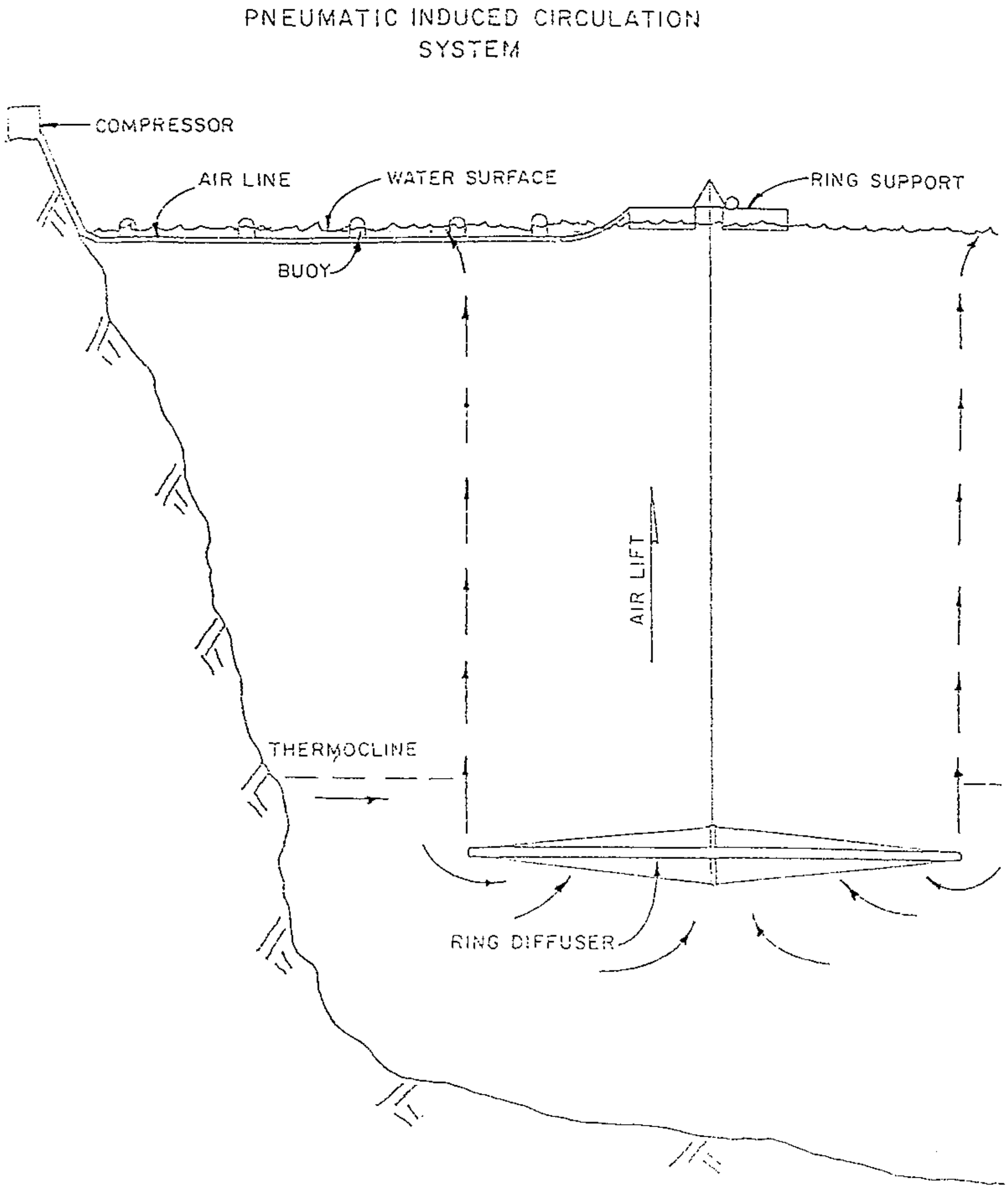
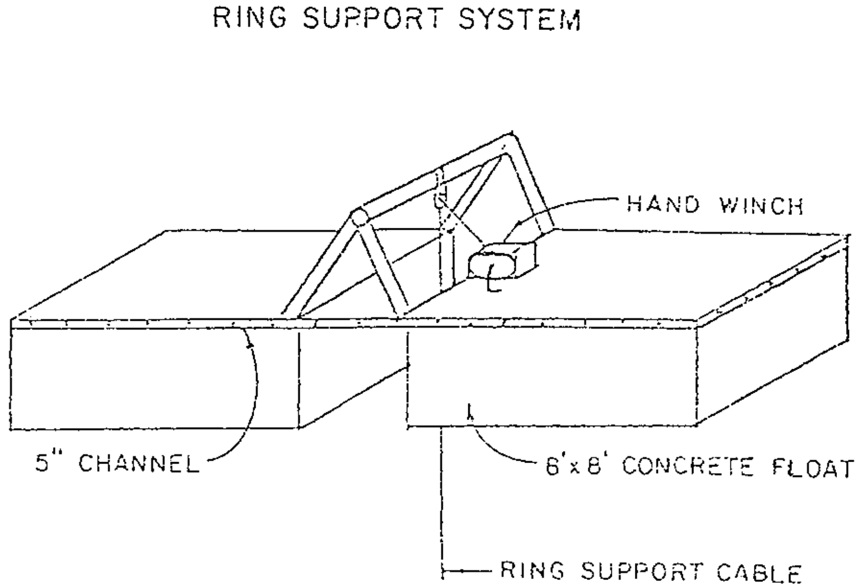


Figure B12. Aeration system used at Perris Reservoir (Brim et al. 1977)

A



B

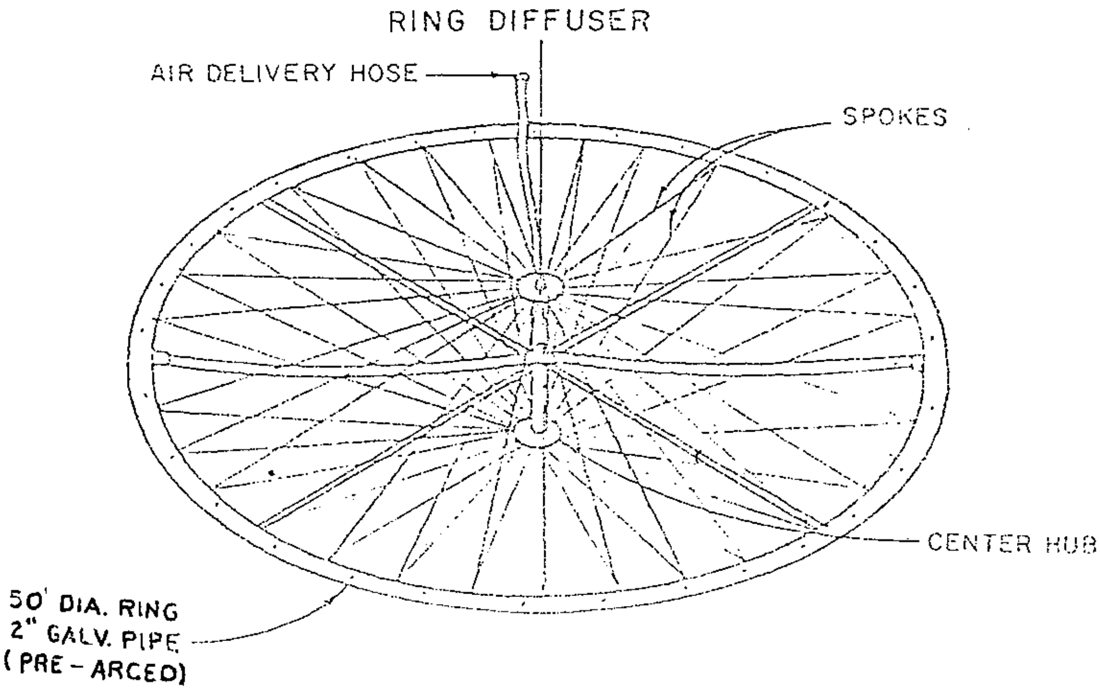


Figure B13. Diffuser ring support float (A) and diffuser ring (B) used at Perris Reservoir (Brim et al. 1977)

Skinner Reservoir Aeration System

21. The Skinner aeration system was designed and is operated by the Metropolitan Water District of Southern California. Its design and operating guidelines are nearly the same as for the newer system at Lake Mathews. It is operated primarily for domestic water quality and has been in operation since 1977.

22. The aeration system includes two Sullair 75-hp, electric rotary screw air compressors (Figure B14). Each compressor produces about 315 SCFM of air. The compressors are located on the top of the dam, with an air line extending out perpendicular from the dam face (Figure B15). When in operation, the compressors run 24 hr each day, 7 days a week. The compressors are plumbed into a common line to the diffuser and either or both compressors can be operated at one time (Figure B16). During 1979 the system was operated from May 2 through October 6. Before July 30 only one compressor was operated at a time, while after July 30 both were operated simultaneously.

23. The air line, diffuser ring, diffuser-ring raft, and mode of operation are nearly the same as those described for Lake Mathews.

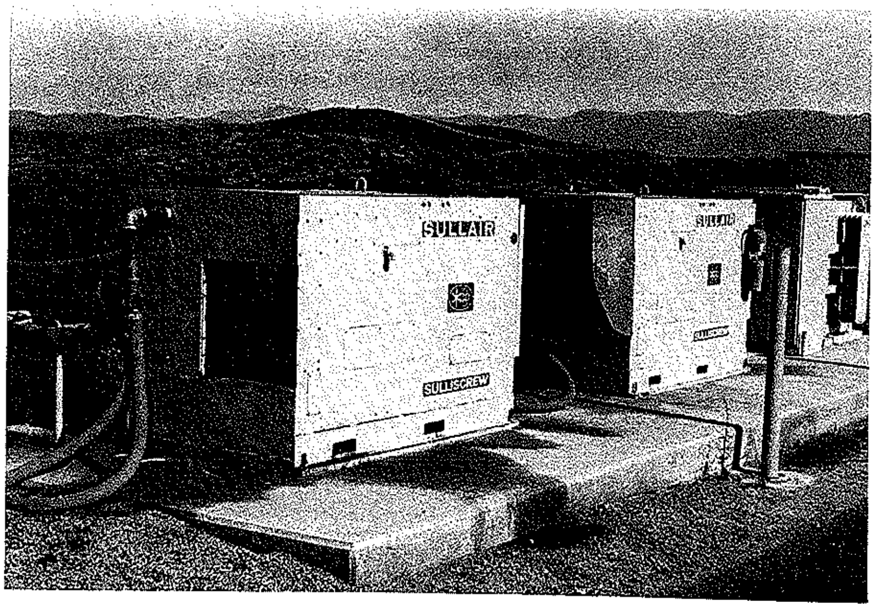


Figure B14. Compressor installation at Skinner Reservoir

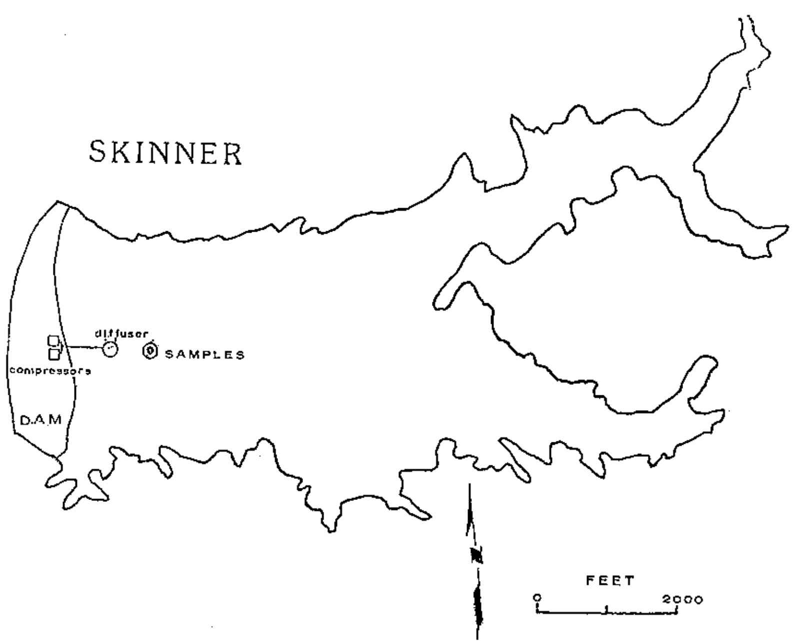


Figure B15. Skinner Reservoir showing compressor installation and outlet tower

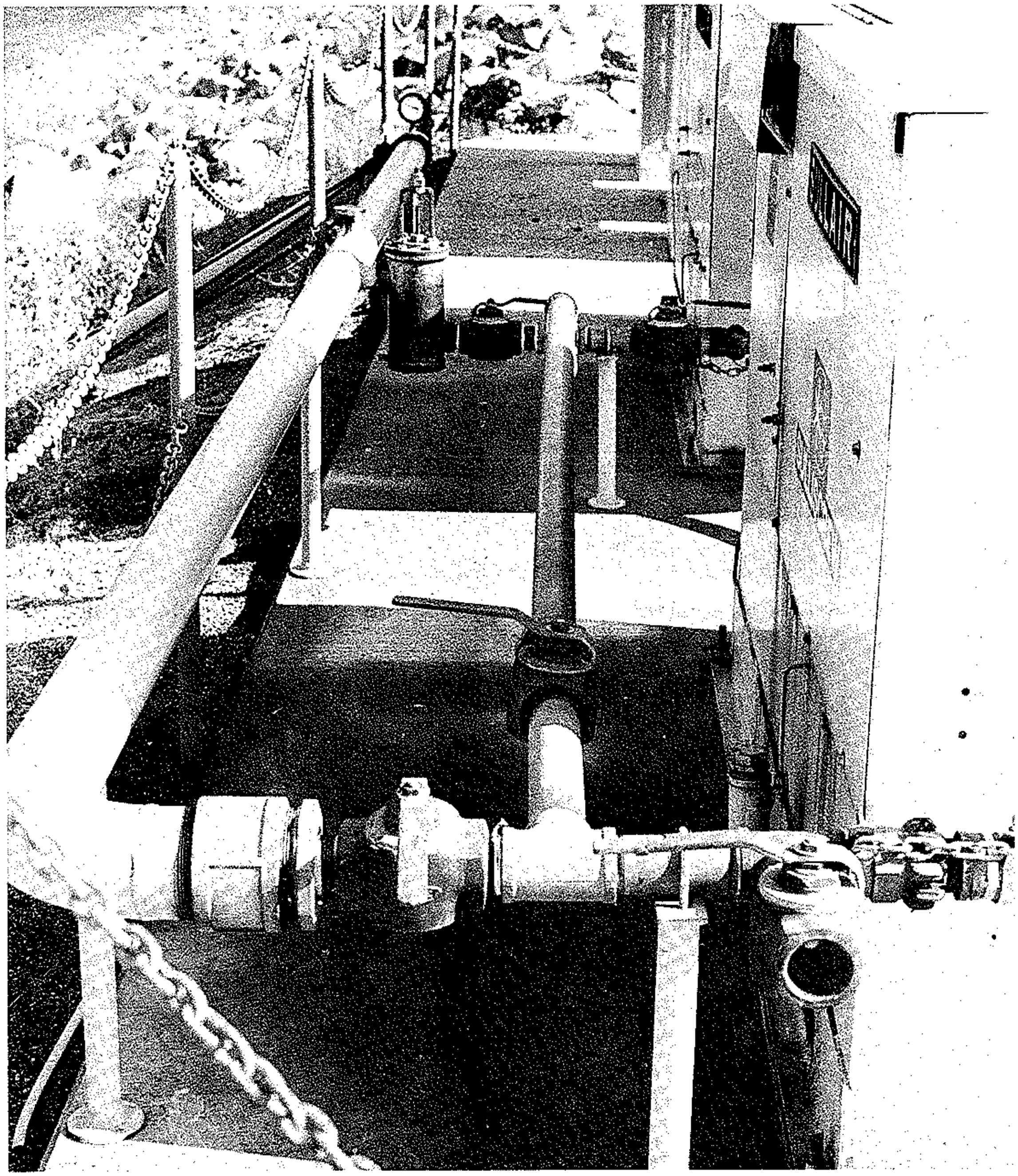


Figure B16. Plumbing connecting the two compressors at Skinner Reservoir

Vail Lake Aeration Sytem

24. We were not able to obtain any detailed information from the lake operators on their aeration system. The reservoir and aeration system was formerly operated by Kacor Realty but was transferred to Rancho California Water District on March 29, 1979.

25. We did observe the aeration system in operation during all three of our visits, but it seemed to have no measurable effect on either the temperature or oxygen profiles. We suspect that the air line was broken below the water's surface but above the thermocline, and, consequently, it did not upwell much deep water. Air and water were upwelled at the face of the dam (Figure B17). We would estimate less than 50 SCFM of air was injected.

26. The air compressor was housed in a small wooden shed, and there were two metal and PVC air lines coming from the shed to the reservoir (Figure B18). These lines ran along the top of the dam (Figure B19) and then ran vertically down the dam face where the air bubbles appeared. The compressor shed was surrounded by a chain-link fence.

27. We collected our samples about 100 to 150 ft off the face of the dam.

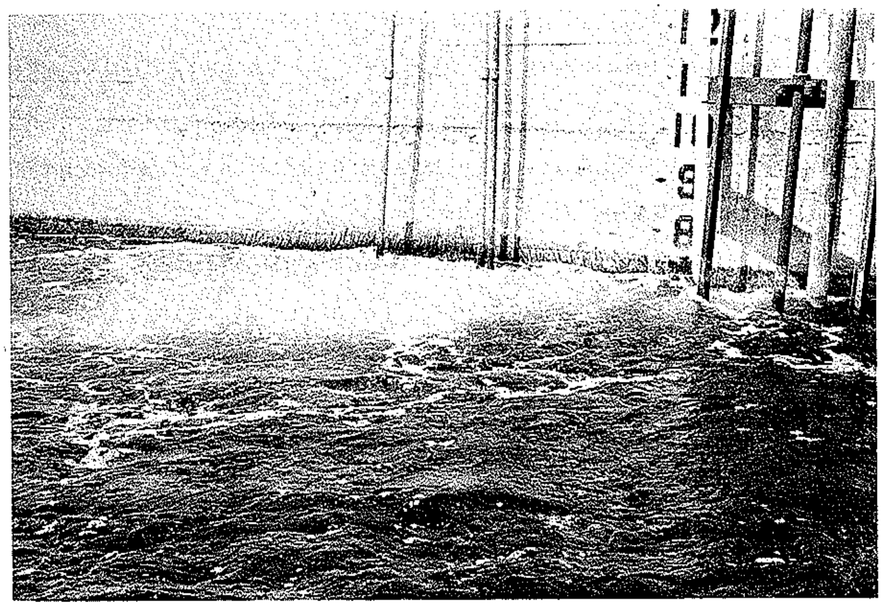


Figure B17. Compressed air bubbling up the face of the dam at Vail Reservoir

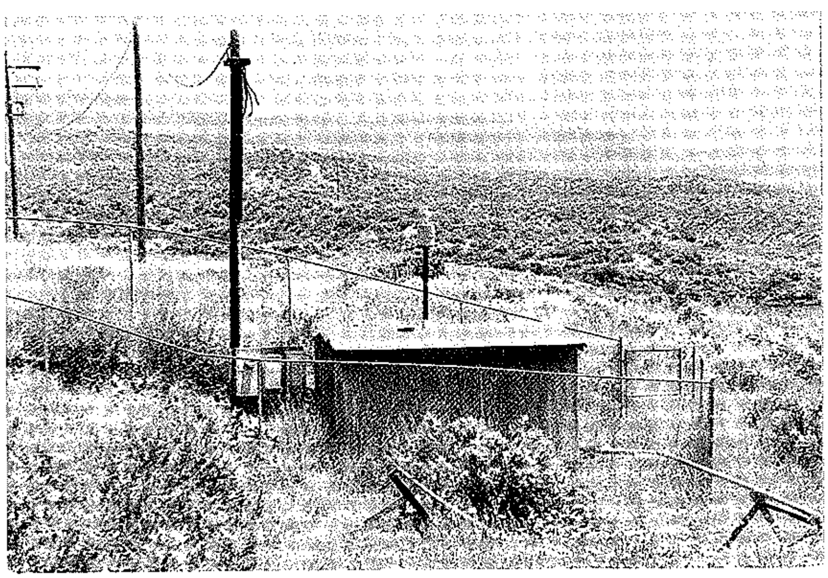


Figure B18. Compressor shed at Vail Reservoir

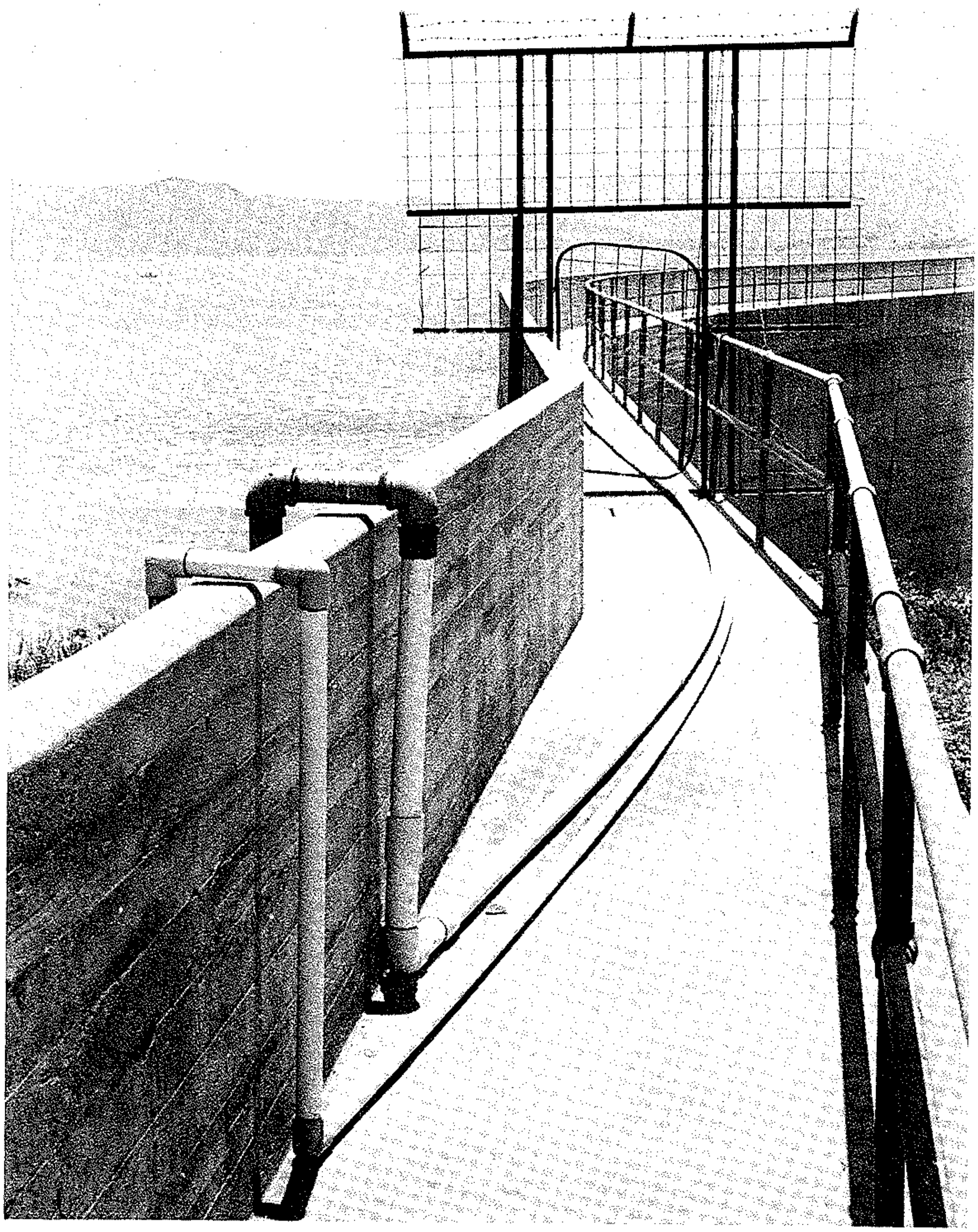


Figure B19. Air lines running along the top of Vail Dam (One line is all PVC, while the other changes from steel to PVC at the top of the wall)

Lake Henshaw Aeration System

28. The Henshaw aeration system is operated by the Vista Irrigation District. It began operation during 1963 following the successful use of aeration at downstream Lake Wohlford. The aeration system is operated primarily for water quality purposes. Because the reservoir is now purposely held at a very low volume, the system does not have much effect on the reservoir. The reservoir is so shallow that it is completely mixed by the wind, with little or no thermal or chemical stratification.

29. The aeration system includes a Schramm 25-hp, electric air compressor (Figure B20). The compressor produces about 100 to 125 SCFM of air. When in operation, it normally runs 24 hr per day, 6 days a week. During 1979, it began operation in May and probably continued operation until October.

30. A 2-in. steel line conveyed the air from the compressor into the deepest point in the lake, about 400 ft upstream from the dam. A 100-ft diffuser section (perforated pipe) was originally attached to the end of the air line, but this section broke off during 1969. Since then, the air has been discharged from the free end and upwells at one location (Figure B21).

31. We collected our samples about halfway between the dam and the bubble plume.

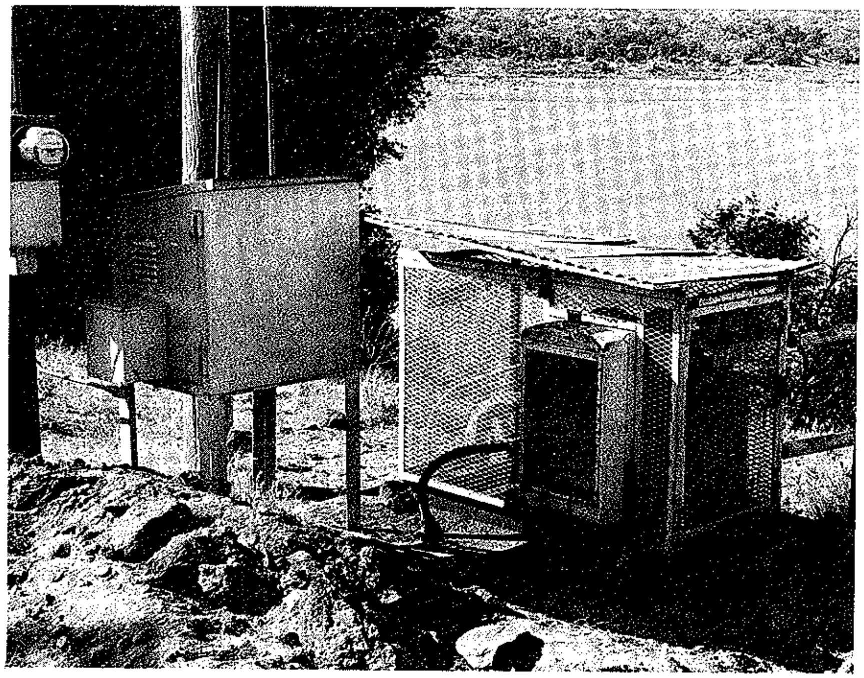


Figure B20. Schram air compressor at Lake Henshaw

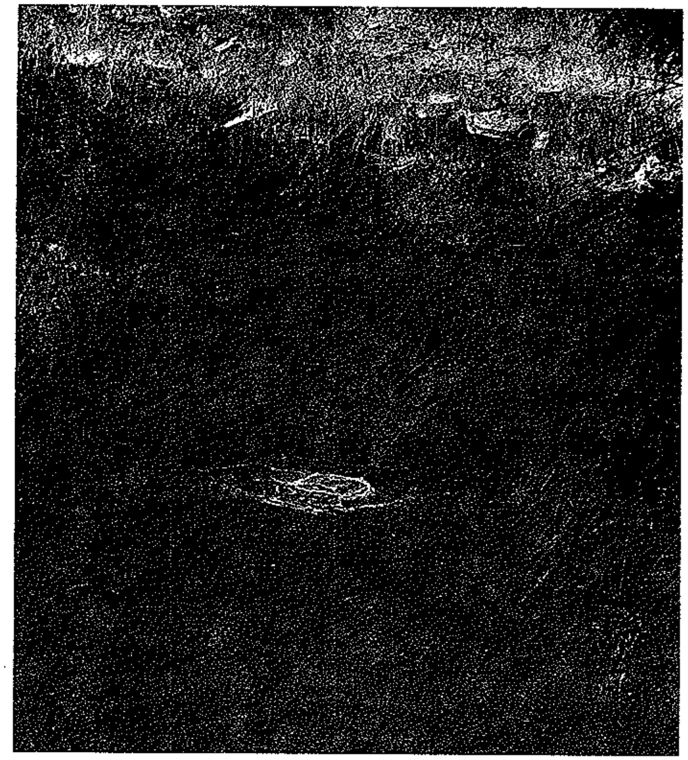


Figure B21. Air upwelling from the end at the broken air line at Lake Henshaw during June 1979

Lake Wohlford Aeration System

32. The original aeration system at Lake Wohlford was designed, installed, and operated by the Escondido Mutual Water Company during 1962. This was one of the first permanent aeration systems in southern California, and one of the most successful. It was originally installed temporarily as an emergency measure to alleviate a fish kill. It also greatly improved domestic water quality and reduced water treatment costs. It reduced chlorine usage alone by $6000 in 1962. This led to a permanent installation. Koberg and Ford (1965) describe the system and its early operation in detail.

33. The aeration system includes a Schramm 50-hp, electric air compressor which produces about 210 SCFM of air (Figure B22). The compressor is housed in a corrugated steel shed and includes a surge tank. The compressor is located near the dam end of the lake (Figure B23). Air is conveyed to the lake through a 2-in. galvanized steel pipe which extends into the lake before joining to a 1-1/2-in. PVC pipe. The PVC pipe extends along the bottom. The last 60 ft of the PVC pipe is perforated with 90 holes, 9/16 in. in diameter. These holes are spirally located around the pipe to equalize pressure. The diffuser section is suspended 5 ft above the bottom by a styrofoam block/cement block arrangement (Figure B24). This suspension was used to prevent stirring of bottom muds and to prevent bottom sediments from entering the diffuser when it is not in operation.

34. Originally, the system was operated for 9 hr each day, 5 days a week, during the operating season. Now it is operated 4 days a week (on the average) for 24 hr each day from May through September. It is occasionally operated during the remainder of the year if needed. During 1979, it began operation on April 10.

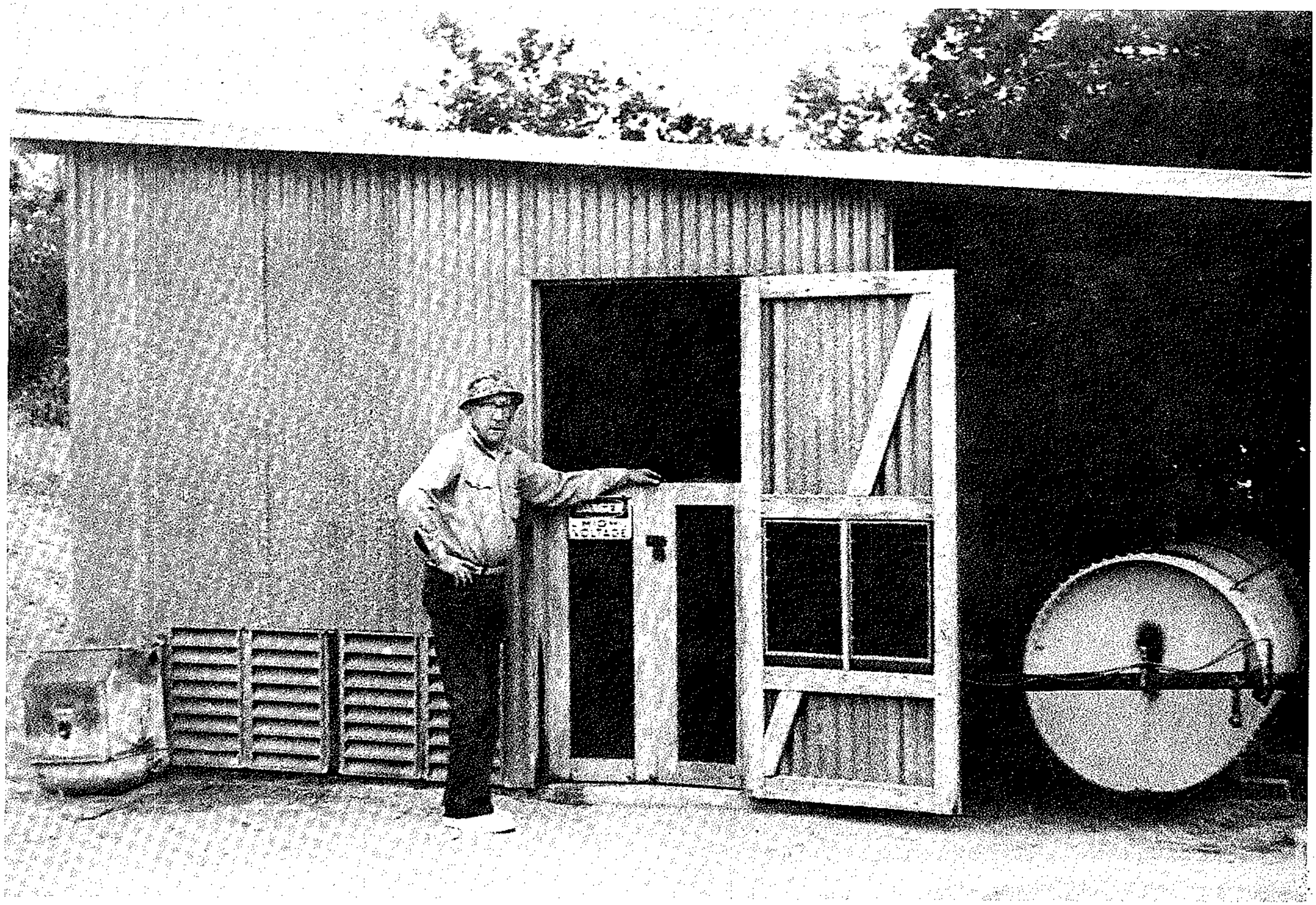


Figure B22. Compressor shed and surge tank at Lake Wohlford

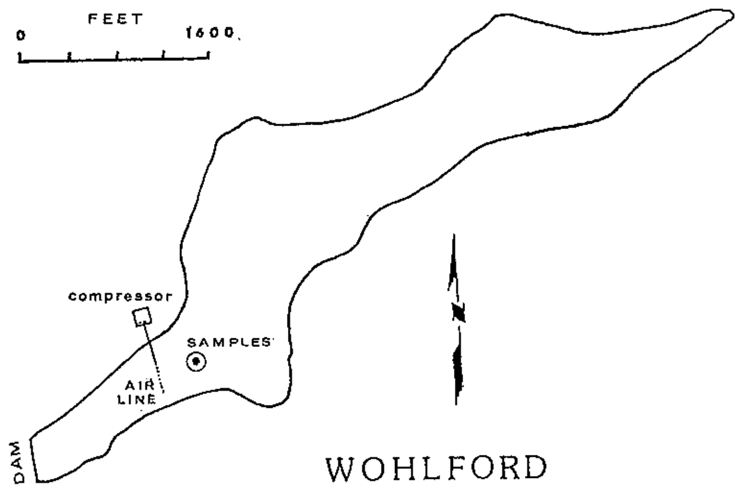


Figure B23. Lake Wohlford, showing location of air compressor

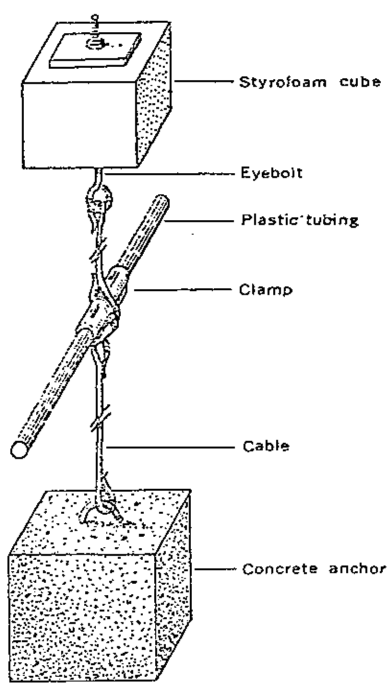


Figure B24. Anchor and suspension system used to support the air diffuser off the bottom at Lake Wohlford (Koberg and Ford 1965)

El Capitan Reservoir Aeration System

35. The aeration system at El Capitan Reservoir was one of the first permanent aeration systems in southern California. It was installed in 1965 as a cooperative project between the California Department of Fish and Game; Water Department, City of San Diego; County of San Diego; U. S. Geological Survey; and Helix Irrigation District. Fast (1968) describes this system in detail.

36. The principal purposes of the aeration system were to improve domestic water quality and to improve fishing quality. Water quality was improved by the aeration, and the compressor has consequently been in operation almost every year since 1965. The fishery probably benefited from aeration, but the benefits are more difficult to quantify.

37. The system consists of a single compressor on shore and a single air line running down along the bottom of the reservoir (Figures B25 and B26). The compressor is a LeRoi 50-S-2 electric, 50-hp, 2-stage reciprocating type. It delivers 215 SCFM. The original installation included a metal cage to protect the compressor from "visitors" (Figure B27). Although the cage had access doors, access to the compressor was still difficult. The cage was later replaced by a fenced enclosure with a corrugated metal roof (Figure B28). The fence could be removed for better access, and the roof helped protect the compressor from the weather.

38. A 2-in. (5.08-cm) aboveground, galvanized steel pipe transports air from the compressor to below the water where it connects with a 1-1/2-in. (3.8-cm) PVC plastic pipe (Figure B25). The steel pipe is used above the water for two reasons: (a) to dissipate heat of compression before the air enters the plastic pipe and (b) to prevent damage to the pipeline from visitors and animals. The plastic is used underwater because it is cheaper, easier to install, and less subject to corrosion. Galvanized pipe is used rather than black steel to reduce corrosion within the pipe. Rust scales could possibly break loose and be swept along by the compressed air where they could clog the diffuser holes.

39. From the end of the steel pipe, a 300-ft length of 1-1/2-in.

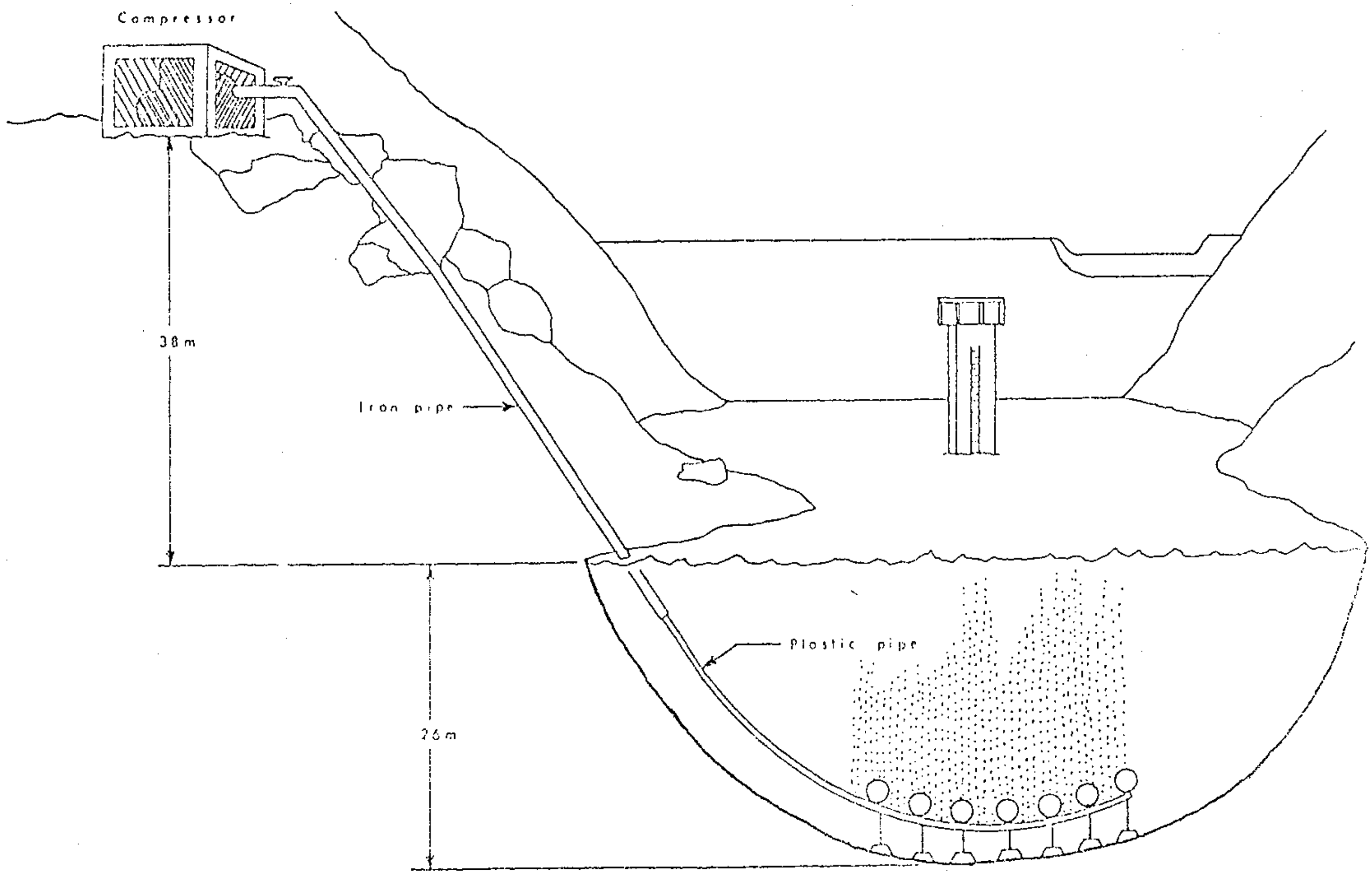


Figure B25. Cross section of aeration system used at El Capitan Reservoir (Fast 1968)

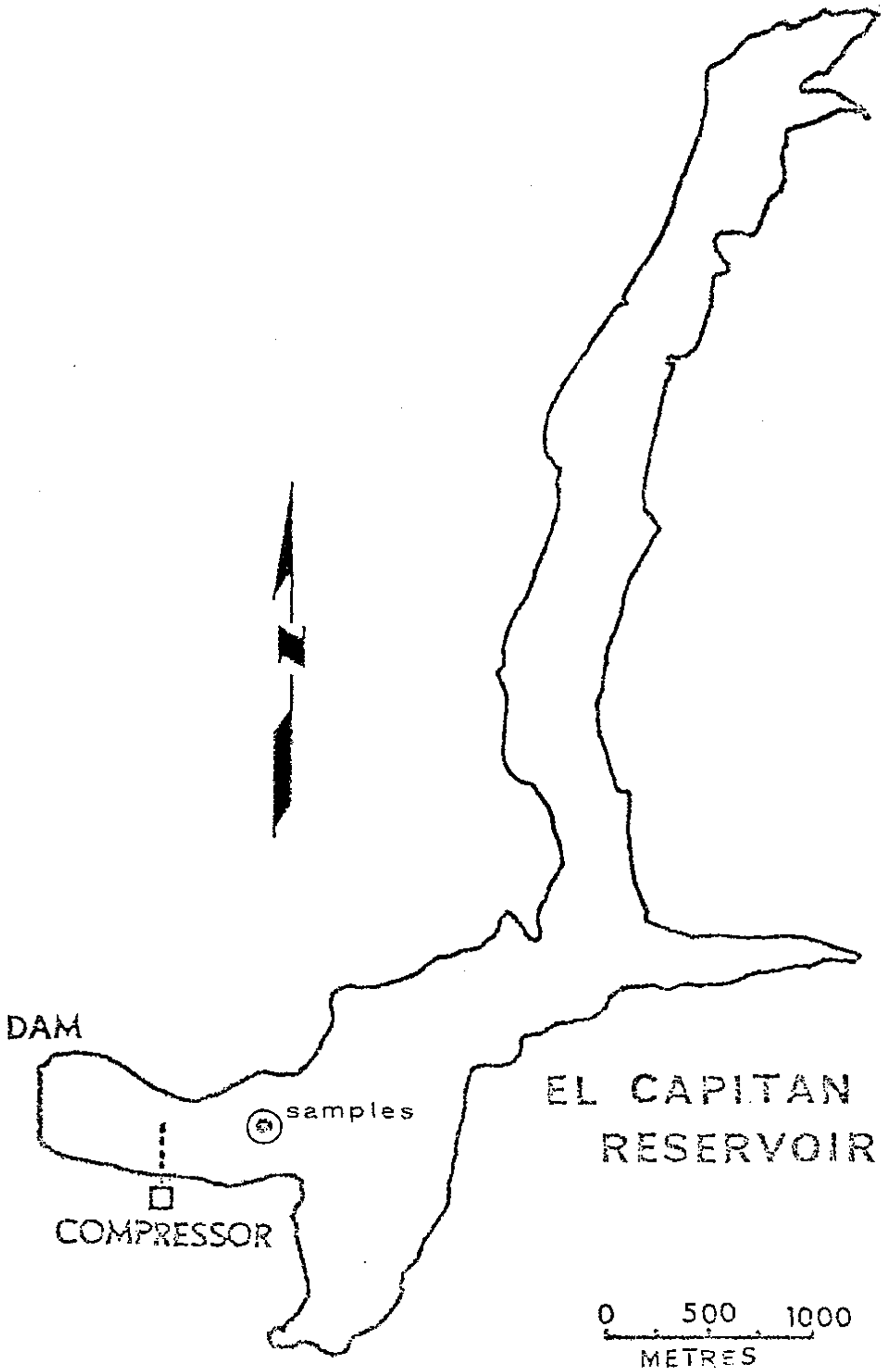


Figure B26. El Capitan Reservoir showing aeration system location and our sampling station

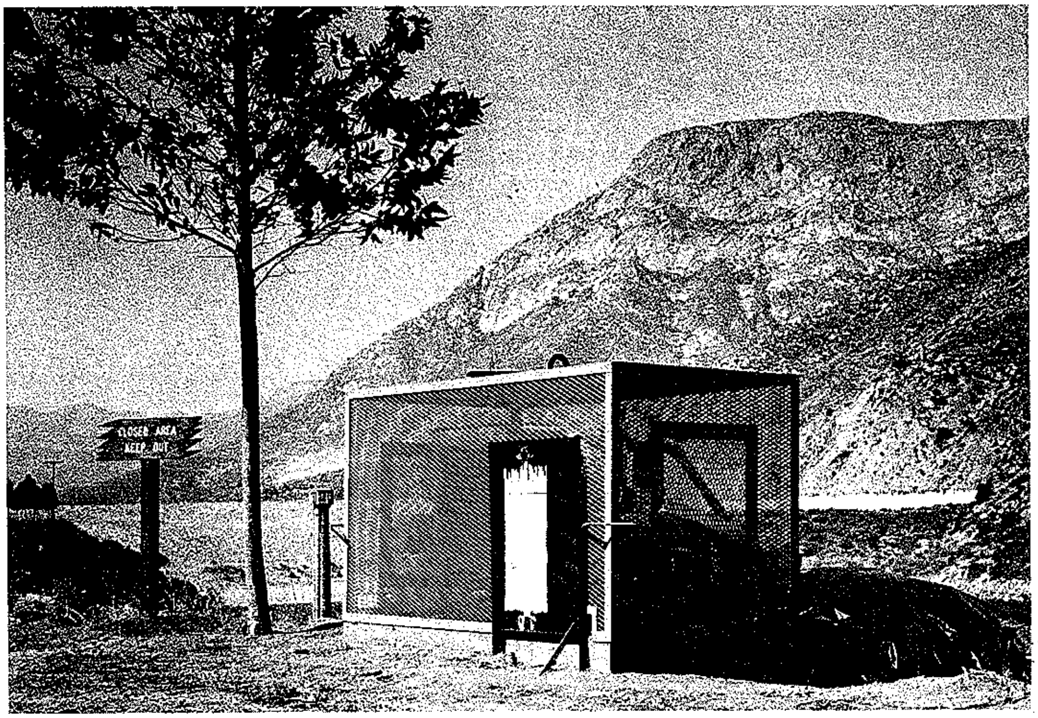


Figure B27. El Capitan compressor with original enclosure (Fast 1968)

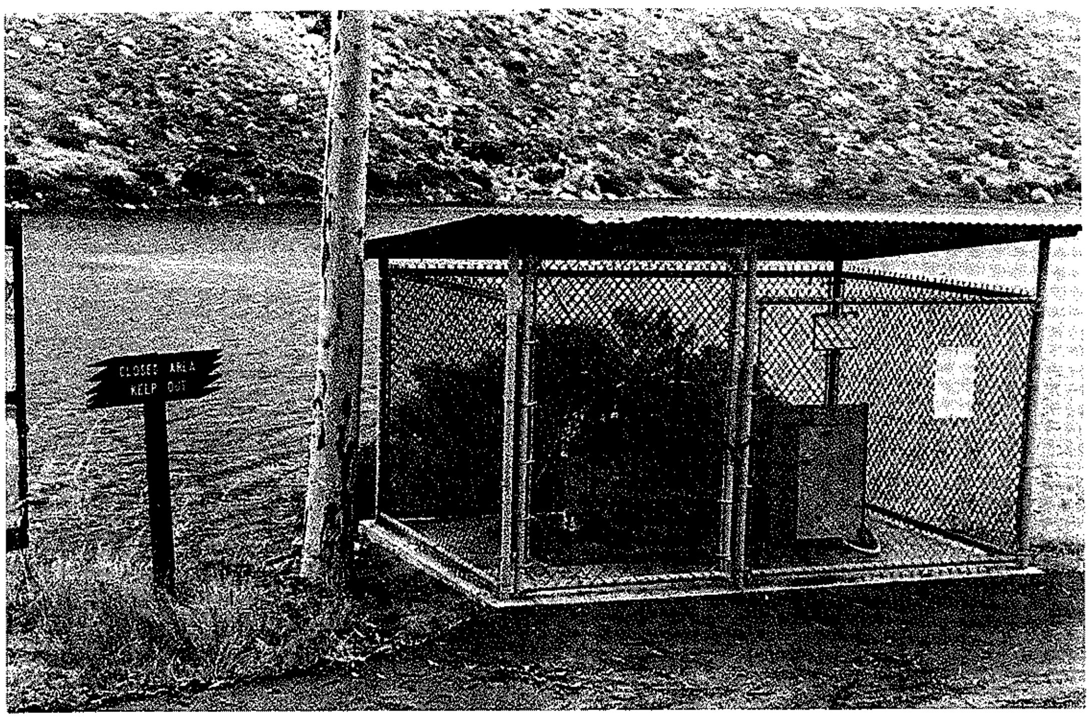


Figure B28. Present El Capitan compressor and enclosure

PVC plastic pipe extends along the bottom. The plastic pipe is weighted by 15 concrete block anchors (Figure B29). The last 100 ft of the plastic pipe are suspended almost horizontally above the bottom by 13 styrofoam floats and lengths of polyethylene anchor rope, similar to the system used at Lake Wohlford (Figure B24). Thirteen sets of floats with anchors are evenly spaced along by 90 holes, 1/8 in. in diameter, and sealed at its distal end. Clusters of three holes, spaced 120 deg apart around the circumference of the pipe, are located on this section of pipe. The clusters are unevenly spaced. Beginning 100 ft from the end of the pipe, the spacing between the first six clusters is 5 ft, clusters 6 through 12 are 4 ft apart, clusters 12 through 21 are 3 ft apart, and clusters 21 through 30 are 2 ft apart. This non-linear arrangement of air holes was intended to produce a uniform air release over the length of the pipe.

40. The diffuser is not at the deepest location in the lake, but it is in slightly deeper water than our sampling station.

41. Compressor operation typically begins in early spring (March or April) and continues through October or November. When operating, the compressor operates continuously 24 hours per day, 7 days each week.

42. The compressor installation was originally designed for a 10,000-acre ft impoundment, although water volumes have far exceeded this value. This year (1980), the reservoir spilled during February with more than 112,800 acre ft.

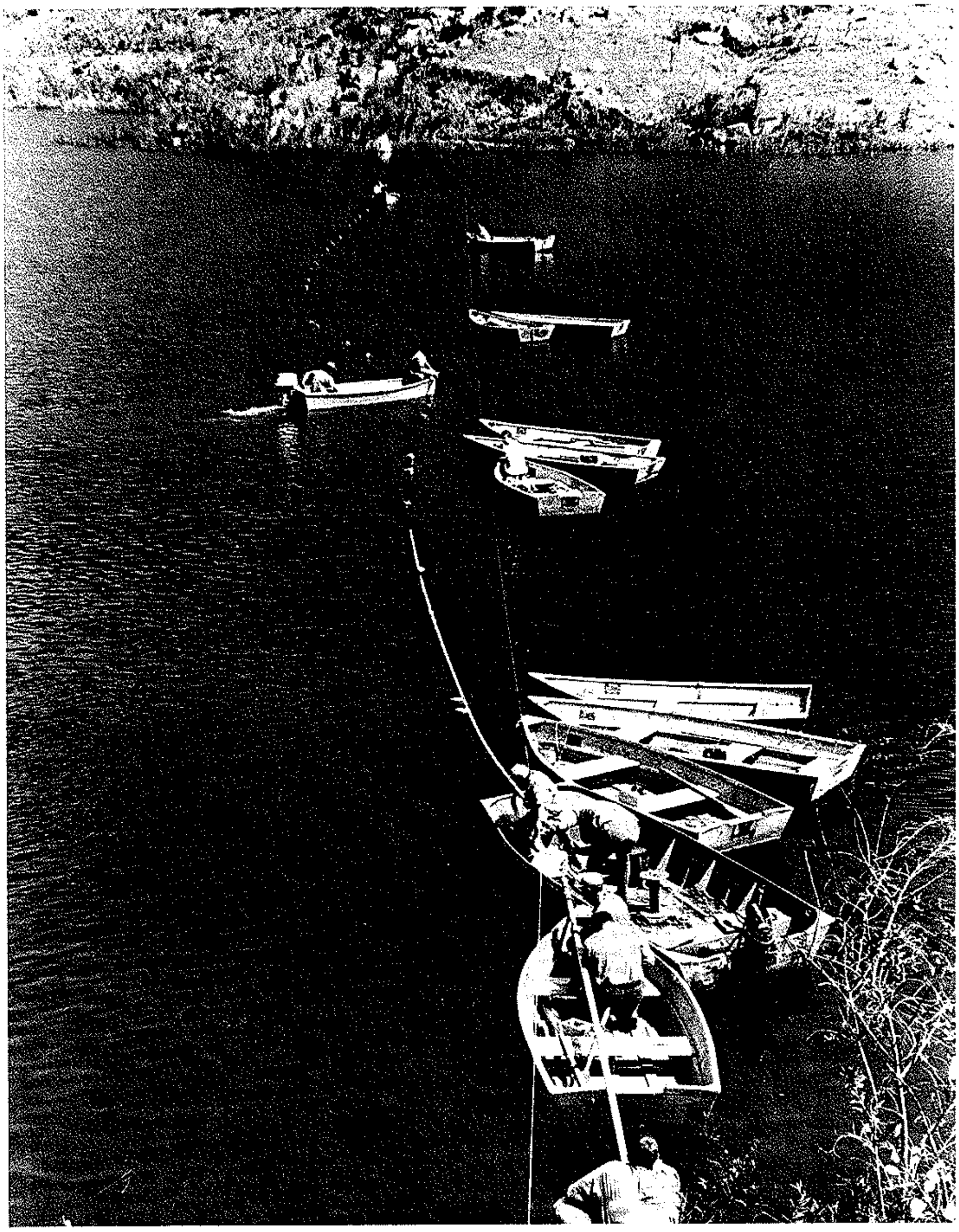


Figure B29. Installation of PVC air line at El Capitan Reservoir during 1965 (Fast 1968) (A steel cable was first stretched across the reservoir from shore to shore. We then placed 13 boats along the cable with a man in each boat. Thirteen anchors were then attached to the air line and the line was lowered to the bottom in unison)

Lake Morena Aeration System

43. The Morena aeration system is operated by the San Diego County Parks Department. The principal purposes for the aerator are to prevent fish kills, improve fishing quality, and control algal growth. This lake is quite eutrophic and has a history of dense algal blooms and fish kills associated with algal decomposition and its associated oxygen depletion. This occurred during our sampling program despite a relatively thorough destratification of the lake.

44. The aeration system includes a Worthington model 50-110 50-hp, electric rotary screw air compressor which produces 240 SCFM of air. The compressor is located in a corrugated steel shed near the dam (Figures B30 and B31). This is the second "permanent" compressor which has been used at the lake in recent years. An earlier compressor blew up with relatively low use. It was an Atlas Copco single stage reciprocating type producing about 230 SCFM of air.

45. Air is conveyed from the compressor into the lake through 270 ft of 2-1/2-in. galvanized steel pipe. Another 230 ft of submerged 2-1/2 in. PVC pipe is attached to the steel pipe before the diffuser section. The diffuser section is 190 ft of 2-1/2-in. PVC pipe. The diffuser section is anchored to the bottom by concrete blocks spaced at 8-ft intervals. A 5-ft length of line separates the block and diffuser such that the line remains 5 ft off the bottom when air is flowing through it. When not in operation, the air line settles to the bottom.

46. The diffuser holes are as follows beginning with the diffuser portion closest to the compressor: (a) the first 70 ft of diffuser has 13 1/8-in. holes, (b) the next 30 ft has five sets of holes drilled at 6-ft intervals, (c) the next 25 ft has five sets of holes drilled at 3-ft intervals, (d) the next 24 ft has six sets of holes drilled at 4-ft intervals, (e) the next 27 ft has nine sets of holes drilled at 3-ft intervals, and (f) the last 18 feet of diffuser has nine sets of holes drilled at 2-ft intervals. The end is covered with a threaded cap. Each set of holes consists of: three clusters of holes

Figure B30. Lake Morena compressor shed

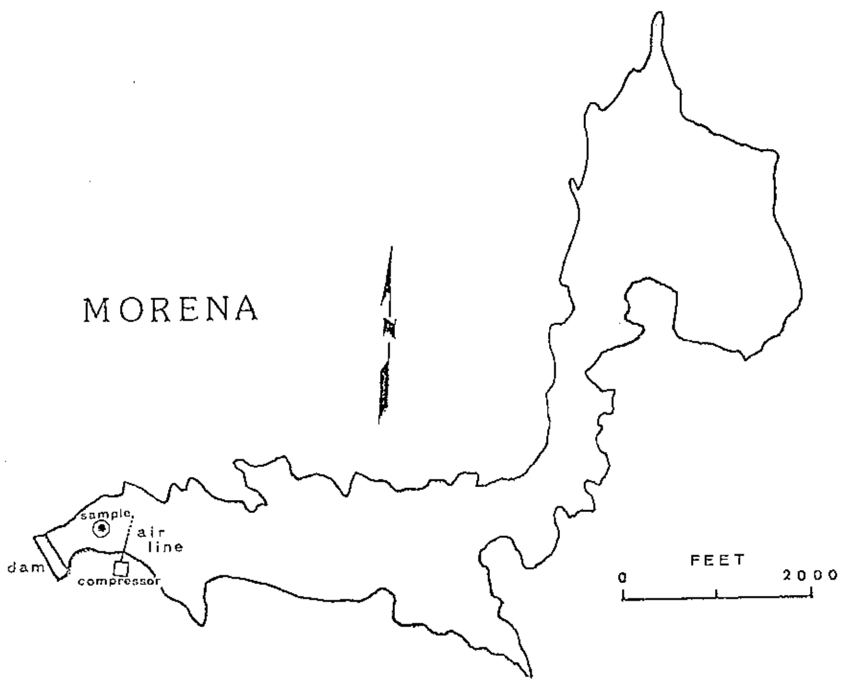


Figure B31. Lake Morena showing the aeration system and compressor location drilled 120 deg apart around the circumference of the pipe; and with each cluster consisting of four 1/32-in. holes drilled close together. Thus at each set, there are 12 holes. Along the last 124 ft of diffusers there are 34 sets, or 408 1/32-in holes total.

47. When in operation, the compressor normally runs 24 hr each day, 7 days a week. Operation normally occurs from April through October or November. During 1979, operation began during April 18 and continued through our last sampling date.

Lake Murray Aeration System

48. The Lake Murray aeration system is operated by the City of San Diego's Water Department. It is operated primarily to improve domestic water quality.

49. The aeration system includes a Worthington model R-50 50-hp, electric rotary screw air compressor which produces 240 SCFM of air. The compressor is housed in one of the buildings at the nearby Alvarado Water Treatment Plant. Air is conveyed from the compressor into the lake through a 2-in. iron pipe and then into 2-in. PVC plastic pipe. The diffuser section has 1/32-in. holes of unknown number and is of unknown length.

50. The diffuser section is not in the deepest part of the lake. It was installed on the crest of an old dam just forward of the present dam. The air plume is well developed and even (Figure B32), but it does little to the thermal and chemical stratification in the deep part of the lake. It primarily mixes the epilimnion, which is already well mixed by wind action. This system could easily mix the entire lake if the diffuser were properly placed at the deepest point.

51. When in operation, the aeration system operates 24 hr each day, 7 days a week. Its operation during 1979 is unknown, but it was operating during our June and August visits. We collected our samples about 300 ft up lake from the bubble plume.

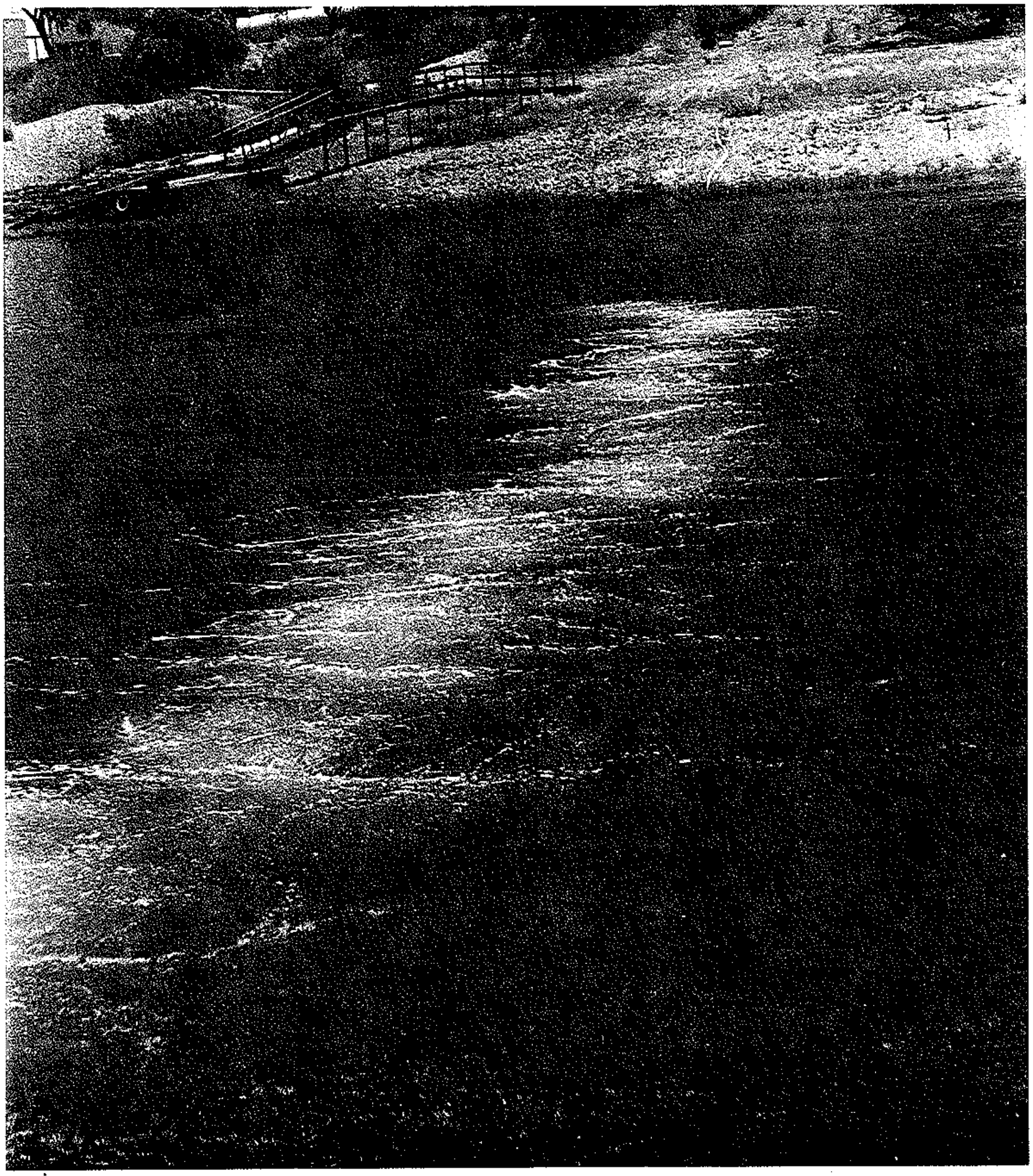


Figure B32. Bubble plume at Lake Murray

Lake Casitas Aeration System

52. Lake Casitas has been artificially aerated since 1968. Barnett (1971, 1979) and Howard (1972) described the original aeration system and its effects on the lake. The system was designed and operated by the Casitas Municipal Water District for domestic water quality control and for fisheries benefits.

53. The original system consisted of two Sullair 75-hp, electric rotary screw air compressors on shore. Each compressor produces 315 SCFM of air. The air is conveyed down the face of the dam and into the lake through a 3-in. iron (nongalvanized) pipe. The pipe is suspended just below the surface by 55-gal steel drums. At the end of the line a 210-ft pipe was attached to form a horizontal "T". Four hoses hung from the "T" at 70-ft intervals, and a single diffuser was attached to the bottom of each hose. The diffuser consisted of a short piece of iron pipe with holes drilled in it. Each diffuser was essentially a point-source diffuser. The diffuser depths normally varied between 140 and 160 ft.

54. During 1977 the aeration system's diffusers were redesigned and modified by the U. S. Bureau of Reclamation, Casitas Municipal Water District and Limnological Associates. Instead of four point-source diffusers, it consisted of seven 100-ft lengths of linear diffusers. These diffuser lengths were suspended in a line, more than 700 ft long. Each diffuser could be operated independently. Each diffuser section consisted of 1-1/2-in. PVC plastic pipe with 1/25-in. (1-mm) holes drilled at 1-ft intervals along the pipe. Thus, there were 700 holes along the 700 ft of diffuser.

55. During 1977 and 1978, air was injected through the entire 700 ft of diffuser. Either 315 or 630 SCFM of air was injected, as described in the results section of this publication. During 1979, only 400 ft of diffuser was used with 315 or 630 SCFM of compressed air.

56. The diffuser was suspended at the 150-ft (46-m) depth by surface floats with tether lines between the floats and the diffuser. A special buoyancy compensator system was used to raise and lower each

section. The principle on which this system works was described by Ogilvie and Scanlen (1975).

57. Aeration normally occurs at Lake Casitas from April until late October. It begins soon after thermal stratification is clearly evident and terminates after convective cooling in the fall has caused the lake to mix down to the diffuser depth.

58. The U. S. Bureau of Reclamation in cooperation with the Casitas Municipal Water District has been experimenting with new diffuser designs at Lake Casitas since 1977. The Water District has one of the most responsive lake monitoring programs of any that we know of.

Table B1

Description of the Location of the Diffuser System for Each of the Sampled Reservoirs

Reservoir	Diffuser Location
Puddingstone	Single ring diffuser located 6 to 10 ft shallower than the water depth at the sampling station. The diffuser stands 4 to 6 ft off the reservoir bottom in approximately 45 ft of water
Mathews	Two ring diffusers suspended at the 110-115-ft depth below the water surface
Perris	Two ring diffusers, the first of which was suspended 30 ft below the water surface. The second ring rested 10 ft above the reservoir bottom in a region near the outlet which was 90 ft deep during the June sampling period
Skinner	One ring diffuser located near the reservoir bottom in a region near the deepest location in the reservoir
Vail	The diffuser air line appeared to be broken during each of the sampling periods. The break was suspected to be above the thermocline, i.e., above the 26-ft depth below the water surface
Henshaw	100-ft diffuser section broke off from the air supply line in 1969. Air was supplied during this study from the loose air supply line near the bottom of the reservoir
Wohlford	One linear diffuser suspended just above the reservoir bottom near the deepest location in the reservoir
El Capitan	One linear diffuser suspended just above the reservoir bottom, approximately 20 ft above the deepest depth in the reservoir. The diffuser elevation, however, was below the maximum sampling elevation
Morena	One linear diffuser suspended 5 ft above the reservoir bottom near the deepest location in the reservoir
Murray	One linear diffuser located on an old submerged dam crest approximately 20 ft above the deepest location in the reservoir
Casitas	One linear diffuser suspended 150 ft below the surface of the reservoir
Cachuma	No aeration system was operated at this site

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Fast, Arlo W.
Supersaturation of nitrogen gas caused by artificial aeration in reservoirs / by Arlo W. Fast and Robert G. Hulquist (Limnological Associates, Kaneohe, Hawaii). -- Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station ; Springfield, Va. ; available from NTIS, 1982.
136 p. : ill. ; 27 cm. -- (Technical report ; E-82-9)
Cover title.
"September 1982."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army under Contract No. DACW39-79-M-2666 (EWQOS Work Units IIIB.1 and IIIB.4)."
"Monitored by Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station."
At head of title: Environmental & Water Quality Operational Studies.
Bibliography: p. 70-72.

Fast, Arlo W.
Supersaturation of nitrogen gas caused by : ... 1982.
(Card 2)

1. Nitrogen supersaturation. 2. Reservoirs--Aeration. 3. Reservoirs--Nitrogen content. 4. Water--Aeration. I. Hulquist, Robert G. II. United States. Army. Corps of Engineers. Office of the Chief of Engineers. III. Environmental & Water Quality Operational Studies. IV. U.S. Army Engineer Waterways Experiment Station. Hydraulics Laboratory. V. Title VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; E-82-9.
TA7.W34 no.E-82-9