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ARTIFICAL DESTRATIFICATION OF RESERVOIRS: HYDRAULIC LABORATORY --ETC(U)
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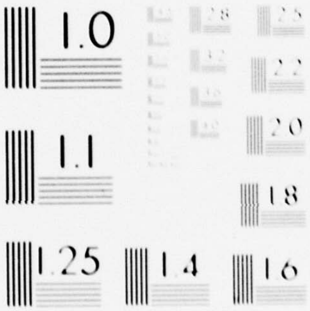

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A

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UNITED STATES OF AMERICA

DEPARTMENT OF THE ARMY
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1. The work reported herein was conducted as part of Work Unit 31605 (IIIB), "In-Reservoir Techniques for Improvement of Environmental Quality," of the Corps' Environmental and Water Quality Operational Studies (EWQOS) Program. Work Unit 31605 (IIIB) has the objective of developing engineering technology to improve water quality within a reservoir through laboratory investigations and field demonstrations.

2. This work involved laboratory testing of methods to mix a density-stratified reservoir. The two most common methods used are pneumatic (aeration) and hydraulic (pumping). Although both methods were investigated, this work unit concentrated on the hydraulic method. The effect of various geometric configurations of destratification methods was tested, and a dimensional description of the mixing process was developed. An example of planning and preliminary design of a hydraulic destratification is included within the report as well as comparison of the results of the work to prototype testing.

3. Future work under the EWQOS Program in this work unit will concentrate on refinement of the design procedure, evaluation of the environmental effects of destratification on a reservoir, and possible field demonstration of developed technology.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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

Methods of generating mixing in a density-stratified reservoir were experimentally investigated in a laboratory tank. Pneumatic (air bubbling) and hydraulic (water pumping) methods of destratification were studied, but efforts were concentrated on hydraulic destratification. The orientation of the diffuser and intake was found to influence the effectiveness of hydraulic destratification. Experimental results were used to relate mixing time to pumping conditions

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CONT

and reservoir size and stratification. The results are presented with the intent of being used for the planning and preliminary design of hydraulic destratification systems.

PREFACE

The study reported herein was sponsored by the Office, Chief of Engineers, U. S. Army (OCE), as part of the Civil Works General Investigations, Environmental Quality Research Area and Reservoir Water Quality Research Program. The work unit (CWIS No. 31042) entitled "Methods of Enhancing Water Quality" supported the subject study.

The investigation was conducted during the period November 1973 to December 1976 in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, and the general supervision of Mr. J. L. Grace, Jr., Chief of the Structures Division and Reservoir Water Quality Branch (Physical), and Mr. J. P. Bohan, former Chief of the Spillways and Channels Branch. Mr. E. E. Eiker, OCE, was Technical Monitor of the Reservoir Water Quality Research Program and Mr. Grace was the Laboratory Program Manager. This report also presents the results of Work Unit 31605 (IIIB) of the Environmental and Water Quality Operational Studies (EWQOS) Program. Program Manager of EWQOS was Dr. J. L. Mahloch.

The study was conducted by Mr. M. S. Dortch. This report was written by Mr. Dortch and reviewed by Mr. Grace and Mr. D. G. Fontane, Acting Chief of the Reservoir Water Quality Branch (Physical).

Directors of WES during this study were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	0.405	hectares
acre-feet	1233.482	cubic metres
cubic feet per hour	28.31685	litres per hour
cubic feet per second	0.02832	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
foot-pounds per second	1.356	watts
gallons per minute	3.785412	litres per minute
horsepower (electric)	746.00	watts
miles (U. S. statute)	1.609344	kilometres
pounds per cubic feet	16.018	kilograms per cubic metre
square feet	0.092903	square metres

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

ARTIFICIAL DESTRATIFICATION OF RESERVOIRS

Hydraulic Laboratory Investigation

PART I: INTRODUCTION

Background

1. When density stratification develops in a reservoir, the hypolimnion may become deficient in oxygen due to an oxygen demand and the inhibition of oxygen transport to this region from the surface. Under these conditions the hypolimnions of some impoundments become anaerobic. Changes occurring under anaerobic conditions that affect water quality are the dissolution of trace metals, the release of nutrients that may stimulate eutrophication, the release of aesthetically displeasing hydrogen sulfide, and depression of the pH. Oxygen deficiency in the hypolimnion reduces the habitat available to fish and can result in poor downstream quality if this water is released without sufficient reaeration or oxygenation.

2. Dissolved oxygen (DO) content in the epilimnion of a reservoir is usually at saturation level because of the gas transfer process at the air-water interface. Density stratification hinders circulation and internal mixing and therefore restricts the transport of oxygen from the epilimnion to the hypolimnion. If density stratification could be prevented or eliminated, the overall oxygen content in the hypolimnion could be increased. For a reservoir to be destratified by means other than the natural overturn or local winds, sufficient energy must be added through artificial means.

3. Although destratification of a reservoir is usually intended to increase the DO content and improve the water quality, other desirable or even undesirable changes could result. Destratification will warm the hypolimnion and cool the epilimnion. Loss of warm or cold water may be of concern to fisheries. Probable changes in release temperatures must be taken into consideration. It has been suggested

that cooling of surface waters would reduce evaporation. Cooling of surface waters would increase surface heat exchange which could result in increasing the total heat budget of the lake. Some success in using destratification to control algal blooms has been reported[1,2] while other efforts[3,4] have found increases in the standing crop of blue-green algae. For example, if nutrients from the hypolimnion are circulated into the photosynthetic zone, an accelerated phytoplankton growth could result. However, in most reported cases, destratification has caused a considerable enhancement of lake water quality by allowing oxygen transport throughout the lake. The impact of destratification on all water quality parameters should be considered before implementation.

4. There are numerous methods of transferring oxygen to the hypolimnion. All of the methods can be characterized into one or both of two basic categories: hypolimnetic aeration/oxygenation and destratification. The difference between the two basic methods is that hypolimnetic aeration/oxygenation is the oxygenation of the hypolimnion without mixing between the epilimnion and hypolimnion, while destratification is the mixing of these two regions permitting oxygen transport from the surface by circulation and diffusion. Air can be released into the hypolimnion such that the rising bubbles result in gas transfer and mixing, thus providing aeration and destratification. Hypolimnetic air diffusion was tested at Table Rock Reservoir[5] in an effort to increase the DO of power releases without destratifying the lake; stratification was necessary to maintain desired cold water releases. Generally, however, oxygen has been used for hypolimnetic diffusion because of its much higher absorption efficiency, and air has been used primarily for destratification. Additionally, hypolimnetic aeration using air at sufficient depths can result in excessive nitrogen supersaturation which could be hazardous to fish. At Table Rock, air injection through the turbine vent tubes was found to be more effective and economical than aeration through lake diffusers. Hypolimnetic oxygen diffusion upstream of a low-level release structure has been shown to be a feasible approach[6,7] to increase the DO content of hypolimnion water that is released downstream without

the benefit of significant downstream aeration. Hypolimnetic oxygenation also appears to be a feasible means of improving the DO content within the hypolimnion of small impoundments and especially within the locality of the diffuser system. However, hypolimnetic oxygenation has not been demonstrated to be a practical or economical means of improving DO content throughout the entire hypolimnion of large impoundments.

5. Artificial destratification has been tested in numerous case studies[8,9,10,11] as a means of increasing the total DO content of reservoirs and lakes. There are, generally, two methods of creating destratification: (a) mechanical (hydraulic) pumping and (b) release of compressed air near the bottom (pneumatic destratification). The hydraulic concept involves pumping water from one region of the reservoir and jetting it into another region of different density. With pneumatic destratification, an air-water plume causes mixing as it rises to the surface. Both methods have been shown to be effective in small lakes. A survey[12] of case studies indicated that pneumatic destratification has been field tested much more extensively than hydraulic destratification. Pneumatic destratification has been studied in large lakes and reservoirs (capacity greater than 100,000 acre-ft,* for example) with success ranging from limited (Lake Cachuma[13]) to good (Casitas Reservoir[14]).

6. Although hydraulic destratification has not been field tested as extensively as pneumatic destratification, its use certainly appears to be worth further consideration. A literature review indicated that at only one field site has an attempt been made to compare the effectiveness of mechanical and diffuser-air pumping.[15] These researchers found the diffused-air pump to be more efficient, in general, than the mechanical pump. However, the comparison was not adequate because the hydraulic inefficiency and excessive internal losses of the mechanical pump system were not considered. Hydraulic destratification can be an

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* A table for converting U. S. customary units of measurement to metric (SI) units is given on page 3.

effective means of mixing and may be more efficient than air for mixing large reservoirs and lakes.

Purpose and Scope of Study

7. The overall objective of this study was to investigate the design parameters and provide guidance relative to engineering means for artificial destratification of reservoirs and lakes.

8. The scope of this effort was limited to the use of laboratory experimental facilities. This was considered to be the most practical approach considering that this is the Corps' initial general investigation on the subject. Field applications do provide valuable information, but laboratory investigations have a great technical (because of controlled conditions) and economical advantage, especially when studies are of a general nature. Physical and mathematical models of specific destratification projects would be of benefit during development and design, but are not within the scope of this general investigation. Field applications are ultimately necessary to prove the success of a system.

9. Both destratification methods, hydraulic and pneumatic, were initially studied in an effort to compare the effectiveness of the two methods. The comparison presented in this report indicated that mechanical pumping was more effective than diffused-air pumping for destratification. When considering the two methods for field use however, it is not known how representative the comparison may be. It is felt that laboratory studies of hydraulic destratification can be used to develop criteria for field application. It is not difficult to achieve similarity of induced mixing created by a buoyant water jet. However, achieving similarity of induced mixing created by an air-water plume is much more difficult. Because the hydrostatic pressure in a laboratory flume exposed to atmospheric pressure is much less than the hydrostatic pressures found in the field, it is difficult to produce the bubble size, bubble density, and rise velocity that would occur in the field. These parameters can affect the mixing characteristics, thus making it

questionable as to whether these laboratory studies of pneumatic destratification can be extrapolated to field work. Because of difficulty in extrapolating results, because the laboratory comparison discussed in this report favored hydraulic destratification, and because air absorption at sufficient depths can result in significant levels of nitrogen supersaturation with respect to atmospheric pressure, further study of pneumatic destratification was eliminated from the scope of this investigation. Therefore, evaluation of hydraulic destratification techniques was the primary purpose of this study.

PART II: EXPERIMENTAL FACILITY

Description

10. A 36-ft-long by 3-ft-wide by 2-ft-deep rectangular, transparent plastic flume (Figure 1) was used to simulate a generalized impoundment. A two-layer density stratification representing the hypolimnion and epilimnion was generated using saline and fresh waters. The density difference and thickness of the two layers could be varied for different tests. The total volume of water in the flume was altered for different tests by varying the depth of water in the flume and by shortening the length of the flume.

11. A wide range of density differences (0.001 to 0.007 g/ml) was tested. This range includes the density differences encountered in lakes due to temperature differences. Density measurements were obtained with a density probe consisting of a conductivity and temperature sensor (Figure 2). Because even small temperature differences can have an effect on density when working with density differences this small, it was necessary to measure water temperature and to account for its effect on density. Both temperature and conductivity readings were used to compute a density value as described in detail in another study.[16] The conductivity sensor was calibrated with solutions of known temperature and specific gravity (obtained with a hydrometer) so that the temperature and conductivity values measured in the tests could be converted to density in grams per millilitre.

12. Mechanical pumping was achieved with a 0.20-hp centrifugal pump. The pump discharge was regulated with a hand valve and monitored with a rotameter. The water flow rate could be varied from 0.10 to 1.35 gpm. Mixing was induced in the flume by withdrawing water from either the upper or lower layers of the pool and jetting it into the other layer of different density. A schematic presentation of the test facility is shown in Figure 3. For the pneumatic destratification tests, diffused air was supplied by a 0.5-hp compressor and was regulated by a rotameter and valve. The air flow rate could be varied from 0.5 to 50

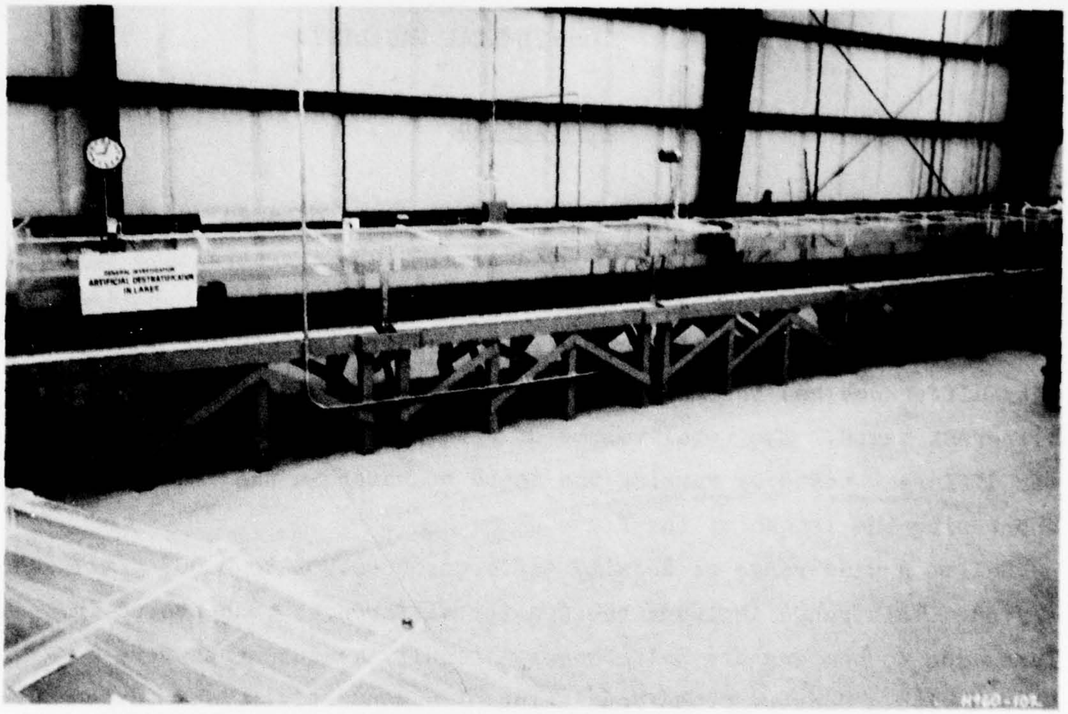


Figure 1. Destratification test model

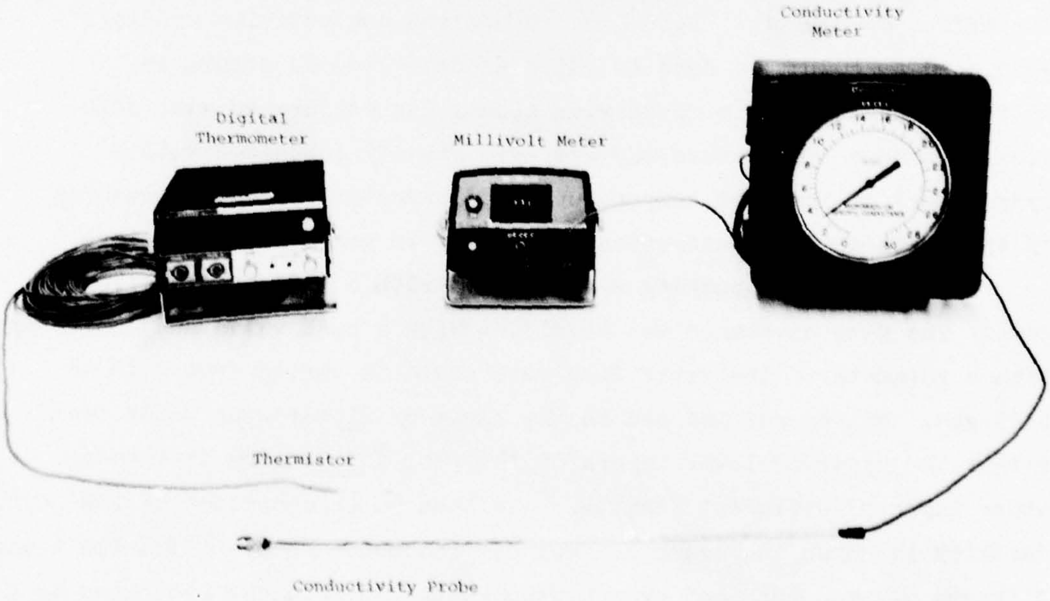
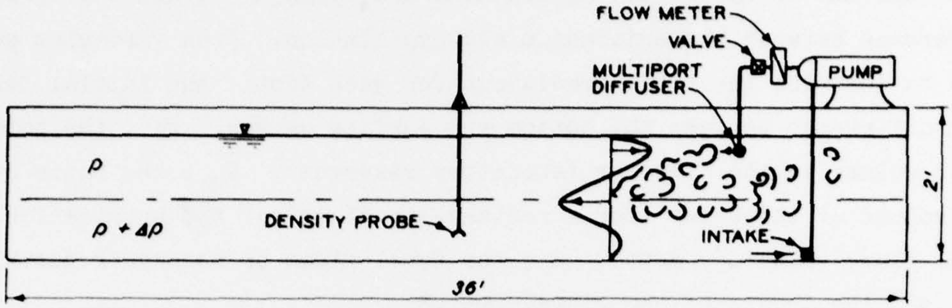


Figure 2. Density measurement instrumentation



ELEVATION

NOTE: FIGURE NOT DRAWN TO SCALE

Figure 3. Schematic of test model

standard cubic feet per hour (scfh). The air was released vertically from a diffuser on the bottom.

13. The water or air discharge was released through a multiport diffuser. Diffusers with different port diameters made it possible to change the exit velocity for a given discharge rate. It was also possible to change the orientation of the pump intake and the diffuser to determine the effect of intake-diffuser orientation on hydraulic destratification.

14. The continuous natural change in stratification that occurs in a reservoir or lake was not provided in the model. With the model located in a temperature-controlled shelter, it was possible to maintain a fairly constant air temperature through each test. To minimize surface heat exchange, the flume water was allowed to equilibrate with the air temperature. By eliminating surface heat exchange effects, the scope of study was maintained while reducing the complexity. When destratification is tested in the field, meteorological effects should be included in the analysis of a system.

Experimental Methods and Procedure

15. The effects of the size of a rectangular reservoir and its particular density stratification on the requirements for destratification were investigated by varying the flume length and water depth, the

thickness and volume of the hypolimnion and epilimnion, and the density difference between the epilimnion and hypolimnion. Five variables were used to describe the flume conditions for each test: the initial density difference between the bottom and surface waters, $\Delta\rho$; the total water volume in the flume or laboratory reservoir, V_R ; the ratio of the volume or thickness (for a rectangular flume) of the hypolimnion to total flume volume or depth, β ; the total flume or reservoir depth, d_R ; and the length of the flume, L_R .*

16. The amount of stratification was measured throughout each test so that changes caused by the destratifying system could be determined. Stability has long been used by limnologists as a measure of the intensity of stratification and is calculated according to the following definition: the energy required to lift the weight of the entire body of water the vertical distance between water mass center of gravity when homogeneous and the mass center of gravity when the impoundment is stratified[17] Stability may also be thought of as the minimum energy required to completely mix a stratified body of water. The equation for stability, S , is written as

$$S = \gamma_w V_R (H - Y) \tag{1}$$

where γ_w is the specific weight of water, V_R is the total reservoir volume, and H and Y are the water mass centers of gravity when the reservoir is homogeneous and stratified, respectively. The center of gravity for a stratified condition was computed from density-versus-depth profiles obtained by traverses with the density probe. To avoid strong density fluctuations that would result with turbulent mixing, the probe was positioned away from the diffuser. When the diffuser was located at one end of the flume, the density probe was stationed at half the length of the flume. When the diffuser was located at half the flume length, the probe was positioned at one end. An initial density

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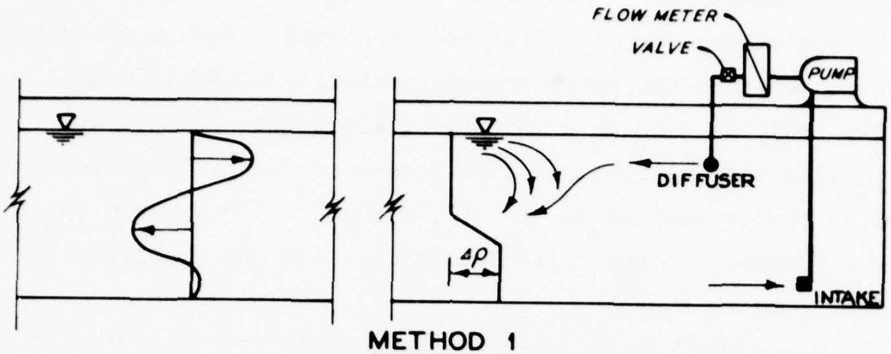
* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

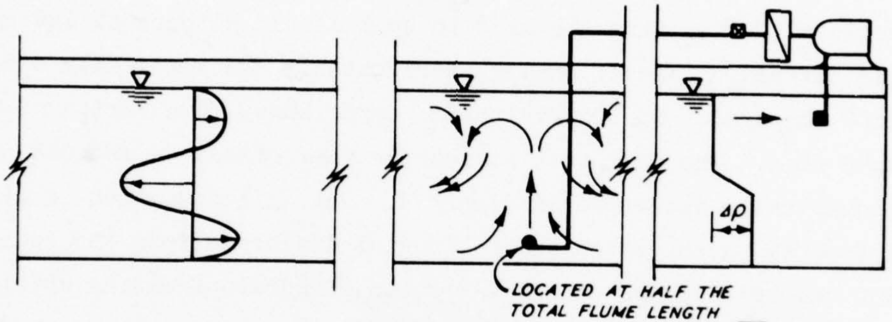
profile was taken prior to pumping. Throughout each test, density profiles and elapsed pumping time were recorded. Each density profile was used to compute the corresponding stability so that changes in stability could be used as a measure of the degree of destratification achieved with respect to time. The degree of destratification was expressed as the percent mixed, or $(S_i - S)/S_i \times 100$, where $S_i - S$ was the difference in the initial stability and the stability at some time after pumping began.

17. The effect of diffuser-intake orientation on hydraulic destratification was investigated. Specifically, hypolimnetic withdrawal and eplimnetic diffusion were compared to epilimnetic withdrawal and hypolimnetic diffusion. Additionally, horizontally and vertically directed jets were compared. To achieve these comparisons, four series of tests were conducted. The four test series are categorized as methods 1-4 and are schematically described in Figure 4. Method 1 consisted of withdrawal from the hypolimnion and horizontal discharge into the epilimnion. Method 2 was oriented such that water was withdrawn from the epilimnion and discharged vertically upward into the hypolimnion. For method 3, water was withdrawn from the epilimnion and discharged horizontally into the hypolimnion. Method 4 consisted of withdrawal from the hypolimnion and vertical discharge downward in the epilimnion. The intake and diffuser were positioned as close to the surface or bottom as possible for all tests. This was done to maximize the density difference and depth between the intake and diffuser and to eliminate any effects that might result if the vertical position of the diffuser or intake were varied within the water column.

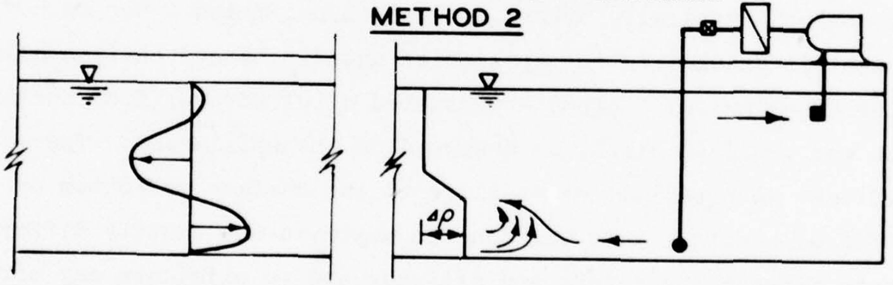
18. To provide a variation in port velocity for a given flow rate, three diffusers with different port diameters were used in the hydraulic destratification investigation. Details of the diffusers are shown in Figure 5. To minimize the number of variables, the diffuser ports were uniformly distributed across the width of the flume, and the number of ports and spacing were held constant. It is realized that the dilution characteristics of multiport diffusers is a study in itself and such an effort was not within the scope of this study. However, multiport



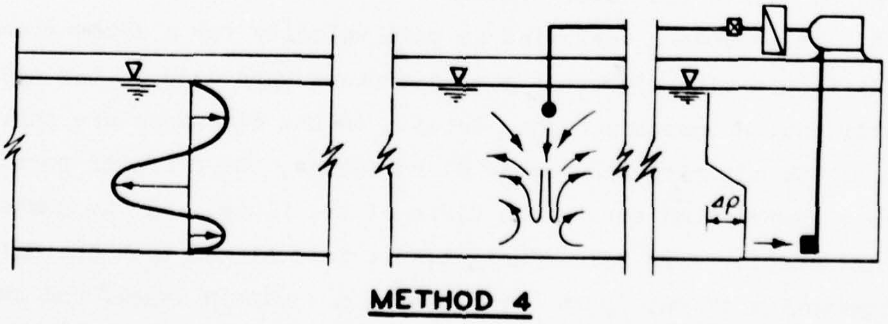
METHOD 1



METHOD 2



METHOD 3



METHOD 4

Figure 4. Test series of diffuser-intake orientations

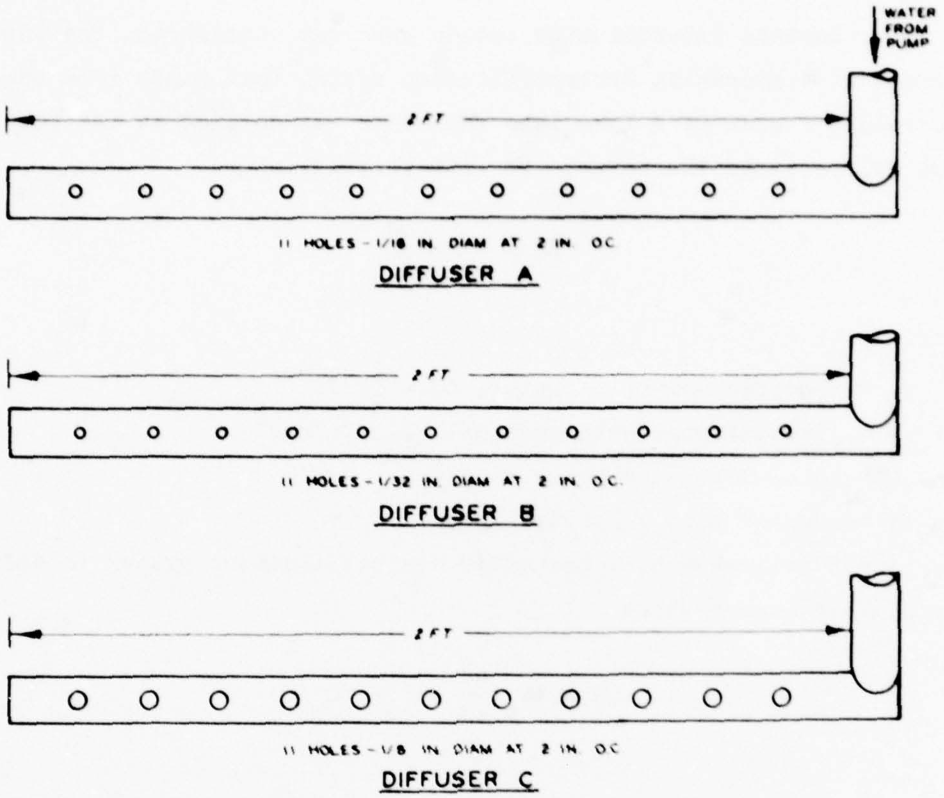


Figure 5. Diffuser details

diffusers were used to be representative of systems anticipated for destratification of large impoundments.

19. By diffuser selection and discharge regulation, it was possible to test a variety of pumping conditions for each diffuser-intake orientation. The discharge rate was held constant throughout the duration of any one particular test. The average port velocity was computed by dividing the discharge rate by the total port area of the multiport diffuser. The pump and supply line design and losses were not considered in the analyses. The pump and supply line losses are referred to as internal losses and affect the internal performance. The effect that the jetted discharge has on mixing is referred to as external performance. This study considered only external performance for two reasons: comparison of destratification test results is much simpler when only external performance is considered and internal design features are beyond the scope of this study.

20. Because internal line losses were not considered, the input of power of a hydraulic destratification system that pumps from one temperature region of a lake into the other was defined as the power input delivered to the water, PW (ft-lb/sec), where

$$PW = \gamma_w Q \frac{V^2}{2g} \tag{2}$$

and

γ_w = specific weight of water, 62.4 lb/ft^3

g = gravitational acceleration, 32.2 ft/sec^2

Q = total discharge rate, ft^3/sec

V = average port velocity, ft/sec

Power input delivered by a pneumatic destratification system is defined in a similar manner where

$$PW = \left(\gamma_a \frac{V^2}{2g} + \gamma_w h\right) Q_a \tag{3}$$

and

γ_a = specific weight of air at standard temperature and pressure, 0.0766 lb/ft^3

V = average port velocity of air, ft/sec

h = depth of air diffuser below water surface, ft

Q_a = volume flow rate of air, scfs

With the hydraulic system, the energy required to pump against the hydrostatic pressure is equivalent to the difference in head created by density differences only and is therefore negligible. However, for the pneumatic system, air must be forced to the bottom to induce mixing. Therefore, the energy required to overcome the hydrostatic pressure must be considered. For practical applications, the velocity head of the flowing air will be small with respect to the hydrostatic pressure, therefore allowing power input delivered by a pneumatic system to be calculated from

$$PW = \gamma_w h Q_a \tag{4}$$

21. The pneumatic destratification tests were conducted with diffuser B (Figure 5) and an aquarium-type, porous diffuser stone. The diffuser was positioned on the bottom of the flume at half the flume length with the air diffused vertically up (Figure 6). Several air flow rates were tested. The pneumatic destratification test conditions are presented in Table 1.

22. For the pneumatic and hydraulic destratification tests, each test could be characterized by the reservoir conditions (V_R, $\Delta\rho$, β, d_R, L_R). For hydraulic destratification, pumping conditions consisted of the diffuser size (A, B, or C); the pumping rate, Q ; the average port velocity, V ; and the diffuser-intake orientation. Most tests were conducted until substantial or total destratification was achieved. The tests prolonged by a small pumping rate and port velocity were usually halted short of total destratification because of monitoring difficulties associated with long testing time. Conditions tested and results obtained with hydraulic destratification are presented in Tables 2-5.

23. As a result of the energy dissipation of a rising air-water plume or a jetted water discharge, ambient water is pulled toward and

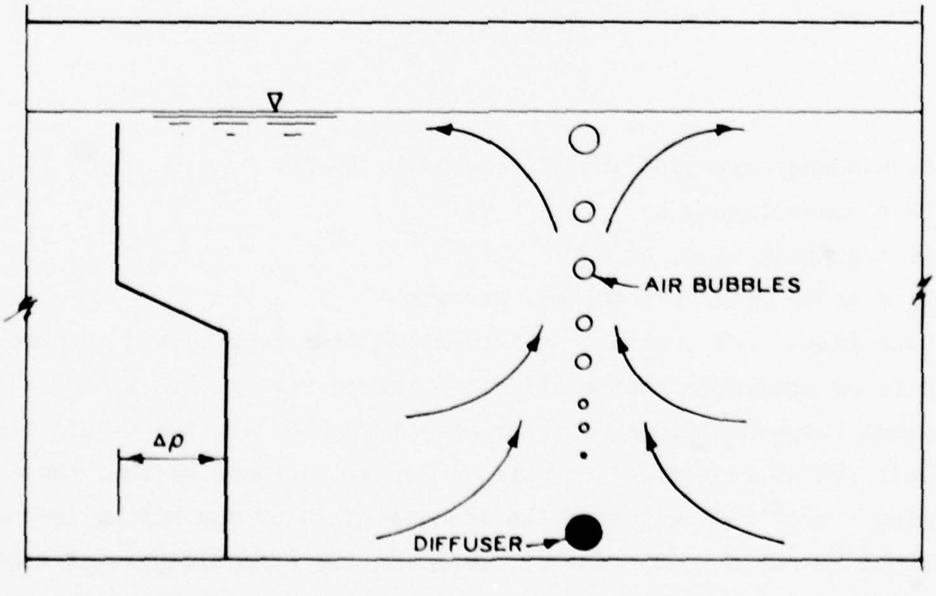


Figure 6. Pneumatic destratification

mixed with the plume or discharge. This process is referred to as entrainment. Because of entrainment, an induced water flow results that can be much larger than the air flow rate or the water pumping rate. At various times during the testing program, it was desirable to obtain an estimate of the entrainment characteristics created by a particular pumping condition. The volume flow rates of the induced currents, as compared to the initial pumping rate, are a direct indication of the amount of entrainment. Velocity profiles were used to determine the flow rate of these currents. Vertical velocity distributions were obtained by dropping dye particles into the flume and recording with video equipment the displacement of the resulting dye streaks. Integration of the velocity profile from the surface to the bottom yielded a unit discharge. Assuming uniform flow laterally, the unit discharge was converted to a volume flow rate by multiplication of the unit discharge by the width.

24. There are several ways to compare the effectiveness of various destratification systems. One method that has been used by other researchers for comparing effectiveness is the energy input per unit volume that is required to mix a reservoir. This is computed from

$$\frac{\Delta E}{V_R} = \frac{PW \cdot \Delta t}{V_R} \qquad (5)$$

where

ΔE = energy expended in the reservoir, hp-hr

PW = power input, hp

Δt = pumping time, hr

V_R = total reservoir volume, acre-ft

The power input, PW , should be determined from Equations 2 or 4 for hydraulic or pneumatic destratification, respectively. It is emphasized again that these equations consider only the power applied within the reservoir and neglect power required to drive the pump system, thus providing a true indication of the effectiveness of the mixing technique. Equation 5 is not a good means of comparing the effectiveness of destratification systems because it does not take into account changes in reservoir stability or the energy of stratification overcome by the mixing device.

25. Another parameter often used to compare the effectiveness of destratification systems is the destratification efficiency, D.E. (percent), which is computed from

$$D.E. = \frac{\Delta S}{\Delta E} \times 100\% \qquad (6)$$

where ΔS is the change in stability that occurs during the pumping period. Equation 6 gives a much truer description of the effectiveness of a system than does Equation 5, but there are sometimes difficulties in using Equation 6 to compare systems. In the field, varying meteorological conditions can affect ΔS and the ΔE required to obtain a degree of destratification, making it difficult to compare systems. Even with controlled reservoir conditions, D.E. can vary throughout a destratification test. An example of how D.E. can vary with pumping time is shown in Figure 7. As the reservoir approaches a completely mixed state, the mixing process becomes less efficient. There are ways to use D.E. to effectively compare systems, and D.E. was used as a reference in this study as will be discussed later.

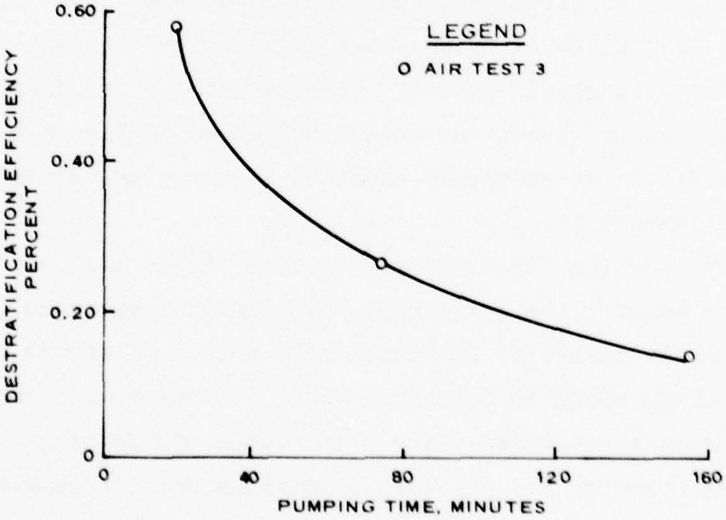


Figure 7. Effect of mixing time on destratification efficiency

PART III: EXPERIMENTAL RESULTS

Description of Mixing

26. Both of the destratification methods, hydraulic and pneumatic, created similar mixing characteristics. Flow conditions within the laboratory flume are considered to be representative of what would happen in the field. The flow conditions basically can be divided into two parts: (a) turbulent mixing zone near the diffuser; and (b) gravity-driven density currents, induced entrainment flow, and withdrawal flow in the far field. After encountering entrainment and turbulent mixing near the diffuser, the kinetic energy of the jet is significantly reduced and the diluted discharge seeks a neutrally buoyant level in the water column. Upon achieving neutral buoyancy, the flow is dominated by gravity and spreads as an intermediate density current or interflow, which means it flows within the intermediate depths of the pool. The energy of the rising air-water plume and of the hydraulic jets causes an induced entrainment flow. This induced current, reverse to the direction of the interflow and at a different level of the water column, moves towards the diffuser and is entrained by the water jets or air-water plume leaving the diffuser. This current is referred to as the entrainment current. Additionally, withdrawal of water by the pump intake creates a small withdrawal current. Examples of flow regimes for the hydraulic pumping configurations tested are shown in Figure 4. The pneumatic destratification system produced flow regimes similar to that of method 2, Figure 4.

27. Away from the turbulent mixing zone, three distinct stratification regions exist: the epilimnion, hypolimnion, and zone of interflow. The zone of interflow increases with pumping time and eventually a completely mixed state is reached. Water density within the interflow zone approaches a homogeneous state with respect to pumping time. This phenomenon was observed for all test conditions and diffuser-intake orientations investigated. Mixing with respect to time can best be described by comparing density profiles as shown in Figure 8. As

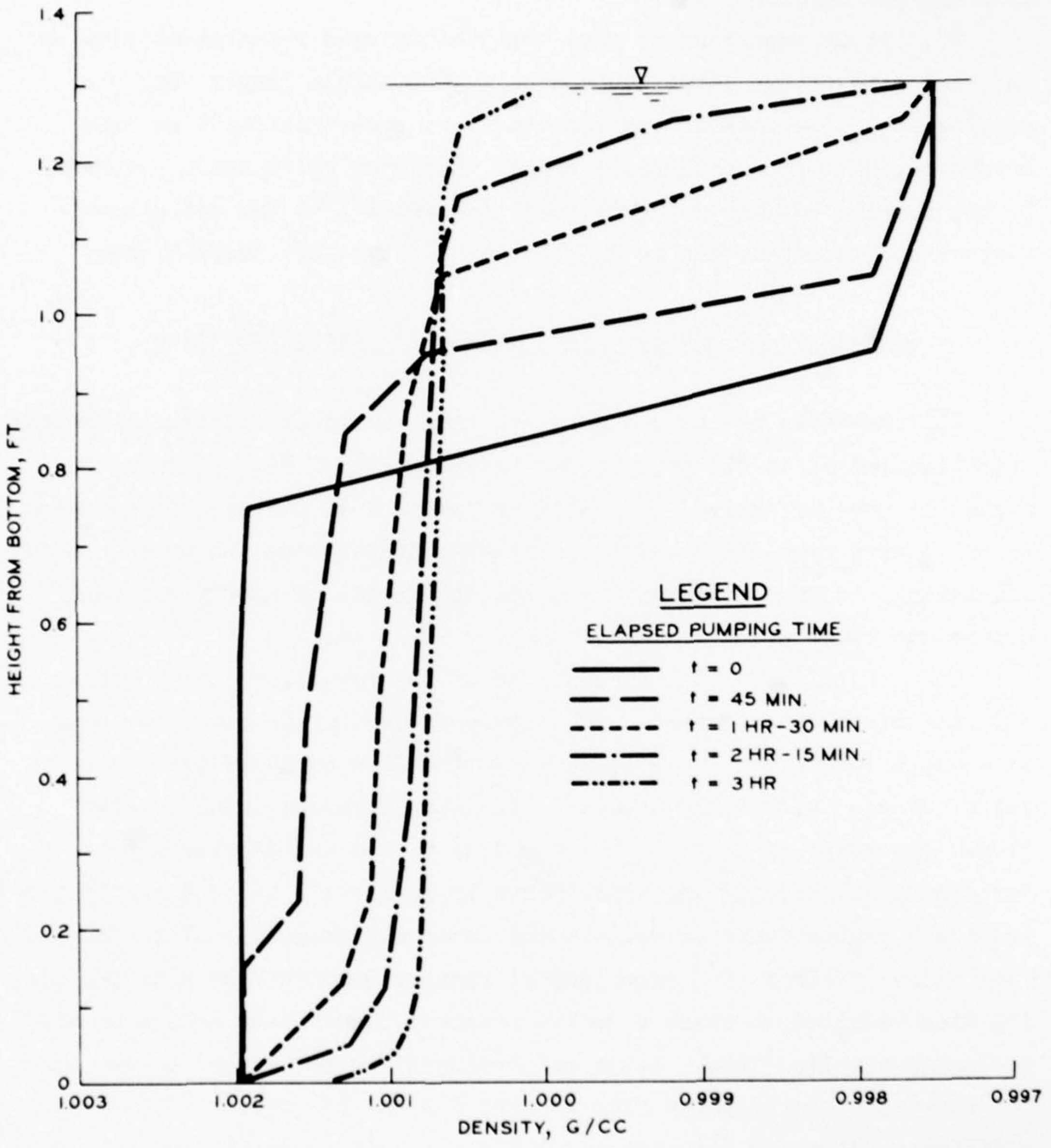


Figure 8. Typical mixing results from artificial destratification

shown by the plots, mixing at the surface and bottom occurs more slowly. It was difficult to reach a completely mixed state at the surface and bottom. However, in the field the diurnal heat exchange and wind would help mix the surface water.

28. It is important to note that the induced entrainment flow and the flow rate of the interflow can be significantly larger than the pumping rate. Because of the induced flow, a destratification rate occurs that can be considerably higher than that which would occur due to the pumping rate only. Some tests indicated that the entrainment current and interflow can be as great as 20 times the pumping rate.

Comparison of Hydraulic and Pneumatic Destratification

29. Probably one of the more pressing questions concerning destratification raised by planners and designers is which destratification system is more effective, hydraulic or pneumatic? During this research effort, tests were conducted to determine which system, under laboratory conditions, is more efficient from the standpoint of energy expended within the lake during mixing.

30. It is useful to discuss some of the results found by others studying air bubble systems. The flow produced by air bubbles rising in a water column shows similarities to the flow produced by a water jet discharged vertically upwards. The air discharge induces water flow. The ratio of the water volume flux to the air discharge rate was shown analytically and experimentally by Kobus[18] to be directly proportional to the depth of release and inversely proportional to the air flow rate. Brainard's[19] experimental results demonstrated that the mixing time required to reach a desired percent mixed state decreased with increased air flow rate. Kobus and Brainard, respectively, showed that the ratio of induced water flow to air flow and the destratification efficiency decreases with increased air flow rate. Similar results were found in this study as indicated by Figure 9. Brainard's results indicated that the mixing time, which is inversely proportional to the induced water flow, decreased with air diffuser depth but the

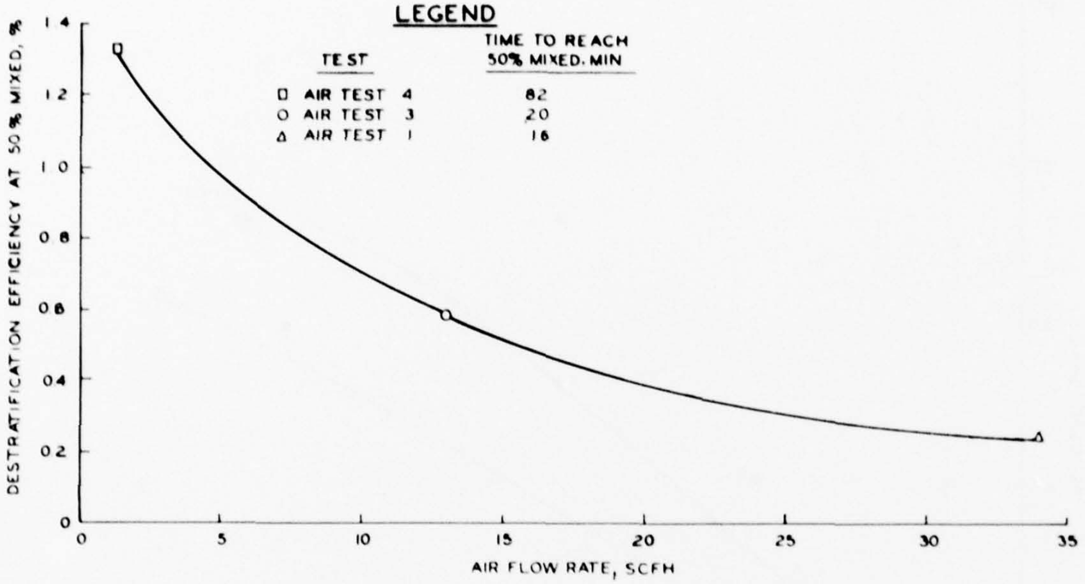


Figure 9. Effect of air flow rate on destratification efficiency

destratification efficiency did not change. This seems reasonable since the input energy increases with the diffuser depth.

31. Zieminski and Whittemore[20] reported that for larger bubbles, bubble radii above the range of 0.024-0.031 in., mixing time does not depend much on bubble size. However, below this range the bubble size does have an effect on mixing time and induced water flow. Zieminski and Whittemore showed that the induced water flow increases and the mixing time decreases with a decrease in bubble size for a constant depth and air flow rate. Similar results were found in this study as demonstrated by Figure 10.

32. Air test 5, which used the diffuser stone, was compared with the hydraulic destratification test B3. The diffuser-intake orientation of test B3 is characterized as method 2 (Figure 4). The powers delivered to the water for these two tests were approximately equal. Additionally, approximately the same initial conditions (V_R, β, $\Delta\rho$, d_R, L_R) were set up for both tests so that a comparison of the effectiveness of the two methods could be made. As shown by Figure 11, the hydraulic mixing occurred faster than the pneumatic mixing thus

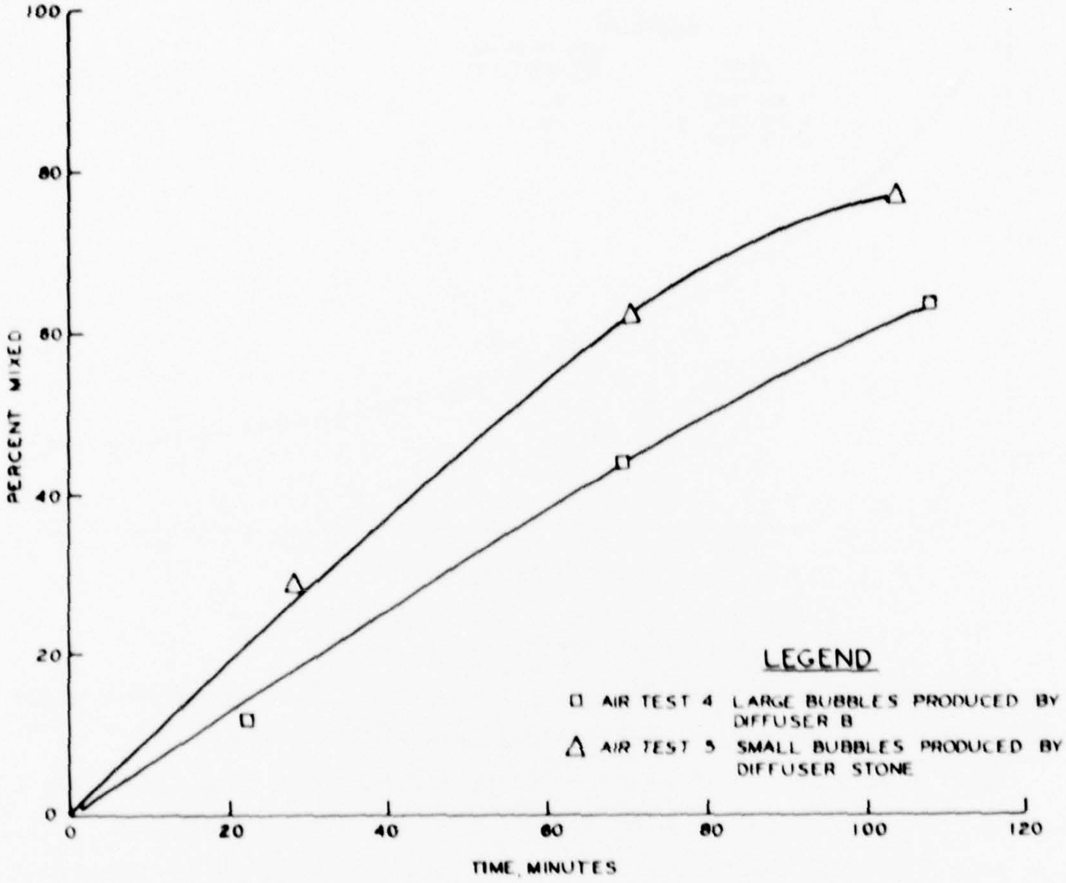


Figure 10. Effect of bubble size on destratification

indicating a higher efficiency since the power inputs were about equal.

33. The comparison made in Figure 11 is only an indication that hydraulic mixing is at least comparable and possibly more hydrodynamically effective than pneumatic mixing. The comparison is not intended to conclusively determine which system is more efficient because there are questions that can be raised (see paragraph 9) as to whether laboratory air bubble mixing results can be extrapolated to field application. The comparison made in Figure 11 does demonstrate that hydraulic destratification is at least comparable to and possibly more hydrodynamically effective than pneumatic mixing.

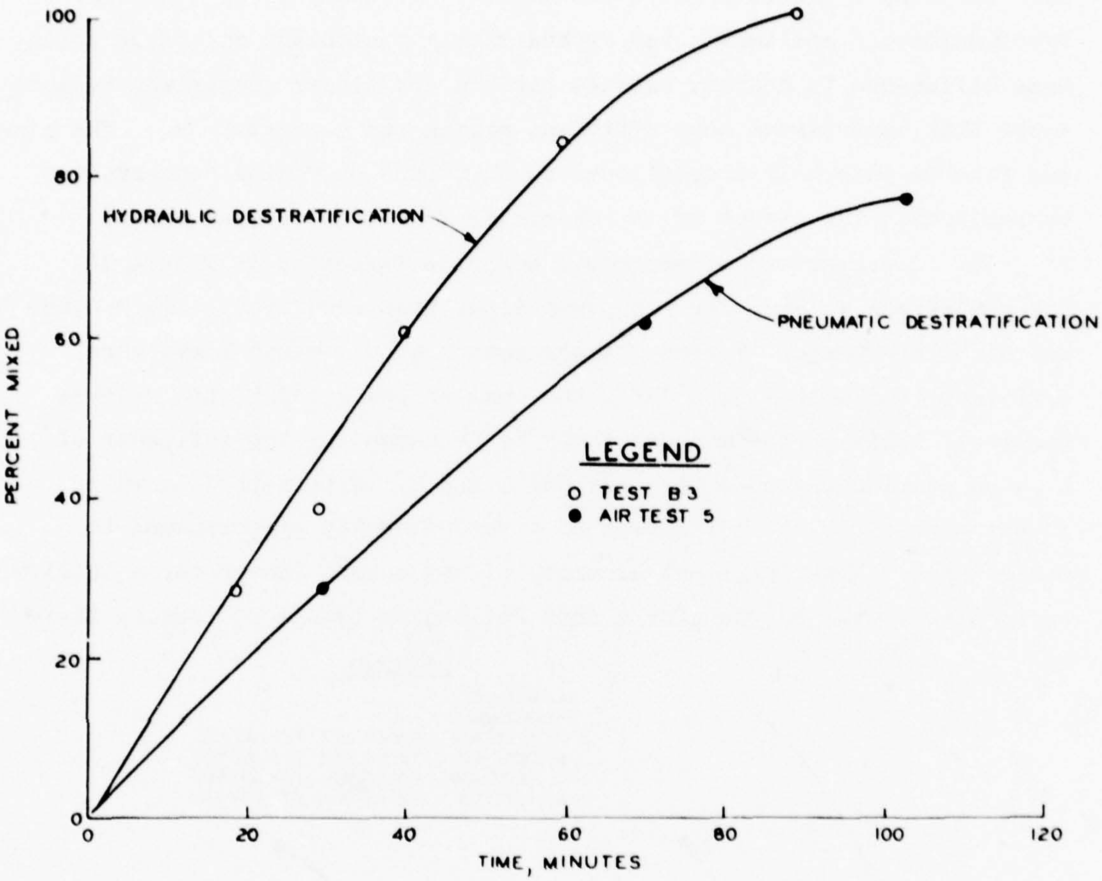


Figure 11. Comparison of hydraulic and pneumatic destratification effectiveness

Diffuser-Intake Orientation

34. Four basic methods of diffuser-intake orientation (Figure 4) were tested to determine their effect on mixing. The four methods involve either horizontal or vertical direction of the water jets with the diffuser located at either the near surface or bottom. To make a valid comparison for effectiveness, tests with the four methods were selected to provide approximately the same initial reservoir conditions for all tests. Conditions for the selected tests consisted of a water depth of 1.3 ft, water volume of 140.4 cu ft, flume length of 36 ft,

and $\beta = 0.65$. Additionally, the density difference, $\Delta\rho$, of the hypolimnion and epilimnion was approximately equivalent for these tests. Some difference in density existed but did not hinder comparison because tests that experienced more efficient mixing had a greater $\Delta\rho$. The mixing rate is inversely proportional to $\Delta\rho$, thus providing conservative comparisons. The effect of $\Delta\rho$ on mixing will be discussed later.

35. A comparison of methods 1 and 3 is presented in Figure 12. The comparison is made for two power input test conditions, PW = 0.284 and 0.001 ft-lb/sec. For the larger power input, method 1 was more efficient than method 3, and for the smaller power input, the reverse was true. This phenomenon was found to be caused by the influence of β when pumping was used with methods 1 and 3. With method 1, water is entrained from the epilimnion at a rate directly proportional to power input. With large entrainment, mixing occurs faster for a shallow epilimnion (large β) than for a deep epilimnion (small β) because there

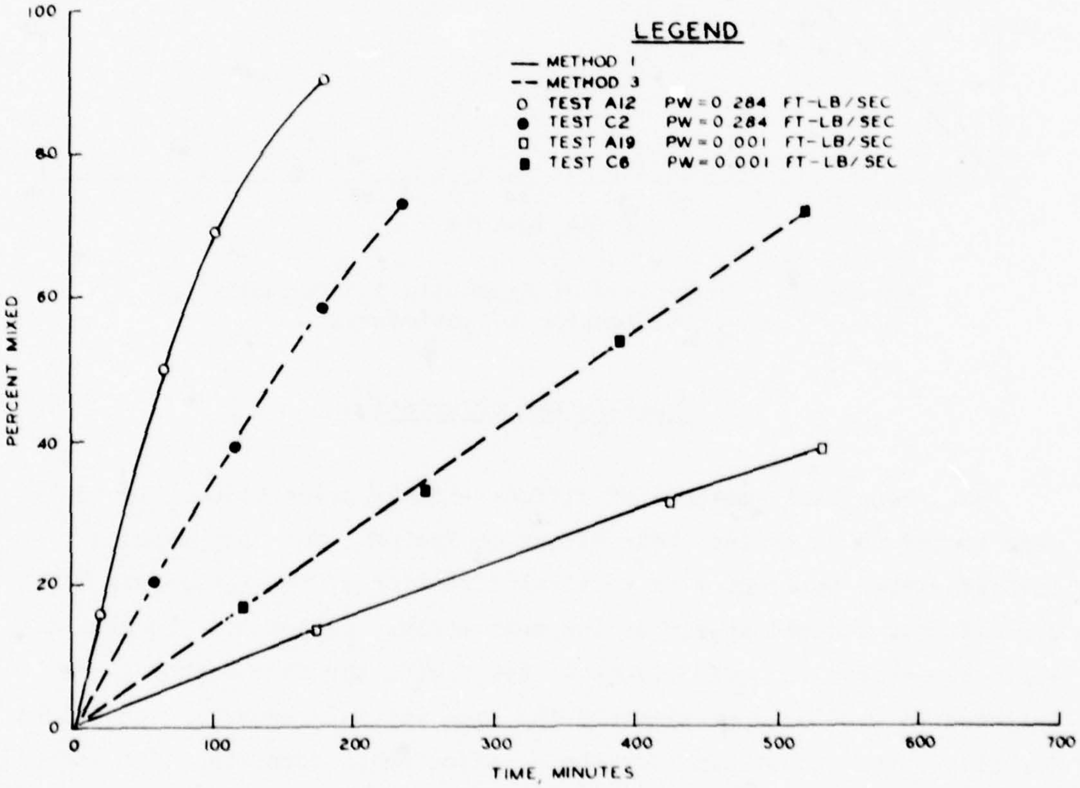


Figure 12. Comparison of pumping methods 1 and 3

is less water to be entrained. With small power input, less entrainment occurs and the rate of mixing is more dependent on the pumping rate rather than the induced or entrained flow. As a result, mixing with low power input and method 1 occurs faster for a deep epilimnion than for a shallow epilimnion because there is less hypolimnion water that must be pumped. Pumping of epilimnion water and entrainment of hypolimnion water occurs with method 3. Therefore, the reverse of the above discussion is true, thus explaining the trend in Figure 12. It is emphasized that these results were obtained in a rectangular tank where $\beta = d_H/d_R = V_H/V_R$; d_H and V_H are the vertical thickness and volume of the hypolimnion. In a true impoundment, volume within a given increment of depth decreases with elevation. So β might have more meaning if it were defined as V_H/V_R rather than d_H/d_R .

36. A comparison of methods 2 and 4 (Figure 13) indicates similar

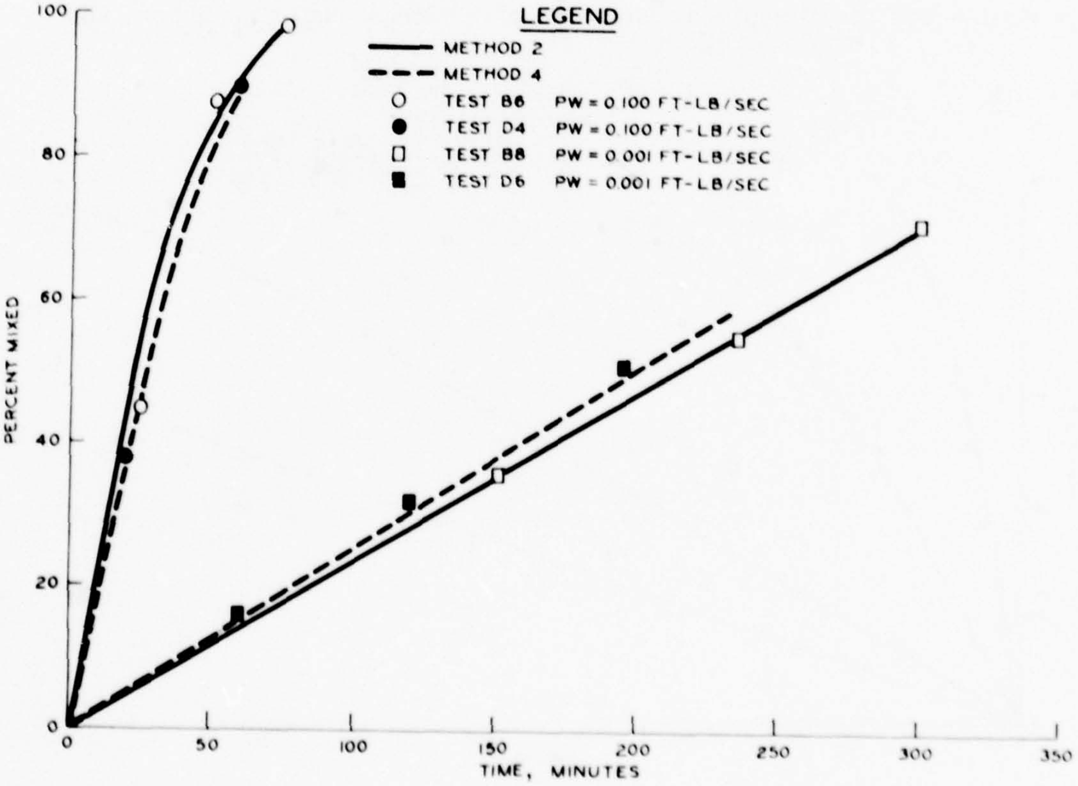


Figure 13. Comparison of pumping methods 2 and 4

test results. For both methods, β had no significant effect on the rate of mixing except with very low power input where little induced mixing was experienced. With either of these two methods, entrainment of bottom and surface waters occurs. For example, with method 2 the initial jet momentum induces entrainment of hypolimnion water, which increases the density of the vertically rising plume. The jet momentum carries the plume to a maximum rise height in the epilimnion which is of less density. As the plume falls to a level of neutral buoyancy, epilimnion water is entrained. This dual entrainment of water from the upper and lower layers of the pool causes a faster rate of mixing than that possible with methods 1 or 3 for the same power input. Figure 14 compares method 2 with methods 1 and 3 for two values of power input. These results indicate that methods 2 and 4 are more efficient than methods 1 and 3.

37. Because of aesthetic reasons, method 2 is recommended over method 4 for field application. Use of method 4 could result in the

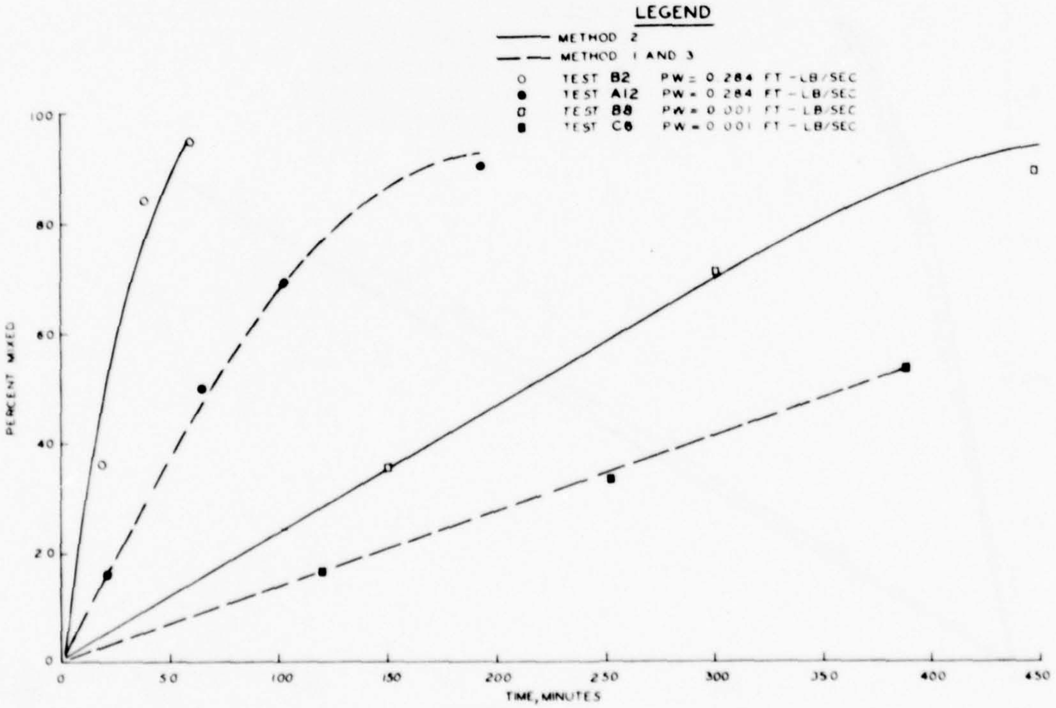


Figure 14. Pumping method 2 compared with pumping methods 1 and 3

release of iron, manganese, hydrogen sulfide, ammonium, and organic compounds in the epilimnion when anaerobic water of the hypolimnion containing these compounds in solution is discharged into the aerobic epilimnion water. The presence of these substances in the surface waters could be a nuisance. Additionally, phosphorus resolublized in the hypolimnion would be pumped into the epilimnion, making it available for uptake by phytoplankton, thus possibly promoting algal blooms. Therefore, tests results obtained with method 2 will be the basis for further analyses presented in this report.

Parameters Affecting Artificial Destratification

38. As would be expected, the rate of mixing for the hydraulic system (method 2 pumping) was found to be directly proportional to the power input, PW , as defined by Equation 2. Additionally, physical characteristics of the impoundment were found to affect the rate of mixing. Throughout the study, results indicated that the rate of mixing was inversely proportional to the reservoir volume and depth, and the density difference between the epilimnion and hypolimnion.

39. Analyses were conducted to combine and nondimensionalize the variables into parameters that can be used to describe the rate of mixing for various physical characteristics and pump discharge conditions. Ditmars[21] suggested the importance of a normalized time, t^* , in the dimensional analysis of destratification where

$$t^* = \frac{tQ}{V_R} \tag{7}$$

where t is the elapsed pumping time. This dimensionless time, which is also equivalent to the fraction of total reservoir volume that has been pumped, was needed to bring meaning to the test results obtained in this study. The percent of destratification for various test conditions is plotted with t^* as shown in Figure 15.

40. In Figure 15, the power input for each test is indicated.

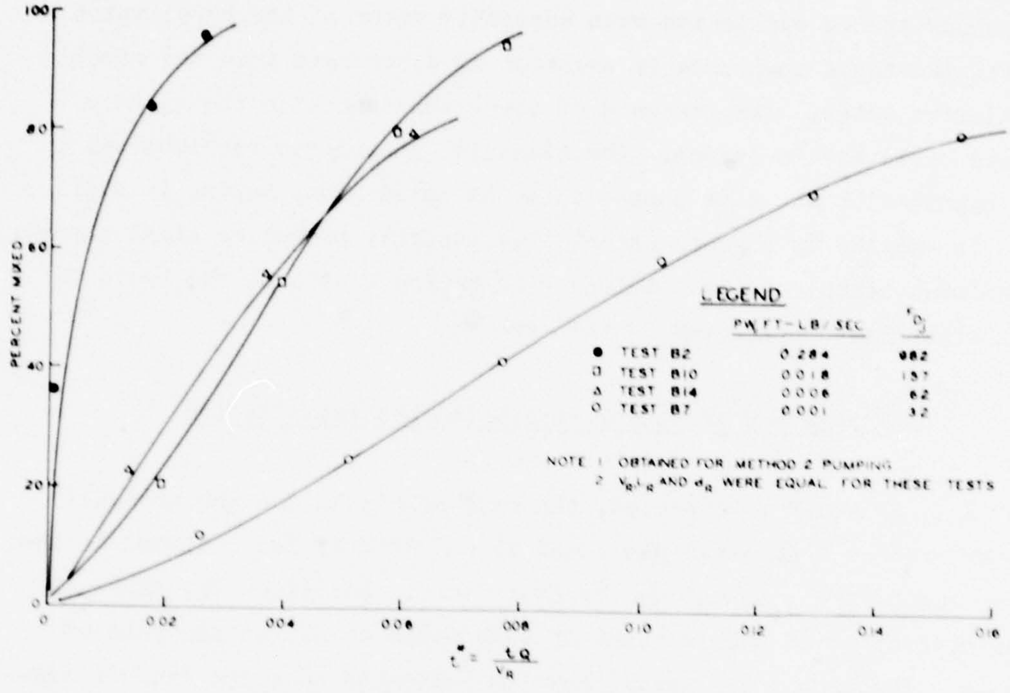


Figure 15. Effect of PW and F_{D_j} on mixing

It should be noted that in general for a given percent mixed state, t* decreases with increasing input of power. However, there were tests that experienced mixing rates equivalent to those of tests with greater power inputs (see tests B10 and B14, Figure 15). Another dimensionless parameter, the jet densimetric Froude number, F_{D_j}, defined as

$$F_{D_j} = \frac{V}{\sqrt{\frac{\Delta\rho}{\rho} gD}} \qquad (8)$$

where

D = individual diameter of diffuser ports, ft

ρ = reference density of water, approximately equal to 1.0 g/ml

was found to have a significant effect on the rate of mixing. As indicated by tests B2, B10, and B7 (Figure 15), t* decreased with increasing F_{D_j} for a given percent mixed state. However, test B14, which had a smaller F_{D_j} and PW and a larger Q compared to test B10, experienced mixing equivalent to test B10. The percent of mixed state for a given t* is proportional to PW and F_{D_j}, but these parameters could not sufficiently describe the destratification characteristics. It was also not possible to use PW in a meaningful dimensionless form.

41. Throughout the literature it is suggested that the mixing rate is directly proportional to the momentum flux ρVQ. A similar trend was found in this study. However, parameters describing the lake characteristics (V_R, L_R, d_R, $\Delta\rho$) were also found to be important. A nondimensional parameter was sought that would include the momentum flux and lake parameters while describing the rate of mixing. A logical nondimensional combination of parameters was found that successfully described the mixing process. The product of the jet Froude number, and the reservoir densimetric Froude number, F_{D_R}, was found to be an effective description of the rate of mixing. The Froude number product is defined as

$$F_j \; F_{D_R} = \frac{V}{\sqrt{gD}} \; \frac{Q}{\frac{V_R}{L_R} \sqrt{\frac{\Delta\rho}{\rho} g \; d_R}} \tag{9}$$

The ratio V_R/L_R is the average cross sectional area of the impoundment in the lateral-vertical plane. F_j expresses the destratifying effect of entrainment induced by the jet momentum and F_{D_R} describes the effect of the spreading interflow on mixing. The product of these two Froude numbers is the momentum flux in the numerator.

42. The percent of total reservoir volume pumped to acquire an 80 percent mixed state, or $t^*_{80\%}$, was used to compare and relate the test results. An 80 percent mixed state was chosen for analyses because the mixing rates were almost constant for most tests up to 80 percent mixed and sharply decreased after 80 percent mixed. A 100 percent mixed state can only be reached in the limit and is impractical to obtain. Mixing results are nonlinear and the mixing rates

are not constant between 80 and 100 percent mixed. An 80 percent mixed state represents an almost totally mixed condition for practical purposes. Test results obtained with method 2 pumping are plotted in Figure 16. The jet Froude number was used in the Froude number product rather than the jet densimetric Froude number because the $\Delta\rho$ contained in F_{D_R} sufficiently described the results while the simultaneous inclusion of $\Delta\rho$ in F_{D_J} did not enhance the description.

43. The fit of the data plotted in Figure 16b, using the method of least squares, resulted in the equation:

$$t^*_{80\%} = 0.00327 \left(F_J F_{D_R}\right)^{-0.585} \qquad (10)$$

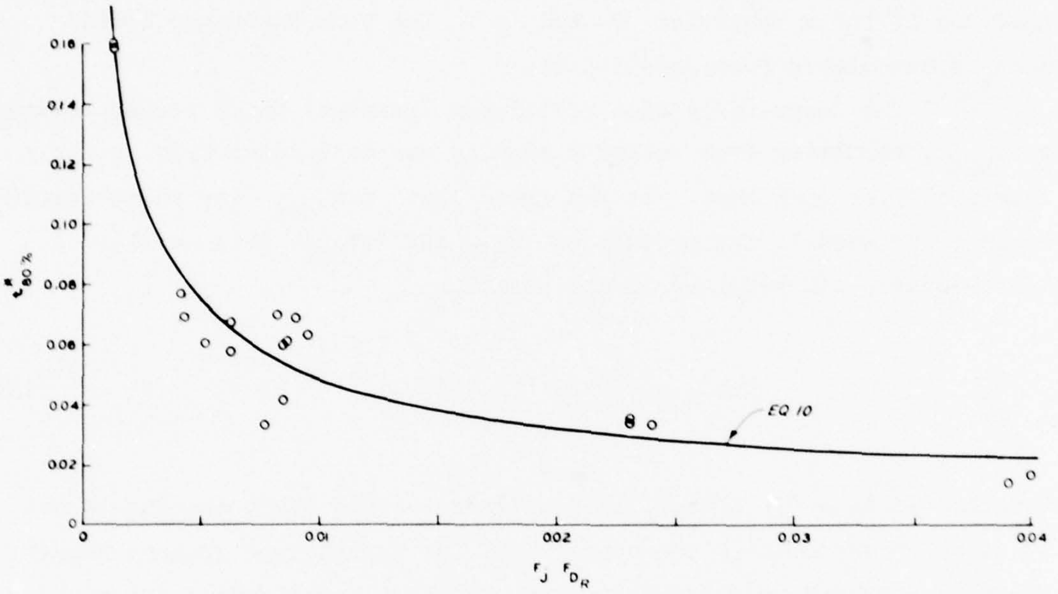
which has a coefficient of determination r^2 of 0.86. The total port area, A, is equivalent to Q/V and $A = n\pi D^2/4$, therefore,

$$D = \sqrt{\frac{4Q}{n\pi V}} \qquad (11)$$

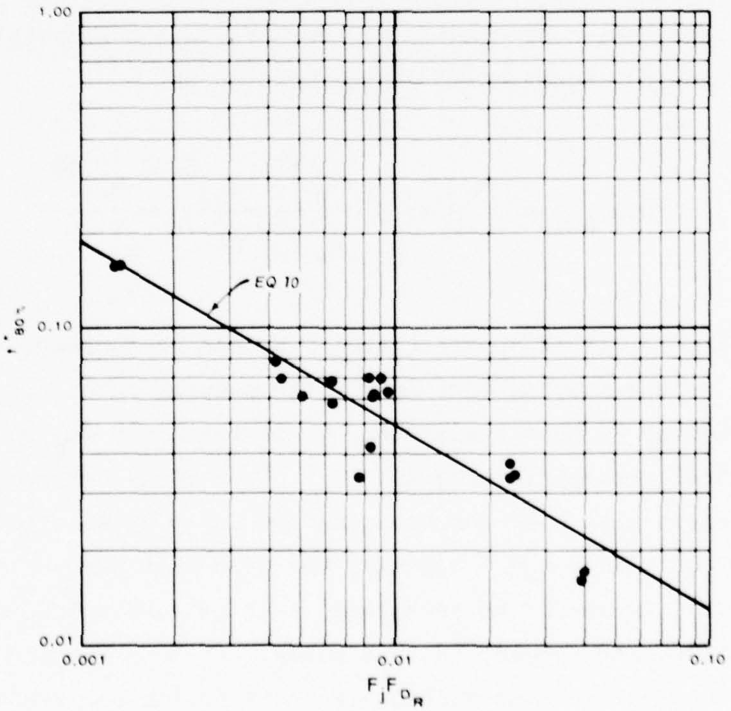
where n is the number of diffuser ports. By substitution of Equations 7, 9, and 11, Equation 10 can be written in terms of three design variables Q, V, and n.

$$V = 4.18 \times 10^{-4} \frac{V_R^{2.17} g^{0.8} \left(\frac{\Delta\rho}{\rho} d_R\right)^{0.4}}{n^{0.2} Q^{1.97} L_R^{0.8} t_{80\%}^{1.37}} \qquad (12)$$

Solving Equation 12 for Q and substituting into Equation 2 result in a relation for power input, PW, in terms of V. By evaluating $dPW/dV = 0$, it can be shown that PW is minimized when V is zero. For all parameters fixed except Q and V in Equation 12 and when V is zero, Q must be infinitely large. Obviously, it is impossible to minimize PW with respect to Q or V. Thus Q should be designed as large as economically and practically feasible to reduce PW. To accomplish an 80 percent mixed state of a given reservoir condition



a. Cartesian plot



b. Log-log plot

Figure 16. Destratification characteristics, method 2 pumping results

in a given time period would require a design velocity, V, to satisfy Equation 12 for a specified Q and n. The port diameters could then be calculated from Equation 11.

44. The destratification efficiency (percent) at 80 percent mixed, $D.E._{80\%}$, resulting from method 2 pumping was calculated from Equation 6 for each test. It was found that $D.E._{80\%}$ for these tests could be related to the product of F_{D_j} and $t^*_{80\%}$ (Figure 17). A least-squares fit resulted in the equation

$$D.E._{80\%} = 84.3\,(F_{D_j}\ t^*_{80\%})^{-1.52} \tag{13}$$

Equation 13 is a fit of the data obtained in this study and should not be used for calculating the actual D.E. for a prototype system, rather Equation 6 should be used with observed data. For planning purposes Equation 13 could be used to estimate $D.E._{80\%}$ for various design conditions. Through substitution of Equations 7 and 8 for $t^*_{80\%}$ and F_{D_j} and substitution of Equation 12 for V in the expression for F_{D_j} (Equation 8), Equation 13 can be written as

$$D.E._{80\%} = 2.43 \times 10^{8}\,\frac{L_R^{1.52}\ t_{80\%}^{1.08}\ Q^{2.60}}{V_R^{2.60}\ g^{0.76}\ d_R^{0.76}} \tag{14}$$

From Equation 14, it is apparent that D.E. can be increased by increasing the allowable pumping time and/or the pumping rate. It was pointed out in paragraph 43 that maximizing Q to the limit of practical and economical restraints reduces PW. This is in agreement with the above statement that D.E. can be increased for a given condition by increasing Q. Although increasing the allowable pumping time can increase D.E., it should be remembered that meteorological effects were not taken into account in this study. If long pumping times are the case, the surface heat exchange and meteorological conditions may have a great effect on the mixing rate and D.E. In actual practice,

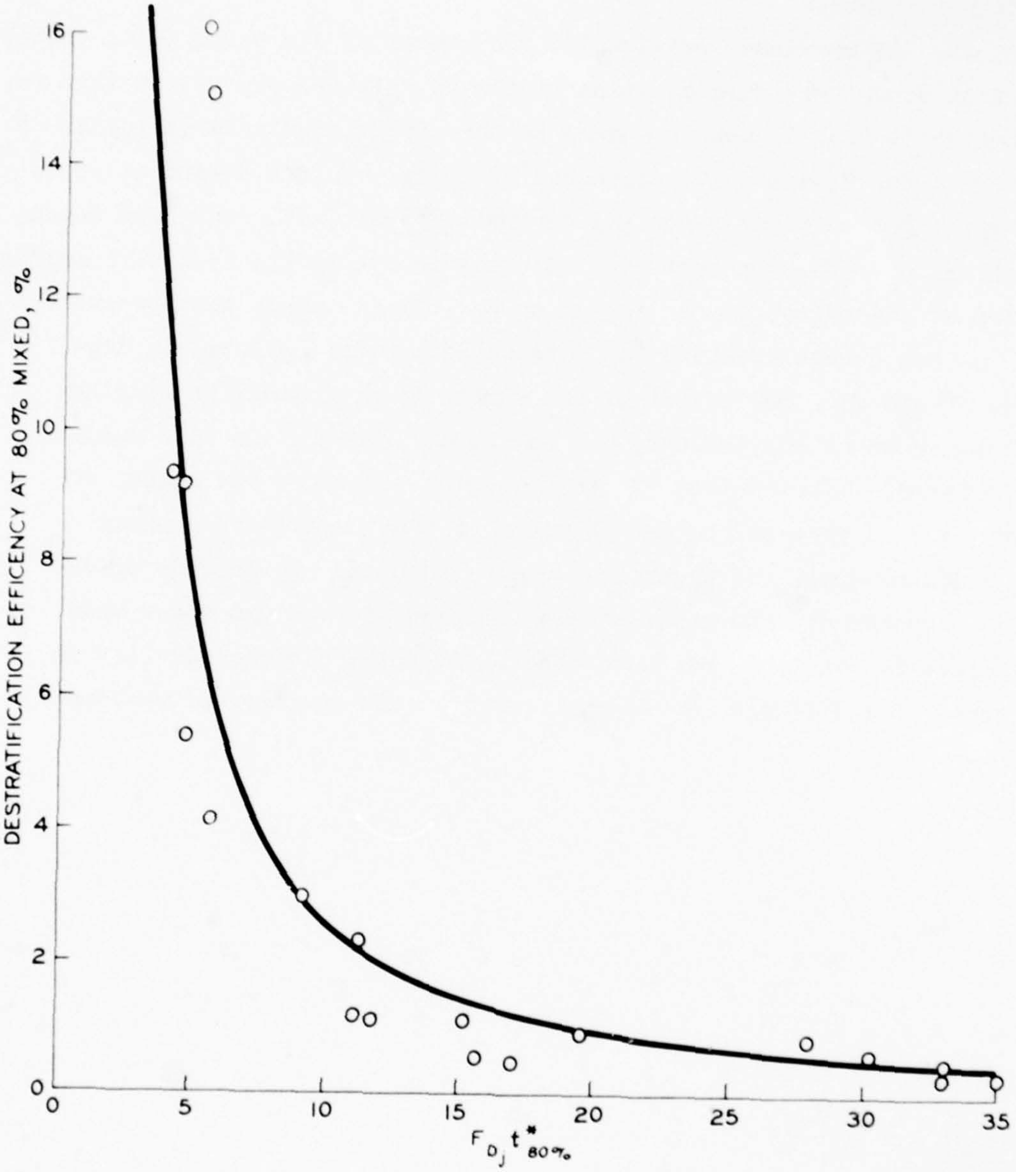


Figure 17. Destratification efficiency, method 2 pumping results

the destratifying energy input rate must be large enough to overcome the stratifying effect of the thermal energy input rate for destratification to occur.

45. As mentioned previously, the number of discharge ports tested in this study were held constant at eleven. It is pointed out that for Equation 14 D.E. is not dependent on the number of discharge ports, n. However, for Equation 12, discharge velocity, V, is dependent on n, suggesting that power input and destratification efficiency are dependent on n. This present contradiction is due to the lack of consideration of the effect of n in the study. It is likely that variations in n could have affected the outcome of the data plotted in Figures 16 and 17. The effect of the number of ports and the spacing is not known at the present, but additional research on this subject is planned. To calculate V for planning purposes, the number of ports should probably be set the same as that used in this study in order to apply the techniques presented here. To provide effective entrainment, the ports should be spaced far enough apart that the jets do not intersect each other. If total destratification is desired, the diffuser should be located at the position of maximum depth.

PART IV: APPLICATION OF RESULTS

Planning Prototype Destratification Systems

46. The results presented in this report are useful for estimating the requirements of a hydraulic destratification system for planning purposes. More work is needed to provide guidance that can be used during the final design stages. An example of how the techniques reported herein can be used for planning is outlined within this section.

47. Assume that hydraulic destratification is being planned for a hypothetical existing reservoir. Characteristics of the reservoir are specified below:

Capacity at average summer pool	300,000 acre-ft
Maximum depth at average summer pool	200 ft
Approximate length at average summer pool	20 miles

Suppose it has been decided that the destratification system will be operated only during late summer (August) when the hypolimnion becomes anaerobic. Previous records indicate that temperature stratification during August is such that a density difference, $\Delta\rho$, of about 0.0025 g/ml exists from the surface to bottom. Also suppose it has been recommended that the pumping period required to mix the reservoir should not exceed 30 days. For practical purposes the reservoir is well mixed at 80 percent mixed, thus $t_{80\%} = 30$ days .

48. All parameters discussed thus far have been specified. A reasonable pumping system should now be selected. Assume that a pumping system that provides 500 cfs can be obtained at a price within the limits of a specified budget. The discharge velocity required to mix the reservoir to the state of 80 percent mixed in 30 days for $Q = 500$ cfs can now be computed from Equation 12. For the present, the value of n in Equation 12 should be set at 11 for the reason discussed in paragraph 45. Substituting values with the units of feet and seconds into Equation 12 gives

$$V = \frac{4.18 \times 10^{-4} \, (1.307 \times 10^{10})^{2.17} \, (32.2)^{0.8} \left(\frac{0.0025}{1} \times 200\right)^{0.4}}{(11)^{0.2} \, (500)^{1.97} \, (1.056 \times 10^{5})^{0.8} \, (2.592 \times 10^{6})^{1.37}}$$

$$V = 21.3 \text{ fps}$$

With these values of Q and V, the requirements of the pump system could be determined. From Equation 11 the approximate diameter of the discharge ports can be determined giving $D = 1.65$ ft . For these values of Q, V, and D, the internal losses such as pipeline, pump, and exit port losses can be evaluated. Of course, the pipeline losses would depend on the diameter and length of pipe, which should be sized to reduce losses while considering cost.

49. With an estimate of the external power requirements (determined from Equation 2 to be 400 hp) and the internal losses, the total power requirements and associated operating costs could be estimated. The operating costs over the expected life of the pump system and the installation costs give a total cost. What has been discussed thus far in this example is the first of a series of iterations. The next step would be to choose another discharge rate, determine the discharge velocity, and again estimate the project total cost. After several iterations, a pumping system that minimizes costs could be selected for further consideration. It may be that minimizing operational costs is more important than minimizing total costs as long as installation costs can be kept below a particular ceiling. For this situation, the design discharge rate should be set as large as possible (see paragraphs 43 and 44).

Comparison to Field Studies

50. The results obtained from this study were applied to two prototype destratification study cases, Lake Vesuvius[22] (conducted in 1964) and Ham's Lake[11,23] (conducted in 1973). A comparison of predicted versus observed results is made to gain some appreciation of the applicability of the results for predicting prototype conditions. Although the pumping and diffuser arrangements for these

two case studies are quite different from that (method 2) used to obtain the results described by Equation 10 and shown in Figures 16a and b, the comparison should provide some insight toward the validity of the technique. Field results obtained from destratification efforts using method 2 pumping arrangements could not be found in the literature.

51. The tabulation below presents the pertinent data of Vesuvius and Ham's Lakes and the pumping characteristics of the destratification systems tested:

	Vesuvius Lake	Ham's Lake
Volume, acre-ft	1260	932
Maximum depth, ft	30	29.5
Approximate length, miles	3	1
Initial density difference, g/ml	0.0036	0.0025
Pump discharge, cfs	6.4	23.7
Discharge velocity, fps	8.4	2.4
Discharge port diameter, ft	1	3.5
Pumping duration, days	8.7	15.1

52. The Vesuvius pumping arrangement could be classified as method 1. The system used at Ham's Lake consisted of a low energy ventilating fan submerged in the epilimnion. The fan forced surface water downward into the hypolimnion. From the Ham's Lake data it could be determined at what point the lake attained 80 percent mixed. From the Vesuvius data the time required to reach 80 percent mixed could not be determined, but the lake was almost totally mixed after 8.7 days. Therefore, the assumption was made that an 80 percent mixed state was reached in 8.7 days. The predicted or calculated dimensionless time or percent of lake volume pumped to reach 80 percent mixed, $t^*_{80\%}$, was calculated for the two study cases using data in the above tabulation and Equations 9 and 10. The calculated and observed values for $t^*_{80\%}$ are shown below.

	$t^*_{80\%}$	
	Calculated	Observed
Vesuvius Lake	0.15	0.11
Ham's Lake	0.30	0.58

53. This comparison is complicated by hydrological and meteorological effects and by the difference in pumping arrangements. It is logical that the $t^*_{80\%}$ calculated for Ham's Lake would be lower than that observed. The low energy pump forces epilimnion water through the thermocline. Some of the kinetic energy of the discharge is expended in overcoming buoyant forces within the thermocline rather than generating entrainment of hypolimnion water. Thus, the effectiveness of this pumping method is expected to be less than that of method 2. Since this study showed pumping with method 2 to be more efficient than with method 1, it would be expected that the calculated value of t^* , which applies to method 2, would be less than that observed at Lake Vesuvius (where method 1 was used); however, just the opposite was found. The observed value of $t^*_{80\%}$ was slightly less than that calculated. However, this may be attributed to the fact that the Vesuvius test was conducted in the month of September when there was a decline in the stability of a nearby control lake. This decline in stability resulting from a change in season would help mix the lake, thus giving a lower t^* value than might be expected. Even after the limitations are considered the comparisons are reasonable and provide encouragement for the use of the technique for estimating destratification system design requirements. There are limitations to Equation 10 and the techniques presented in this report, which indicate the need for future work as recommended in the next section.

PART V: RECOMMENDATIONS AND PLANS FOR FUTURE WORK

54. To expand the applicability of the techniques presented in this report, additional studies have been planned and are ongoing within Task IIIB.1 of the Environmental and Water Quality Operational Studies (EWQOS) Research Program. There are two major areas of study that will receive immediate attention: (a) the effect of reservoir morphology, such as length, depth, width, volume, and surface area, on mixing time needs to be better defined; and (b) the effect of the number, size, and spacing of the diffuser ports on mixing time must be determined. Because the reservoir width was held constant in this study, the effect of reservoir geometry on mixing time was not conclusively defined. Future work must include a variation in reservoir geometry. In addition to investigating the effects of diffuser design, a greater range of pump discharge conditions must be tested to substantiate these design techniques for broader application. There is other destratification work planned within EWQOS. The capability must be developed to assess the effect of hydrometeorological conditions on the performance of particular destratification system designs. This capability should allow simulation of the lake heat budget and stratification with the pump system operating so that systems which start mixing in the spring with continuous or intermittent operation can be sized and tested. The extent of gas supersaturation will be evaluated at existing projects that are using pneumatic destratification. It will also be necessary to evaluate the environmental effects of lake destratification prior to implementation.

PART VI: SUMMARY

55. Artificial destratification is one of several alternatives that can be used to enhance in-reservoir and release water quality. Destratification is accomplished by inputing sufficient work to overcome the energy (stability) of density stratification. Circulation and the reduction in stratification allows the transport of oxygen from the atmosphere throughout the reservoir. It is intended that the results reported herein provide a basis for planning destratification systems and estimating pumping requirements.

56. There are basically two methods of generating mixing in a reservoir: bubbling air (pneumatic) and pumping or moving water mechanically (hydraulic). Both methods were investigated in a laboratory flume. These studies indicated that hydraulic destratification is potentially more effective than pneumatic. Based on these results and other considerations as discussed in paragraph 9, the study concentrated on the aspects of hydraulic destratification.

57. From the hydraulic destratification flume studies, it was determined that a particular intake-diffuser pumping orientation (method 2 or 4) was more effective than two other arrangements. The increased effectiveness was attributed to dual entrainment that occurred with a successively rising and falling plume. Although methods 2 and 4 gave similar results, method 2 is recommended for aesthetic reasons (paragraph 37).

58. A dimensionless description of the mixing phenomena observed in the laboratory studies with the method 2 pumping arrangement was developed. From this an equation was developed for the purpose of estimating the average velocity required to mix a given reservoir to the state of 80 percent mixed (almost totally mixed for practical purposes) in a specified time period for a given pumping rate. The effect of the number and spacing of diffuser ports was not evaluated, but will be addressed in later work. With a specified rate of discharge and the calculated port velocity required to mix a reservoir, the port diameters and the power input for the reservoir can be

estimated. Required input power is reduced and destratification efficiency is promoted by increasing the pumping rate, which decreases the average port velocity required to mix a reservoir in a given period. Of course, the pumping rate can be increased only within the limit of practical and economical constraints. Extending the pumping time restraint for mixing a given reservoir can also increase the destratification efficiency. However, the effect of surface heat exchange over long pumping periods could be quite significant and must be taken into consideration in order to provide an effective system.

59. The results obtained from this study and presented herein can be used in the planning and preliminary design of a hydraulic system for destratification of a reservoir. Additional results from site-specific and generalized laboratory research will extend the applicability of these techniques for more comprehensive use.

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Table 1

Pneumatic Destratification Tests

Test No.	Diffuser	Air Flow Rate, scfh	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
1	B	34	0.00279	0.39	36	140.4	1.3	0	3.80	0
								17	1.81	52
								46	0.67	82
								158	0.26	93
								174	0.05	99
2	B	23	0.00318	0.39	36	140.4	1.3	0	4.37	0
								18	1.77	59
								59	0.59	87
3	B	13	0.00307	0.39	36	140.4	1.3	0	4.10	0
								12	2.85	30
								32	1.33	68
								74	0.74	82
								155	0.22	94
4	B	1	0.00245	0.39	36	140.4	1.3	0	3.02	0
								22	2.67	11
								69	1.71	44
								108	1.11	63
5	Diffuser Stone	1	0.00282	0.39	36	140.4	1.3	0	3.81	0
								30	2.72	29
								70	1.46	62
								104	0.90	76

Table 2

Hydraulic Destratification Tests

Method 1

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
A1	B	0.45	17.1	0.00353	0.39	36	140.4	1.3	0	4.84	0
									58	3.24	33
									111	1.88	61
									173	0.70	86
									224	0.22	96
A2	B	0.31	11.8	0.00332	0.39	36	140.4	1.3	0	4.59	0
									69	4.14	10
									107	3.32	28
									204	2.66	42
									308	2.11	54
									394	1.45	68
A3	B	0.17	6.46	0.00315	0.39	36	140.4	1.3	0	4.35	0
									701	2.88	34
									884	2.54	42
									1440	1.46	66
A4	A	1.2	11.4	0.00452	0.32	36	118.8	1.1	0	4.29	0
									13	2.36	45
									25	1.82	58
									42	1.36	68
									69	0.62	86
									97	0.27	94
A5	A	1.2	11.4	0.00706	0.68	36	118.8	1.1	0	5.18	0
									44	2.89	44
									74	1.33	74
									83	0.88	83
A6	A	0.8	7.62	0.00374	0.32	36	118.8	1.1	0	3.69	0
									138	2.94	20
									283	2.05	45
									439	1.18	68
									637	0.66	82
									788	0.36	90
A7	A	0.8	7.62	0.00475	0.68	36	118.8	1.1	0	3.54	0
									20	2.67	25
									42	1.79	49
									71	0.81	77
									100	0.39	89
A8	A	0.5	4.76	0.00360	0.32	36	118.8	1.1	0	3.54	0
									41	3.13	12
									101	2.64	25
									188	1.82	49
									271	1.32	63
									346	0.92	74
A9	A	0.5	4.76	0.00261	0.68	36	118.8	1.1	0	1.93	0
									35	1.59	17
									68	1.41	27
									100	1.03	46
									147	0.72	63
									180	0.52	73

(Continued)

Table 2 (Concluded)

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
A10	B	0.45	17.1	0.00404	0.39	36	140.4	1.3	0	4.67	0
									70	4.38	6
									149	2.78	40
									198	2.11	55
									333	0.21	95
A11	B	0.45	17.1	0.00105	0.39	36	140.4	1.3	0	1.29	0
									44	0.62	52
									91	0.25	81
									144	0.16	87
A12	B	0.45	17.1	0.00348	0.65	36	140.4	1.3	0	4.24	0
									22	3.58	16
									65	2.13	50
									103	1.30	69
									183	0.41	90
A13	B	0.45	17.1	0.00359	0.27	36	140.4	1.3	0	4.24	0
									46	3.09	27
									122	1.19	72
									186	0.83	80
A14	B	0.45	17.1	0.00313	0.88	36	140.4	1.3	0	1.53	0
									48	0.76	50
									107	0.15	90
A15	B	0.45	17.1	0.00378	0.52	36	140.4	1.3	0	5.13	0
									36	4.12	14
									104	2.75	46
									167	1.58	69
									247	0.59	88
A16	B	0.45	17.1	0.00289	0.27	36	140.4	1.3	0	3.43	0
									58	2.42	30
									120	1.25	63
									185	0.50	85
A17	C	0.45	1.07	0.00358	0.39	36	140.4	1.3	0	4.85	0
									120	4.33	11
									180	3.98	18
									255	3.49	28
									300	3.16	35
									1230	0.34	93
A18	C	1.2	2.85	0.00340	0.39	36	140.4	1.3	0	4.67	0
									107	2.41	48
									200	0.77	84
A19	C	0.45	1.07	0.00328	0.65	36	140.4	1.3	0	3.90	0
									175	3.40	13
									426	2.69	31
									548	2.38	39
									1445	0.47	88
A20	C	1.2	2.85	0.00275	0.65	36	140.4	1.3	0	3.29	0
									39	2.77	16
									88	1.95	41
									189	0.75	77
									264	0.33	90

Table 3

Hydraulic Destratification Tests

Method 2

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
B1	B	0.45	17.1	0.00345	0.39	36	140.4	1.3	0	4.56	0
									20	2.64	42
									40	0.87	81
									60	0.22	95
B2	B	0.45	17.1	0.00363	0.65	36	140.4	1.3	0	4.57	0
									20	2.91	36
									40	0.73	84
									60	0.20	96
B3	C	1.2	2.85	0.00310	0.39	36	140.4	1.3	0	3.52	0
									30	2.14	39
									60	0.53	85
									90	0.02	100
B4	C	1.2	2.85	0.00371	0.65	36	140.4	1.3	0	4.66	0
									20	3.35	28
									40	1.81	61
B5	A	0.8	7.62	0.00339	0.39	36	140.4	1.3	0	4.53	0
									20	3.56	22
									40	1.33	71
									60	0.29	94
B6	A	0.8	7.62	0.00328	0.65	36	140.4	1.3	0	4.20	0
									25	2.32	45
									50	0.52	88
									75	0.08	98
B7	C	0.45	1.07	0.00328	0.39	36	140.4	1.3	0	4.42	0
									60	3.90	12
									120	3.31	25
									180	2.59	41
									240	1.80	59
									300	1.32	70
									360	0.86	81
B8	C	0.45	1.07	0.00334	0.65	36	140.4	1.3	0	4.21	0
									150	2.71	36
									300	1.23	71
									450	0.45	89
B9	A	0.45	4.28	0.00403	0.39	36	140.4	1.3	0	5.42	0
									45	4.43	18
									90	2.37	53
									135	1.56	71
									180	0.82	85
									225	0.09	98
B10	A	0.45	4.28	0.00445	0.65	36	140.4	1.3	0	5.57	0
									45	4.43	20
									90	2.53	55
									135	1.14	80
									180	0.29	95

(Continued)

Table 3 (Continued)

Test No.	Diffuser	Q gpm	V fps	Δρ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
B11	B	0.20	7.60	0.00353	0.39	36	140.4	1.3	0	4.58	0
									60	3.91	15
									120	1.86	59
									180	0.95	79
B12	B	0.20	7.60	0.00317	0.65	36	140.4	1.3	0	4.02	0
									80	2.82	30
									160	1.41	65
									240	0.60	85
									320	0.08	98
B13	C	0.80	1.90	0.00310	0.39	36	140.4	1.3	0	4.26	0
									30	2.95	31
									60	1.37	68
									90	1.05	75
B14	C	0.80	1.90	0.00282	0.61	36	140.4	1.3	0	3.79	0
									30	2.88	24
									60	1.66	56
									90	0.75	80
B15	C	0.20	.48	0.00298	0.39	36	140.4	1.3	0	4.00	0
									120	4.00	3
									240	3.70	8
									360	3.51	12
									480	3.09	23
B16	C	0.20	.48	0.00269	0.61	36	140.4	1.3	0	3.58	0
									60	3.44	4
									120	3.27	9
									180	3.12	13
									240	2.63	27
									360	2.53	29
									480	2.34	35
									600	2.16	40
									660	2.03	43
B17	B	0.20	7.6	0.00306	0.39	36	140.4	1.3	0	4.05	0
									60	3.68	9
									120	3.01	26
									180	2.30	43
									240	2.09	48
									300	1.44	64
									360	0.91	78
B18	B	0.20	7.6	0.00258	0.65	36	140.4	1.3	0	3.15	0
									60	2.68	15
									120	2.13	32
									180	1.42	55
									240	1.19	62
									300	1.01	68
									360	0.65	80
B19	B	0.20	7.6	0.00311	0.60	36	194.4	1.8	0	7.80	0
									45	7.39	5
									90	6.59	16
									135	6.48	17
									180	5.20	33
									225	4.53	42
									270	3.90	50
									315	3.68	53
									360	2.71	65

(Continued)

Table 3 (Concluded)

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	l_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
B20	B	0.45	17.1	0.00352	0.60	36	194.4	1.8	0	8.83	0
									30	6.91	22
									60	4.86	45
									90	2.01	77
									120	1.56	82
									150	0.76	91
B21	B	0.20	7.6	0.00292	0.65	24.5	95.6	1.3	0	2.58	0
									60	1.95	25
									120	1.28	50
									180	0.75	71
									240	0.39	85

Table 4

Hydraulic Destratification Tests

Method 3

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
C1	B	0.45	17.1	0.00287	0.39	36	140.4	1.3	0	3.88	0
									60	2.94	24
									120	2.05	47
									180	1.61	58
									240	1.13	71
									300	0.58	85
									360	0.22	94
C2	B	0.45	17.1	0.00263	0.61	36	140.4	1.3	0	3.42	0
									60	2.72	21
									120	2.10	39
									180	1.44	58
									240	0.09	74
C3	A	0.80	7.62	0.00305	0.39	36	140.4	1.3	0	4.15	0
									60	2.30	45
									120	0.87	79
									180	0.13	97
C4	A	0.80	7.62	0.00312	0.61	36	140.4	1.3	0	3.99	0
									60	2.49	38
									120	1.12	72
									180	0.65	84
C5	C	0.45	1.07	0.00265	0.39	36	140.4	1.3	0	3.57	0
									60	3.35	6
									120	3.45	3
									180	2.97	17
C6	C	0.45	1.07	0.00295	0.61	36	140.4	1.3	0	3.88	0
									120	3.21	17
									253	2.59	33
									388	1.79	54
									523	1.08	72

Table 5

Hydraulic Destratification Tests

Method 4

Test No.	Diffuser	Q gpm	V fps	$\Delta\rho$ g/cc	β	L_R, ft	V_R, ft^3	d_R, ft	t, min	S ft-lb	Percent Mixed, %
D1	B	0.45	17.1	0.00304	0.39	36	140.4	1.3	0	4.10	0
									30	2.44	41
									70	0.81	80
									115	0.26	94
D2	B	0.45	17.1	0.00248	0.61	36	140.4	1.3	0	5.39	0
									18	2.28	58
									55	1.17	78
									115	0.18	97
D3	A	0.80	7.62	0.00232	0.39	36	140.4	1.3	0	3.05	0
									25	1.24	59
									60	0.33	89
D4	A	0.80	7.62	0.00316	0.61	36	140.4	1.3	0	3.99	0
									20	2.48	38
									58	0.39	90
D5	C	0.45	1.07	0.00317	0.39	36	140.4	1.3	0	4.16	0
									48	3.76	10
									95	3.38	19
									180	2.33	44
									275	1.35	68
D6	C	0.45	1.07	0.00293	0.61	36	140.4	1.3	0	3.82	0
									60	3.19	16
									120	2.59	32
									195	1.89	51
									235	1.72	54
D7	C	0.45	1.07	0.0033	0.61	36	140.4	1.3	0	4.21	0
									60	3.42	19
									120	2.87	32
									180	1.56	63
									240	1.59	62
D8	C	1.2	2.85	0.00295	0.39	36	140.4	1.3	0	3.96	0
									30	1.37	66
									60	0.53	87
									90	0.36	91
D9	C	1.2	2.85	0.00335	0.65	36	140.4	1.3	0	4.08	0
									60	1.65	60
									120	0.46	89

APPENDIX A: NOTATION

A	Total port area of the diffuser, ft^2
D	Individual diameter of diffuser ports, ft
D.E.	Destratification efficiency, percent
d_H	Vertical thickness of hypolimnion
d_R	Total water depth of flume or reservoir, ft
F_{D_j}	Densimetric Froude number of the diffuser jets
F_{D_R}	Densimetric Froude number of the flume or reservoir
F_j	Froude number of the diffuser jets
g	Acceleration due to gravity, 32.2 ft/sec^2
H	Water mass center of gravity when the flume or reservoir is homogeneous, ft
h	Hydrostatic head or depth of water on the diffuser, ft
L_R	Length of flume or reservoir, ft
n	Number of diffuser ports
PW	Power delivered to water, ft-lb/sec; power input, hp
Q	Water pumping or total discharge rate, cfs
Q_a	Volume flow rate of air, scfh or scfs
S	Reservoir or flume stability resulting from stratification, ft-lb
S_i	Initial reservoir or flume stability prior to pumping, ft-lb
t	Elapsed operating or pumping time, min
$t_{80\%}$	Elapsed pumping time to reach 80% mixed state
t^*	Dimensionless time or percent of total reservoir water volume pumped
$t^*_{80\%}$	Dimensionless time at an 80 percent mixed state

V	Average port velocity, ft/sec
V_H	Volume of hypolimnion water, ft^3
V_R	Total volume of water in flume or reservoir, ft^3; total reservoir volume, acre-ft
Y	Mass center of gravity when the flume or reservoir is stratified, ft
β	Ratio of hypolimnion volume to total water volume
ΔE	Energy expended in reservoir, hp-hr or ft-lb
$\Delta \rho$	Density difference of epilimnion and hypolimnion water, g/ml
ΔS	Change in stability during pumping, ft-lb
Δt	Pumping time, hr
γ_a	Specific weight of air, 0.0766 lb/ft^3
γ_w	Specific weight of water, 62.4 lb/ft^3
ρ	Density of water, g/ml

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Artificial destratification of reservoirs; hydraulic laboratory investigation / by Mark S. Dortch. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
45, [8], 2 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; E-79-1)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under CWIS No. 31042 (EWQOS Work Unit 31605 (IIIB))
References: p. 44-45.

1. Density stratification. 2. Destratification. 3. Flumes (Hydraulic testing facilities). 4. Laboratory tests. 5. Reservoir stratification. 6. Stratified flow. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; E-79-1.
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