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Aeration of Stockade Lake, South Dakota

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AERATION OF STOCKADE LAKE,

SOUTH DAKOTA

BY

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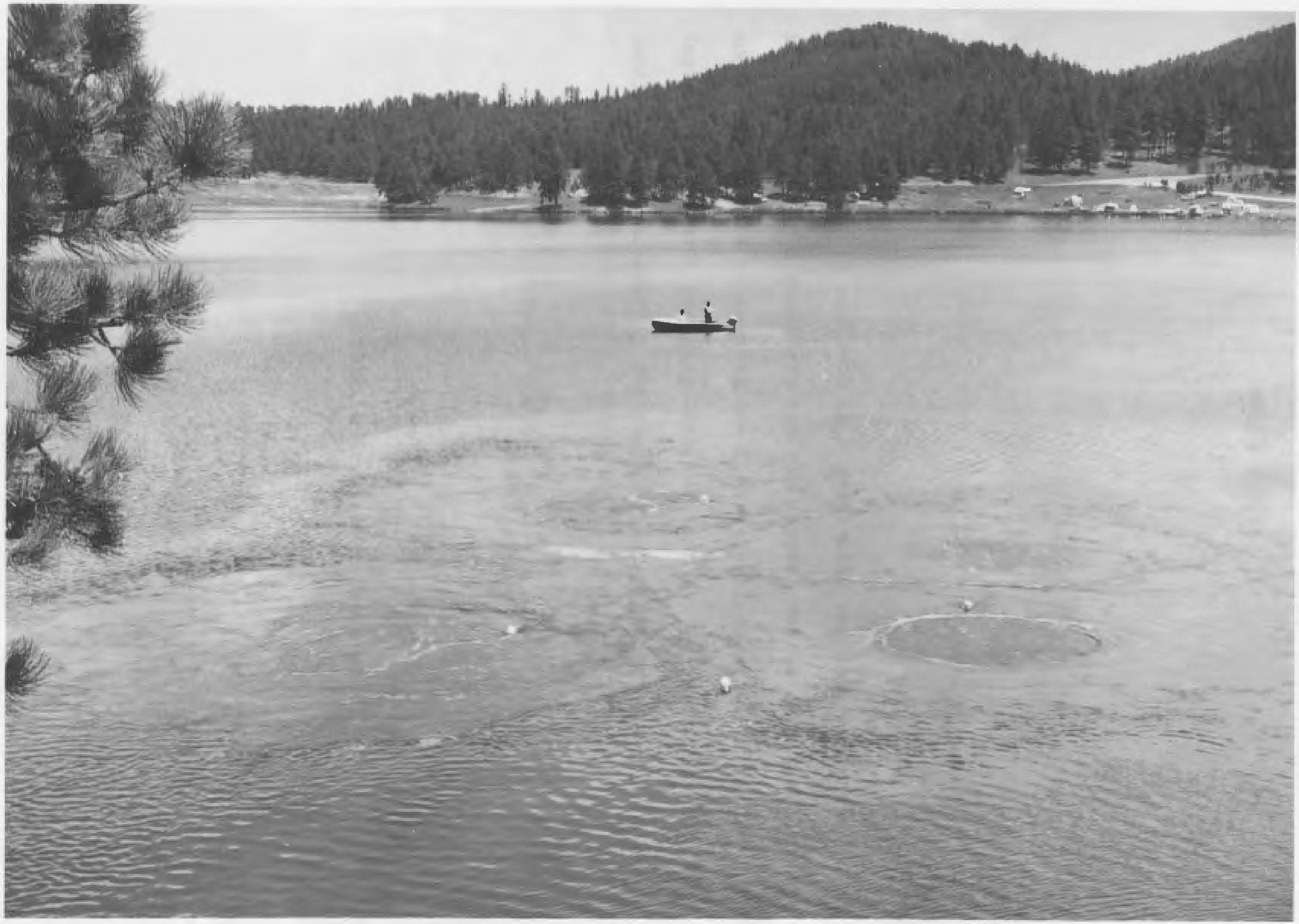

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SOUTH DAKOTA

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

AERATION OF STOCKADE LAKE,

SOUTH DAKOTA

Abstract

LARRY C. VANRAY

Intermittent aeration of Stockade Lake (2,470 acre feet) during the summers of 1967 and 1968 temporarily altered the thermal profile and phytoplankton density. Continual aeration for 48 hours in the deepest portion of this eutrophic lake produced epilimnetic cooling, hypolimnetic warming and apparent reduction of algal populations at three sampling stations in various parts of the lake. Dye, released at the aeration site, was found at all depths throughout the lake after 46½-hours aeration. Air bubbles, rising from diffuser-blocks near the lake bottom, carried cold, hypolimnetic water to the surface at a rate of 4.7 million gallons per hour. A dye-movement study indicated that most of the uplifted water moved a short distance from the aeration area in a radial-horizontal direction, sank to approximately the 15-foot depth and traveled at this depth throughout the lake as eddies dispersed water upwards and downwards. The eddies apparently increased with aeration time. A homothermous condition was not achieved and dissolved oxygen concentrations in the hypolimnion were not raised sufficiently to increase the volume of fish habitat. The effects of aeration described in this paper show that individual lake characteristics and weather may determine the extent of limnological changes.

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INTRODUCTION

Thermal stratification of eutrophic lakes produces conditions which may adversely affect fish populations. Experiments by other investigators have demonstrated that some of these conditions may be reduced or eliminated by artificial circulation. The pattern of circulation currents and limnological changes induced by diffused-air pumping in a stratified, eutrophic lake is described in this paper.

Temperature and density differences which occur in some lakes during summer separate water into layers which differ in chemical content and biological character. The uppermost region of warm water is termed the epilimnion and the zone of rapid drop in temperature which develops below the epilimnion is called the thermocline. The metalimnion includes the thermocline and the zone of temperature gradient on either side of it. The cool, more dense water below the metalimnion is known as the hypolimnion (Reid, 1961). The metalimnion acts as a barrier and prevents the oxygen accumulated in the epilimnion by atmospheric aeration and photosynthesis from mixing throughout the body of the lake. Photosynthesis is essentially inhibited in the hypolimnion by lack of light and organic decomposition reduces the dissolved-oxygen (DO) concentration, thereby restricting fish life to the epilimnion. High temperatures and dense algal blooms near the surface may further restrict the area of the lake environment that will support fish life. Palmer (1962) stated that some algal blooms have produced fish kills by interfering with reaeration, by excluding light necessary for photosynthesis in deeper waters or depleting oxygen through decomposition or respiration. Some blooms release substances toxic to fish. A negative oxidation-reduction potential develops under anaerobic conditions in the hypolimnion and hydrogen sulfide as well as sulfides of iron and soluble manganese appear. Undesirable taste and odor organics, usually toxic, are produced, pH declines and carbon dioxide content increases (Irwin, Symons and Robeck, 1966). Hayes, Reid and Cameron (1958) reported that during the summer, when depths of a stratified lake are depleted of oxygen, iron is reduced to the ferrous state (ferric form is insoluble) and enters solution with nutrients such as phosphorous. Results of laboratory studies (Symons, DeMarco, Irwin and Robeck, 1966) on biodegradation of two synthetic organics, linear alkylate sulfonate (LAS) and 2, 4 - dichlorophenoxyacetic acid (2, 4-D), demonstrated that biodegradation does not proceed rapidly in cold, anaerobic bottom waters of impoundments. Synthetic organics used in pesticides and detergents may reach toxic concentrations if their biodegradation rate is reduced by conditions resulting from thermal stratification.

One of the first experiments in artificial circulation of lakes was conducted by Hooper, Ball and Tanner (1952). A centrifugal pump with a capacity of 25 thousand gallons per hour moved water from near the lake bottom and discharged it at the surface. It was operated during a 10-day period in midsummer. Changes in water temperatures, DO concentrations, alkalinity, conductivity and phosphorus showed that pumping produced artificial circulation of the 71-acre foot test lake, although a homothermous condition was not achieved.

Oxygenation of a portion of the 37,500-acre foot Inniscara Reservoir, Ireland, was accomplished in 1961 by use of Aero-Hydraulic Guns operated continually from May through October (Anon., 1965). Oxygenation of the hypolimnion near the dam-outlet turbines reduced the possibility of discharging the toxic wastes of anaerobic decomposition into the River Lee, an important salmon fishery. The Aero-Hydraulic Gun releases bullet-shaped air bubbles every 5 to 10 seconds. Water is drawn in behind the bubble as it rises in the gun stack (12 ft. long, 12 inch diam.) through ports on the side. Water flow to the surface (gun is anchored on bottom) is continuous due to the momentum of water in the gun stack. Air is supplied to the gun by an electric compressor. One gun can transfer up to 5 million gallons of water to the surface in 24 hours, for an input of less than 1 horsepower.

Ford (1963) and Koberg and Ford (1965) eliminated thermal stratification of a 2,500-acre foot drinking-water reservoir by releasing compressed air through apertures in a plastic tube suspended 5 feet above the bottom. The lake was nearly isothermal after 8 days of intermittent aeration. Air, supplied by an electric compressor, was released along 60 feet of a perforated tube. Elimination of thermal stratification accomplished: a) reduction of hydrogen sulfide content, which resulted in taste improvement and reduction of chlorine dosage,

b) maintenance of 5 parts per million (ppm) DO in the hypolimnion, c) reduction of evaporation and d) elimination of the autumnal lake overturn.

Irwin et al. (1966) destratified four lakes using a pump mounted on a pontoon raft. Temperatures were nearly homogenous in each lake when pumping was terminated. The lakes ranged in volume from 98 to 1,260 acre feet. Water was pumped through a tube (12-inch diam.), extending to near the lake bottom, and discharged at the surface. The capacity of the pump was 4.2 million gallons per day. Pumping periods ranged from 8 hours on the smallest lake to 208 hours on the largest. The entire mass of each lake was mixed by pumping at one site, the deepest part of the reservoir. Only 11.2% of the lake volume had to be passed through the pump in order to mix the largest lake tested, thus indicating the importance of water currents as an aid in destratification. Thermal stratification reoccurred in impoundments protected from wind within 1 week after mixing.

Symons, Irwin, Clark and Robeck (1967) and Symons, Irwin and Robeck (1967a) reported destratification of a 2,930-acre foot lake using the equipment described by Irwin et al. (1966). The lake was pumped for 5 weeks during August and September. Pumping had little affect on surface temperatures but had a marked warming influence at the 35-ft. and 45-ft. depths. A homothermous condition was not achieved. Theoretical considerations regarding hydraulic performance of destratification equipment and lake stability were presented by

Symons, Irwin, Clark and Robeck (1967). Dunst (1967), Wirth and Dunst (1967) and Wirth, Dunst, Uttormark and Hilsenoff (1967) reported destratification of Cox Hollow Lake, 1,200 acre feet, in Wisconsin, using six Aero-Hydraulic Guns. The lake was homothermous at 72.5°F after approximately 6 weeks of gun operation. An electric compressor supplied air to the guns at a rate of 72 cfm. Approximately 50% of the lake volume was affected by oxygen depletion before mixing began. Destratification resulted in: a) presence of DO on the lake bottom after 3 weeks of mixing, b) inhibition of algal growth, c) a homothermous lake condition, d) snails populating bottom muds within 2 months (absent before aeration), e) reduction of iron and manganese concentrations in the hypolimnion and dissolved phosphates at all depths, and f) disappearance of ammonia.

Irwin, Symons and Robeck (1967) and Symons, Irwin, Robinson and Robeck (1967) reported destratification of a 4,6000-acre foot lake by use of a diffused-air system. The lake was mixed periodically throughout the season to maintain water quality. Mixing the lake until temperatures were nearly uniform from top to bottom required 134 hours during early June. An electrical air compressor supplied air through tubes to 16 diffuser stones placed on the bottom in the deepest portion of the lake. A decline of blue-green algal populations was among benefits resulting from destratification.

The hypolimnion of a 33,740-acre foot reservoir was aerated without changing the temperature profile using a method described by Bernhardt (1967). This method was developed to improve the water quality of the hypolimnion by oxygenation while maintaining low temperatures desired in a drinking-water reservoir. Air was released into the water inside and just above the bottom of a large cylinder. This cylinder was open on both ends, and extended from 8 feet above the surface to a few feet above the reservoir bottom. Aerated water could only escape from the cylinder through outlets located in the hypolimnion.

Operation of an Air-Aqua System in Stockade Lake, 2,470 acre feet, did not result in destratification or any noticeable modification of the lake environment (VanRay, 1966; 1967). Tubb (1966) was able to prevent fish kills during the winter using this system. Reasons for prevention of winter kill were not resolved by Tubb's study, but he hypothesized that removal of reduced gases and depression of reducing conditions played an important role. The Air-Aqua System used in Stockade Lake consisted of three ½-h.p. air compressors, each connected to a perforated plastic hose which extended along the bottom of the lake. Each hose had 4,000 air-release holes.

Symons, Irwin and Robeck (1967b) concluded that artificial destratification affected only those water quality parameters which initially showed a concentration gradient with depth or were influenced by the vertical transport of some other water quality constituent. Temperatures decreased in the epilimnion and rose on the bottom. The surface temperature rose again when mixing stopped, but the rise in hypolimnetic temperatures was permanent. Oxygen-demanding materials were brought into the upper layers during mixing, causing a decrease in DO concentration. Dissolved oxygen concentrations increased near the bottom, but not enough to hold steady after mixing, because of the biochemical oxygen demand (BOD). High concentrations of sulfides were avoided in lower waters by mixing. Manganese concentrations were affected similarily. Ammonia nitrogen and nitrate nitrogen showed some increase, especially towards the surface. Organic nitrogen increased near the surface and the bottom. Phytoplankton populations declined due to some environmental change which occurred during artificial destratification, but increased again when mixing stopped. The pH was lowered on the surface, probably due to the upward transport of carbon dioxide, which increased sharply at the surface during mixing. Little effect was noted on alkalinity or conductivity.

Symons, Irwin, Clark and Robeck (1967) listed four major methods currently (1967) available for artificial destratification: mechanical pumping, the Air-Aqua System, compressed air and the Aero-Hydraulic Gun. These methods have been discussed in the preceding literature review. Thomas L. Wirth, Wisconsin Department of Natural Resources, (personal correspondence, April, 1968) indicated a mixing device known as a Helixor may be useful in achieving artificial destratification. One Helixor pumps as much water as six Aero-Hydraulic Guns, according to Wirth.

Development of a practical method of lake aeration and determination of some resulting limnological changes were the objectives of the project described in this paper.

STUDY AREA

Stockade Lake (Fig. 1), located in Custer County, in the south-central portion of the Black Hills, was formed by a dam on French Creek. At spillway level it has 3.5 miles of shoreline, a surface area of 130 acres, a volume of 2,470 acre feet and an average depth of 18 feet. French Creek flows into the lake from the west.

Stewart and Thelenius (1964) reported that the only water which entered Stockade Lake during periods of severe drought was effluent from the Custer sewage treatment plant. Dense algal blooms extending to depths of 5 feet existed throughout the summer as a result of nitrogen and phosphate enrichment. Effluent from the Custer sewage treatment plant was found to be the major source of nutrients entering Stockade Lake in a study conducted by VanRay (1967).

Thermal stratification develops in Stockade Lake in May and persists until mid-September. Oxygen declines to levels critically low for fish life in most of the hypolimnion during the summer and is completely absent just above the bottom muds. Dense mats of algae blanket the lake during summer months. The water is a greenish-brown color throughout the year.

The lake was managed for trout and warm-water species prior to 1960. Deterioration of the fishery prompted chemical rehabilitation in the fall of 1960. Warm-water species were stocked the following year. Overpopulation of fish led to stunting and necessitated another chemical rehabilitation project in the fall of 1965. Approximately

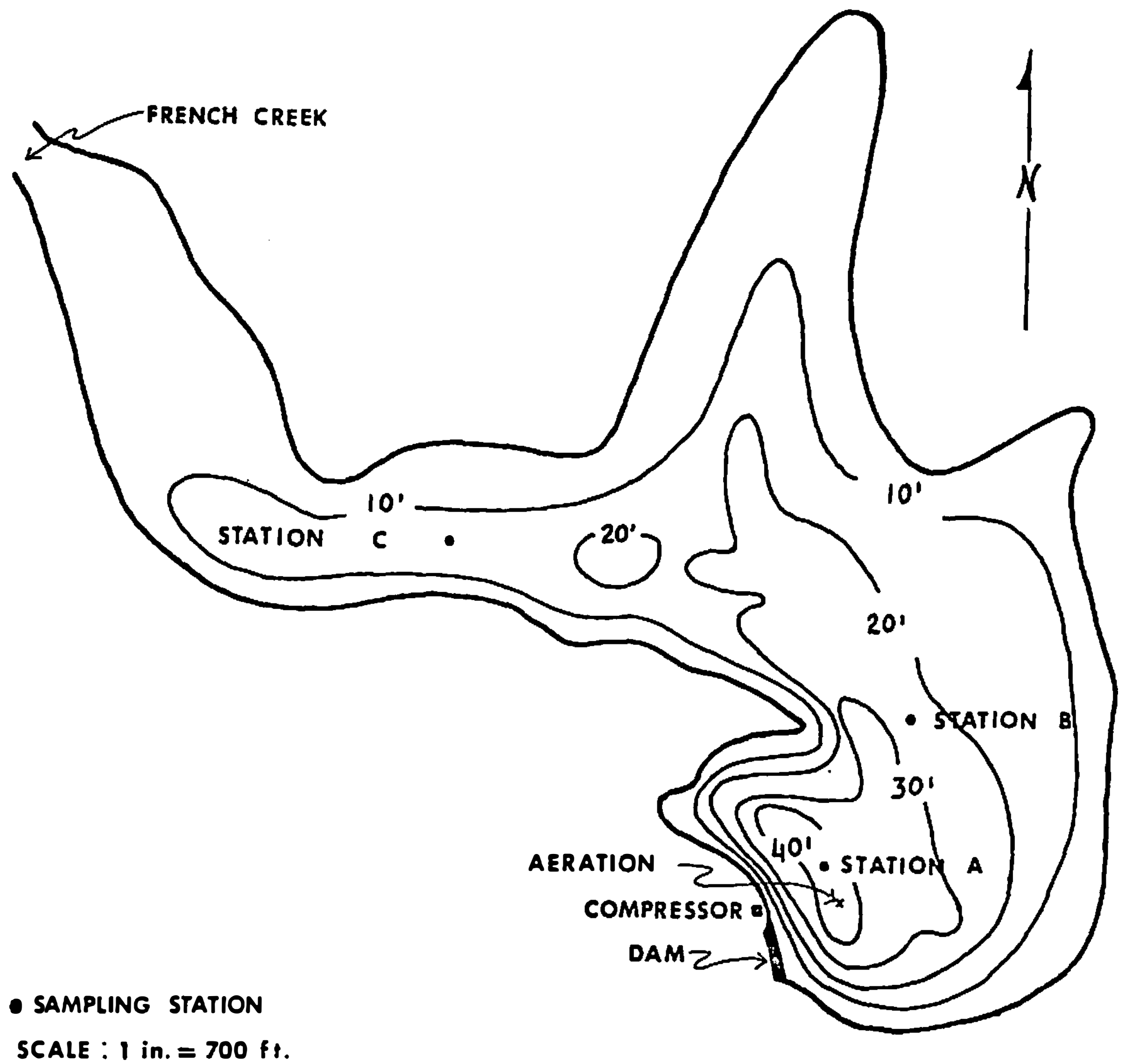

Figure 1. Hydrographic map of Stockade Lake.

40,000-fingerling rainbow trout were stocked in the spring of 1965. A fish kill which occurred during July, 1966, resulted in loss of an estimated 25,000 of these fish. Cause of the fish kill was attributed to a combination of stress factors which prevailed: a) low DO concentrations in the hypolimnion, b) high surface temperatures, and c) a very dense algae bloom. Trout that lived through the summer grew rapidly and provided fishermen with 12- to 14-inch fish during the summer of 1967. Approximately 13,000-fingerling rainbow trout were stocked in both the fall of 1967 and the spring of 1968.

The importance of maintaining and improving the Stockade Lake fishery may be realized by reviewing the findings of the Black Hills Area Resources Study (U. S. Depts. of Agriculture and Interior, 1967): The recreation-tourism industry is the leading revenue producing industry in South Dakota's portion of the Black Hills. Eleven cents of every tourist dollar is spent on recreation. Anglers from throughout the United States spent 325,000 man-days fishing in the nine-county area of the Black Hills in South Dakota and Wyoming in 1964. This fishery was worth more than 1.6 million dollars in sportsman expenditures to the local economy.

Approximately 5,800 camper units, averaging 5.25 persons per unit, used the three camping areas adjacent to Stockade Lake during the 1968 tourist season. Over 600 visitor fishing licenses were sold at the Stockade Lake concession, as compared with 500 in 1967. Each visitor license holder had an average of two children (license not required) fishing with him. This is a projected total of 1,800 non-resident anglers spending an undetermined number of man-days fishing on Stockade Lake during the 3-month 1968 tourist season alone. The lake also provides fishing enjoyment for many resident anglers throughout the year.

MATERIALS AND METHODS

Aeration System

The aeration system used for this project consisted of 16 Haydite building blocks (8 inches x 8 inches x 8 inches) capped on top and bottom by 1/8-inch steel plates. A 1/2-inch steel bolt held the plates in place. The blocks were hollow, with walls 2 inches thick. Asbestos cement was used as a sealer-gasket between the steel plates and blocks. Pipe couplings (1-inch inside diam.) with 1/8-inch orifices opening into each block were joined by a rubber hose (1/2-inch inside diam.) to supply air directly to each block (Fig. 2). An orifice was placed in each block to create head loss and assure that each diffuser received approximately the same volume of air, even if they were at different levels on the lake bottom. Each aeration unit consisted of four diffuser blocks in an angle iron frame. Each unit was supported on legs extending obliquely downwards, holding the diffuser blocks approximately 3 feet from the lake bottom. This prevented stirring and upwards transport of bottom materials when the aeration units were operating. Four aeration units (16 diffuser blocks) were used for this project (Fig. 3). Two hundred feet of rubber hose (1/2-inch inside diam.) extended from the compressor to a manifold pipe (1-inch inside diam.). Four rubber hoses (3/8-inch inside diam.), 50 feet long, connected each aeration unit to the manifold pipe. The four units

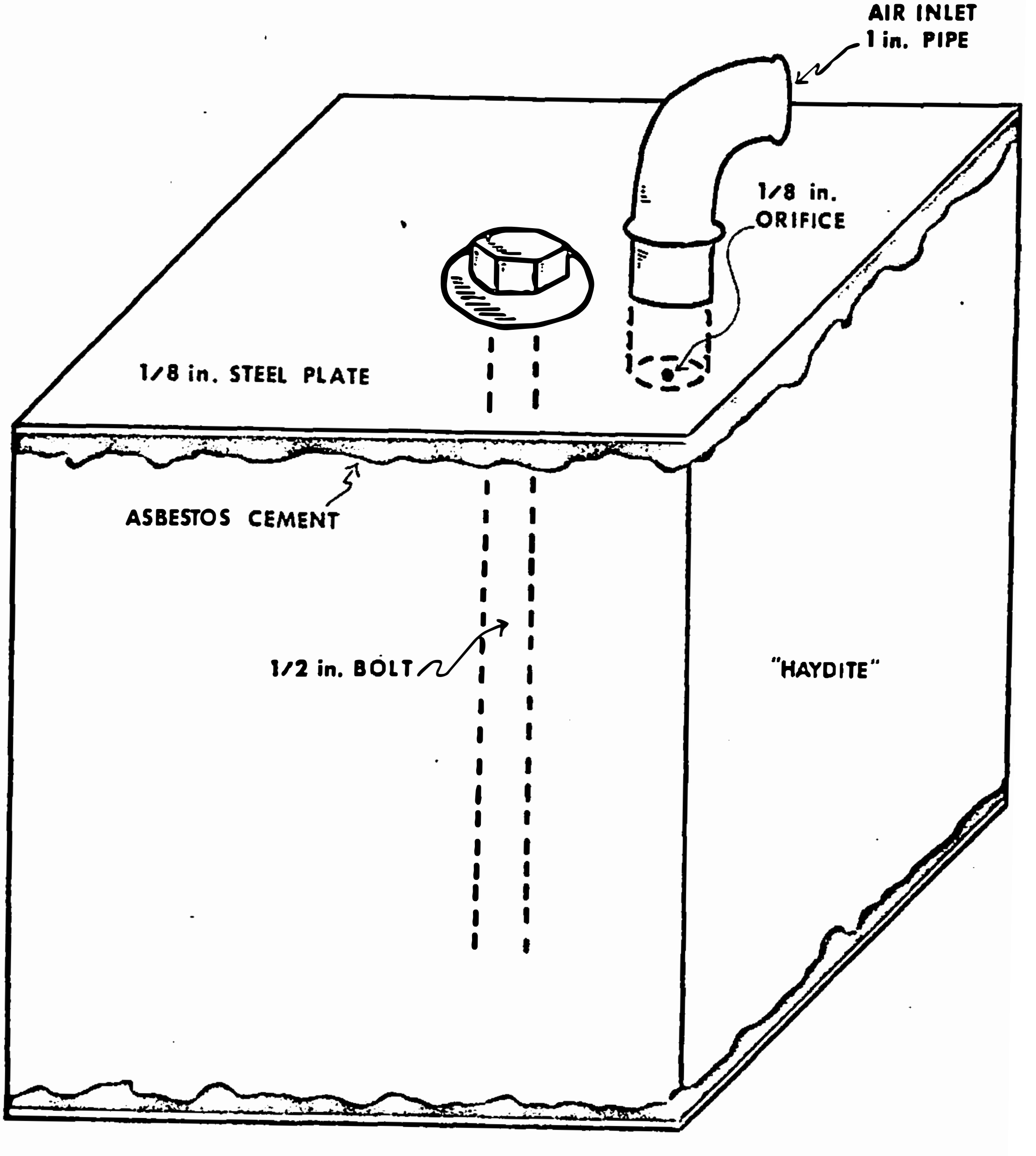

Figure 2. Air-diffuser block.

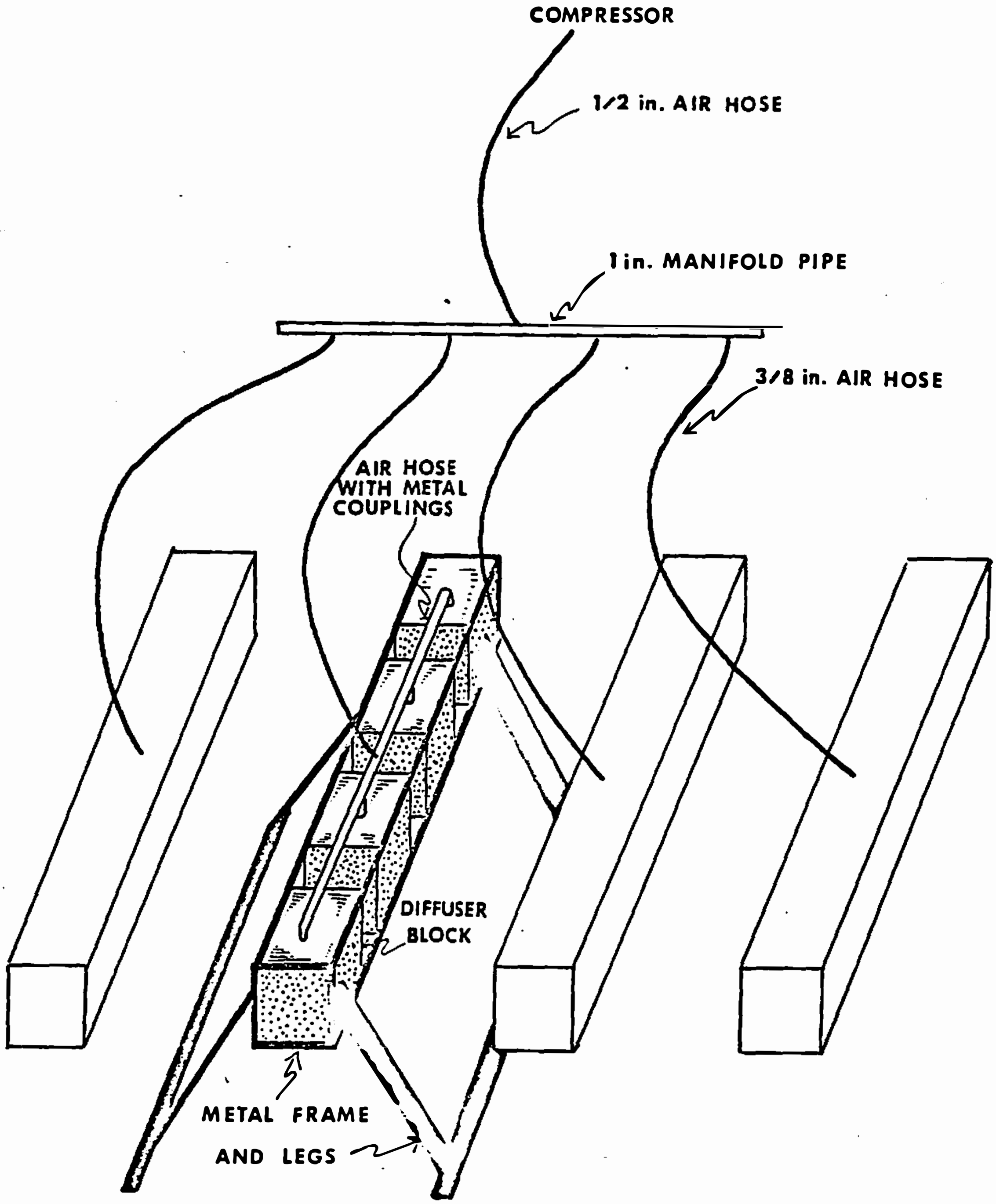

Figure 3. Aeration units with air supply system.

were placed approximately 20 yards apart on the lake bottom at the 42-foot depth, the deepest portion of the lake (Fig. 4).

Air was supplied to the diffuser blocks by a Jaeger, Roto Air-Plus, Model 125, portable air compressor. The compressor was a single stage, oil-cooled, rotary type which delivered 125 cfm. The power supply was a six cylinder, water-cooled, gasoline engine.

Methods

Experiments to determine the limnological changes resulting from aeration were conducted during summers 1967 and 1968. Three tests (I, II, III) were conducted in 1967, and three (IV, V, VI) in 1968.

Test I was to determine the approximate length of aeration time required to produce changes in temperature profile. The aeration system was operated for periods of 4 hours, 12 hours and 24 hours on consecutive days. A 48-hour operation period followed after a 1-day lapse. The test period was 21 June through 26 June.

Test II was to determine some of the limnological changes which would result from operating the aeration system 48 consecutive hours. The test period was 13 July through 15 July.

Test III was to determine some of the limnological changes which would result from aerating during daylight only. The aeration system was operated 4 hours, 8 hours, 10 hours and 4 hours on consecutive days, a total of 26 hours. The test period was 25 July through 28 July.

Test IV was to determine the pattern of mixing motions or water currents resulting from aeration. Some limnological parameters were

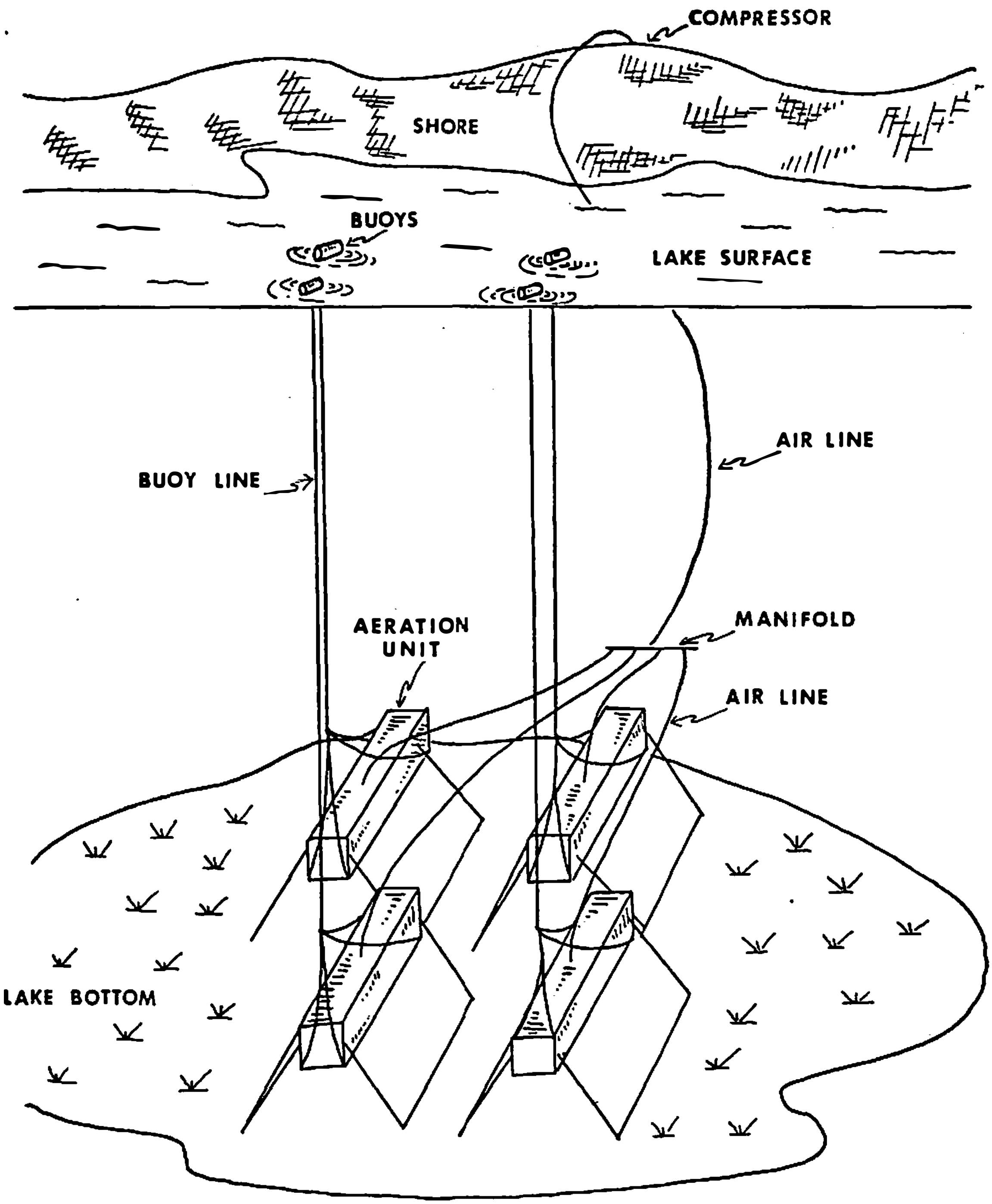

Figure 4. Aeration system in place for operation.

also measured during this test. A fluorescent dye was released and its movement within the lake traced during 48 hours of continual aeration. The test period was 19 July through 21 July.

Test V was initially intended to be a repetition of Test III, aeration during the daylight only. It was necessary, however, to aerate 24 consecutive hours in terminating the experiment to achieve the desired results. The aeration system was operated 9 hours, 13 hours, 14 hours and 24 hours on consecutive days. Some limnological parameters were measured to determine changes in water quality. The test period was 8 July through 12 July.

Test VI was conducted to determine the rate at which the aeration units transferred water from the bottom of the lake to the surface. The test was conducted 21 August.

Water quality parameters were measured at sampling stations A, B and C, (Fig. 1), during Tests I-V, except no samples were taken from Station B during Test I. The need for an intermediate station was not obvious until data from Test I had been analyzed. Station A (42 ft. deep) was proximal to the aeration system during the 1967 tests. It was moved approximately 100 feet further away from the aeration units in 1968 to assure that it would be outside direct influence of uplifted water. The Station A depth was 32 feet during the 1968 tests. Station C (16 ft. deep) was in the inlet bay. Sampling was conducted prior to each aeration period, at least three times per day during each test and at 1-week intervals following each test.

Parameters sampled were: 1) water temperatures, measured with a Yellow Springs Instrument Company resistance thermometer, 2) pH, determined colorimetrically by use of pH indicators and Hellige comparator discs, 3) phenolphthaline and methyl orange alkalinity, 4) dissolved oxygen, determined by the Alsterberg (Azide) modification of the Winkler method, 5) carbon dioxide, and 6) hydrogen sulfide, determined by use of a Hach Chemical Company test kit. Tests used for alkalinity, dissolved oxygen and carbon dioxide are described in Standard Methods (Amer. Publ. Health Assoc., 11th ed., 1960). Temperature was measured from surface to bottom at 2-foot intervals while pH, alkalinity, carbon dioxide and hydrogen sulfide were sampled from surface and bottom depths only. Dissolved oxygen was sampled from surface to bottom, usually at 10-foot intervals. Samples were collected with a 1-liter Kemmerer water bottle. All analyses were conducted in the field at the time of sampling. Weather conditions were recorded each time sampling was conducted.

Rhodamine WT, 20% solution (density, 1.2), a fluorescent dye, was used to trace water currents in Test IV. Rhodamine WT is described as having very low sorption tendencies (Turner Associates, 1968). The dye was pumped from containers, carried in a boat, through a hose and released into the water just above the diffuser blocks at approximately the 40-foot depth. The dye was applied 15 minutes before aeration began. The amount of dye released was sufficient to treat the entire lake at a concentration of 20 parts per billion (ppb) by volume. Sampling to determine dye movement was conducted at 22 stations (Fig. 5) from surface to bottom at 5-foot depth intervals. The samples were collected with a 1-liter Kemmerer water bottle and emptied into 300-ml. glass bottles labeled for each station and depth. Sampling began at stations 1 through 5 after 1 hour of aeration and extended to other stations to keep ahead of the dye as it moved throughout the lake. A Turner Model 111 fluorometer was used for sample analyses. Concentrations of 0.01 ppb may be reliably detected with this instrument (Turner Associates, 1968).

A fluorescein dye, Uranine, was used in Test VI to determine the rate at which the aeration units transferred water from the lake bottom to the surface. The dye was lowered in a plastic sack to a known depth directly above one aeration unit. The aeration system was then put into operation, the sack containing the dye severed completely and time from dye release to its appearance on the surface recorded. The surface area of the water "boil" (see frontispiece) over the aeration unit and the volume of the hypothetical cylinder of rising water were determined, thus enabling calculation of the flow rate through the cylinder.

The addition of vertical legs to the aeration units in 1968 to keep them 3 feet from the lake bottom, thereby reducing disturbance of bottom mud by aeration, was the only change made during the 2-year study period. Initially, three horizontal legs extended from each unit.

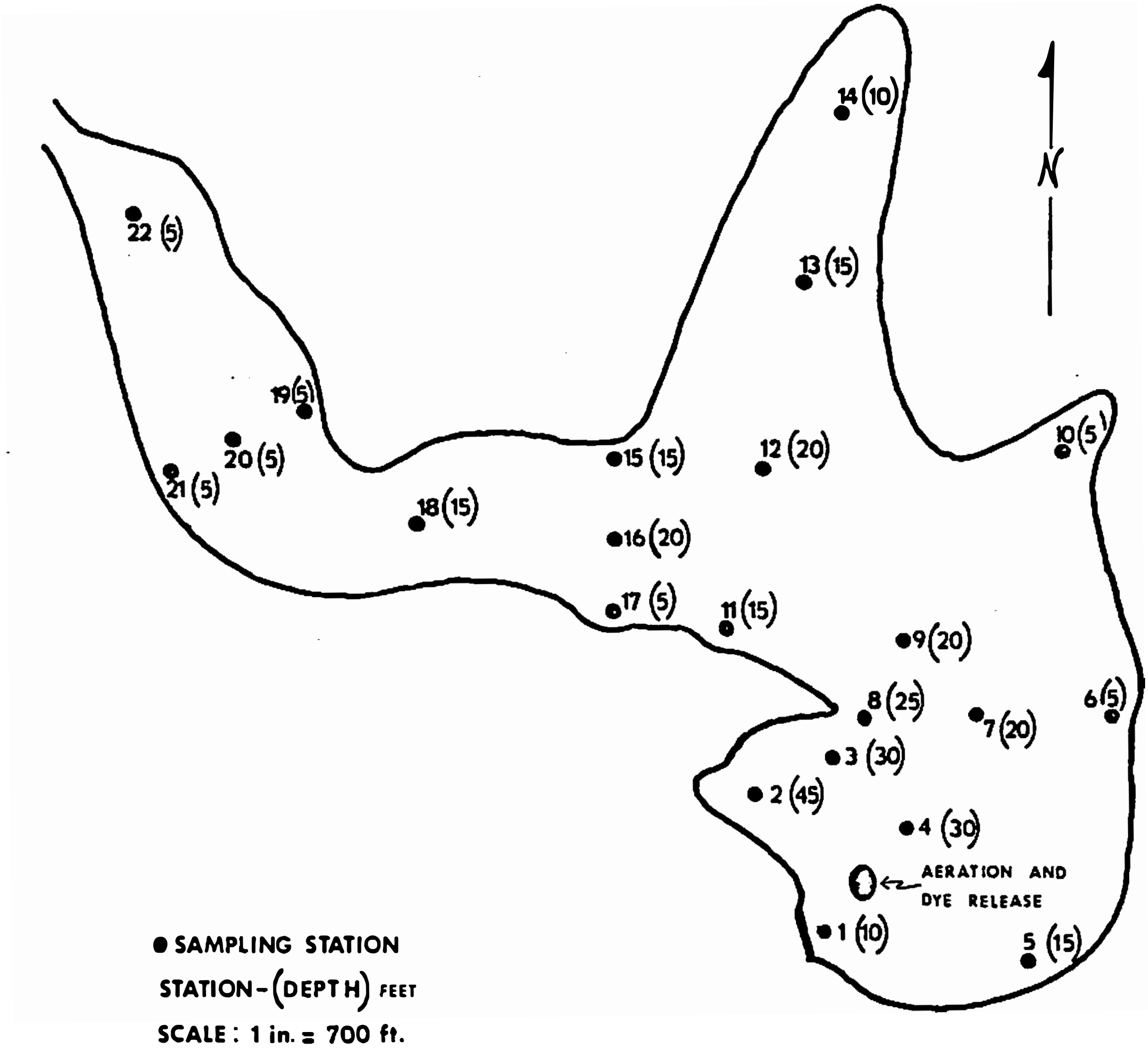

Figure 5. Location and depth of sampling stations for dye movement study.

RESULTS AND DISCUSSION

Pumping Rate

Each aeration unit acted as a pump. Temperature measurements near the aeration units showed cold, hypolimnetic water was lifted to the surface by air bubbles rising from diffuser blocks. A "boil" of water and air bubbles rose 6 inches above the level of the lake surface over each aeration unit.

Test VI revealed that the four aeration units had a combined pumping rate of 4.7 million gallons per hour (mgh). The pumping rate of one aeration unit was calculated by multiplying the volume (6,855 gal.) of a hypothetical cylinder (38.5-ft. height; 5.5 ft. diam.) of water over one aeration unit by the time (21.5 sec.) taken for dye to pass from the bottom to the top of the cylinder. This rate multiplied by four (number of aeration units) gave the combined pumping rate. Koberg and Ford (1965) reported an increase in "boil" size during their experiment and concluded the mixing rate increased with operation time. The pumping rate of 4.7 mgh, therefore, may have been the minimum achieved in the Stockade Lake tests because the measurements used to calculate this rate were made only 10 minutes after the compressor was started.

Wirth and Dunst (1967) reported six Aero-Hydraulic Guns handled about 2.3 mgh with an air input of 72 cfm. Irwin et al. (1967) reported a pumping rate of about 26.7 mgh with an air input of 115 cfm, for the prototype of the diffused-air system used in the Stockade

Lake tests. This rate is approximately six times greater than the rate achieved in Stockade Lake. Irwin et al. (1967) assumed, in calculating the 26.7 mgh rate, that the time to create a 2°C temperature change in the deepest portion of their test lake was the time required to circulate the entire contents of the hypolimnion once. The results of Test IV, which will be discussed later, showed temperature changes which occurred in the deepest portion of Stockade Lake were due to circulation of more than just hypolimnetic water. The technique of calculating pumping rates used by Irwin et al. (1967), therefore, would not be applicable to Stockade Lake and could account for the sizable difference in rates. Irwin et al. (1966) destratified four lakes using a mechanical pump with a capacity of 4.2 million gallons per day, a much lower rate than that of the diffused-air system used on Stockade Lake.

Mixing Currents

Temperature measurements showed that water carried to the surface by rising air bubbles flowed in a radial-horizontal direction approximately 45 ft. before sinking. Water currents resulting from operation of the prototype diffused-air system were described by Symons, Irwin, Robinson and Robeck (1967, p. 1286, 1287): "Float studies indicated that a strong radial, horizontal velocity away from the boil area occurred approximately 10 ft. below the lake surface. This indicates the rising water has been warmed sufficiently during its movement to the surface, so as to sink only 10 ft., and thus not return to the hypolimnion."

The pattern of mixing currents throughout Stockade Lake caused by aeration in one location was determined in Test IV, a dye-movement study. Concentrations of dye detected at various stations were assumed to be a valid indication of the dispersal of water lifted to the surface by aeration (Figs. 5-13). Dye was detected at stations 1-9 within 4 hours (Fig. 6 and 7). Dye reached station 13 within 6 hours and extended to station 15 within 8 hours (Fig. 8). Dye extended to station 16 within 10½ hours and was detected as far away as station 19 within 13½ hours (Fig. 9). Within 22 hours, dye was found at stations 20 and 21 (Fig. 10), and had reached station 22 within 25½ hours (Fig. 11). Sampling after 34½-hours aeration revealed dye concentrations at all stations except number 21 (Fig. 12). The next sampling, 12 hours later, showed dye to be at all stations and more evenly distributed depth-wise than at the previous sampling period (Fig. 13). Limnological parameters measured during this test remained variable with depth, although dye had been found at all stations and depths. The fall-1967 overturn in Stockade Lake produced homogenous concentrations of these parameters. The mixing currents responsible for dye distribution throughout the lake, therefore, seem to be of lesser magnitude than those which occurred during the overturn. Mixing in magnitude of an overturn could possibly have been achieved by longer periods of aeration.

Peak concentrations of dye were found most frequently at the 15-ft. depth, indicating the main current of pumped water moved

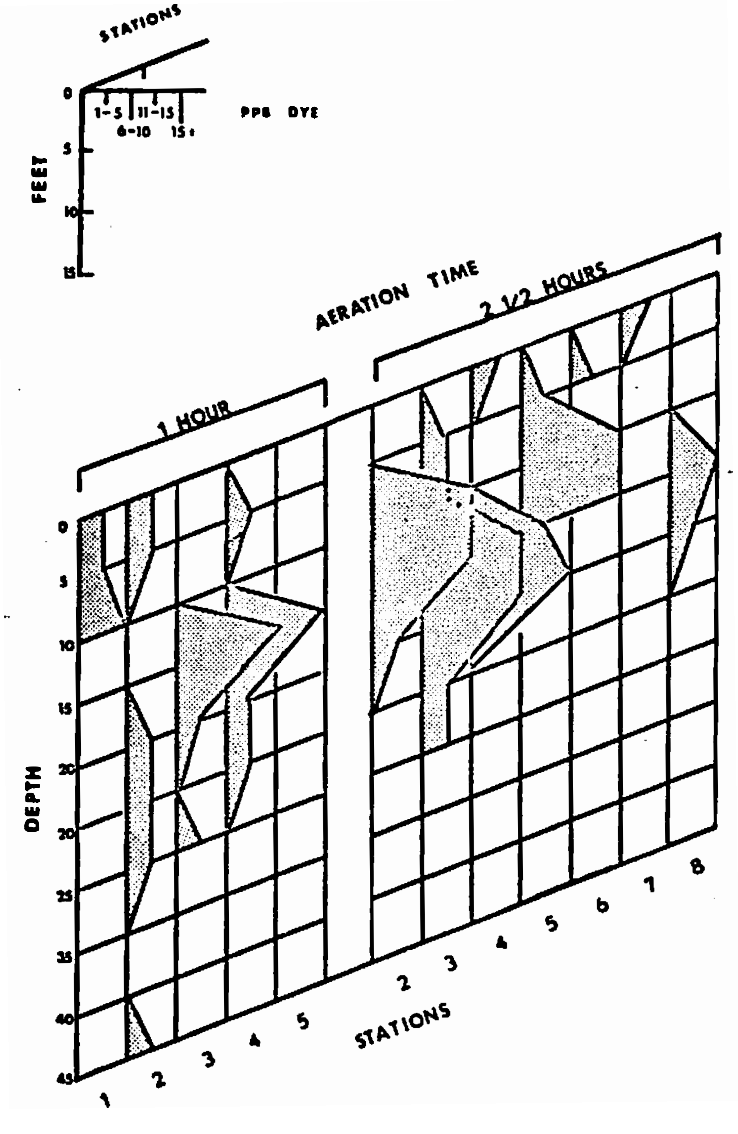

Figure 6. Dye concentrations at stations sampled 1 hour and 2½ hours after dye release and beginning of aeration.

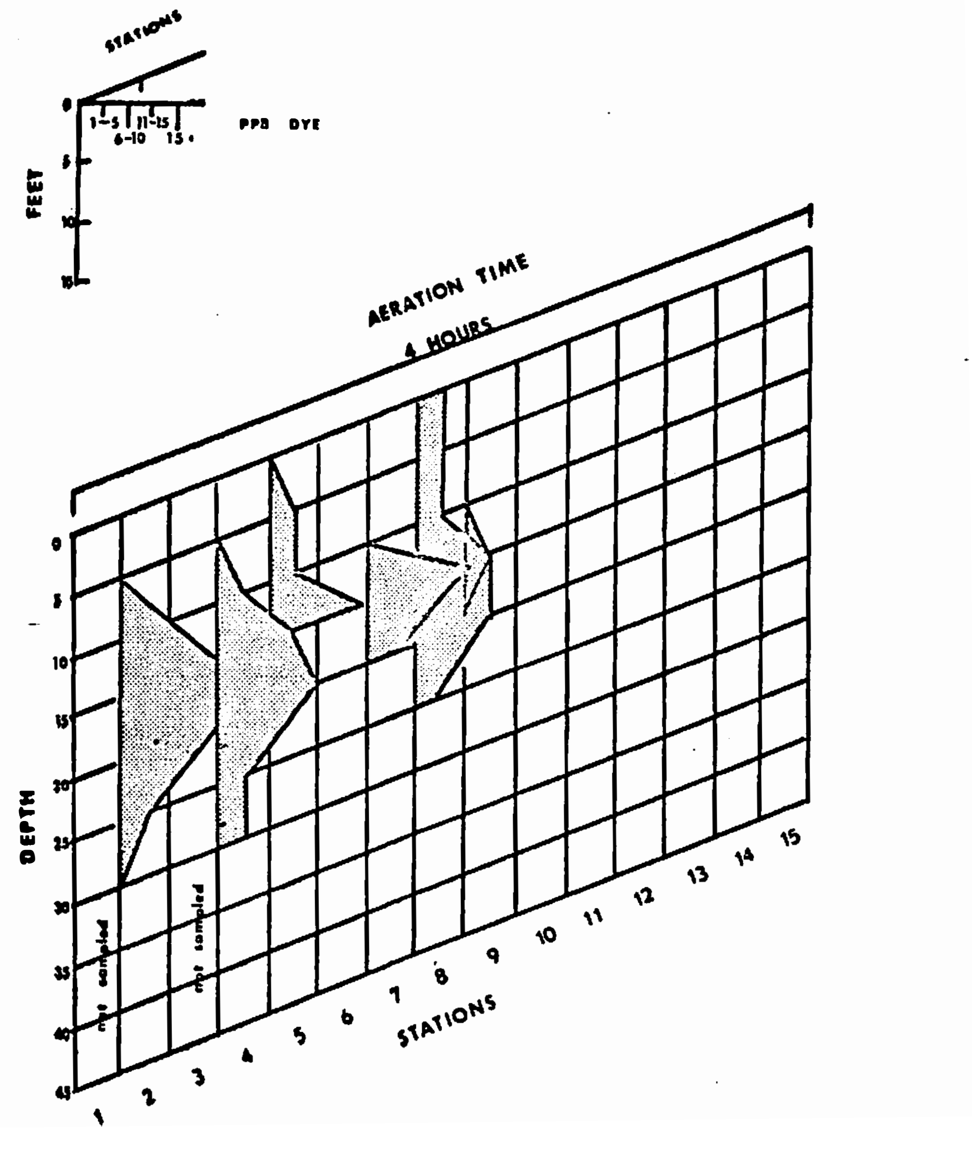

Figure 7. Dye concentrations at stations sampled 4 hours after dye release and beginning of aeration.

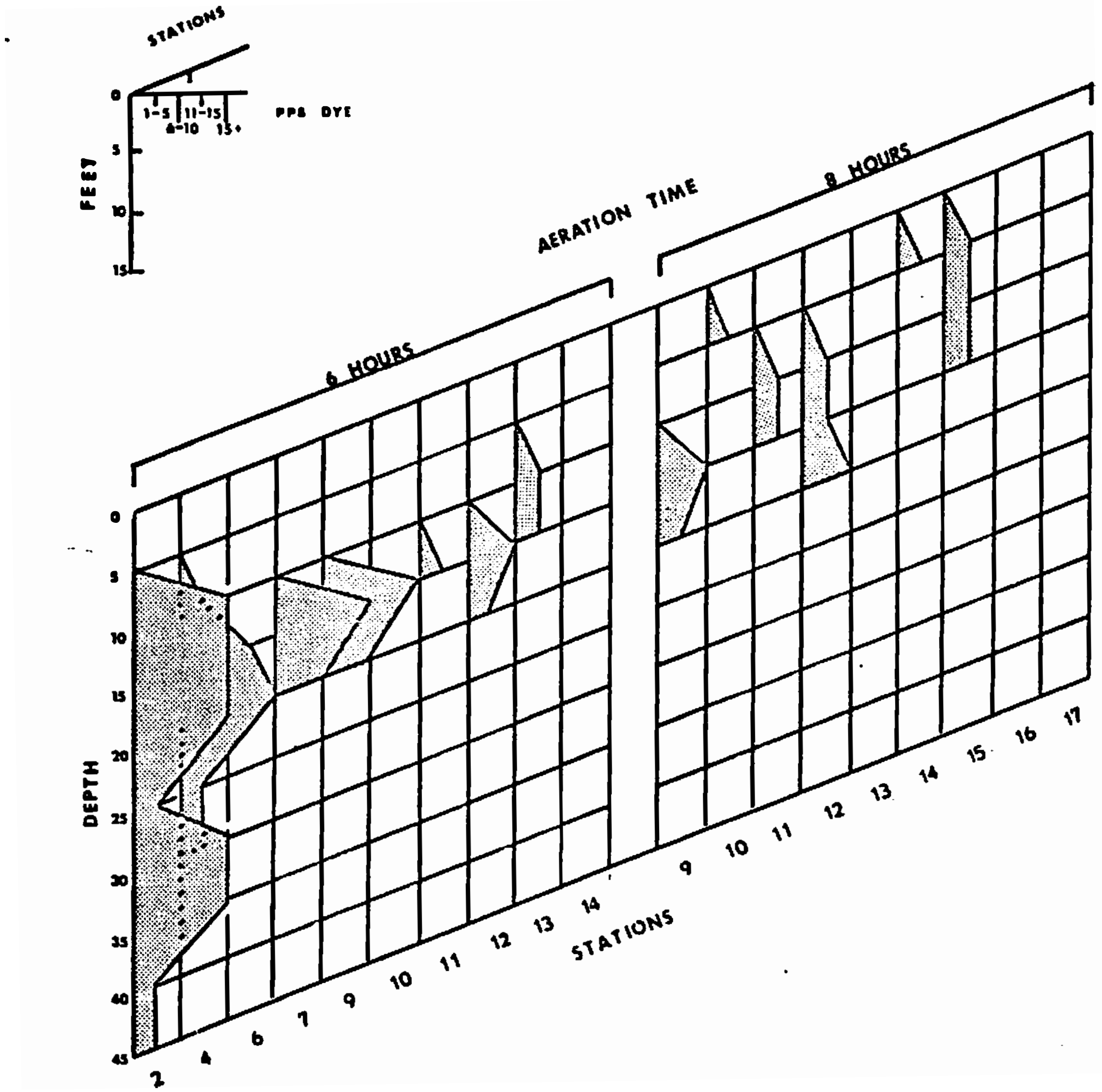

Figure 8. Dye concentrations at stations sampled 6 hours and 8 hours after dye release and beginning of aeration.

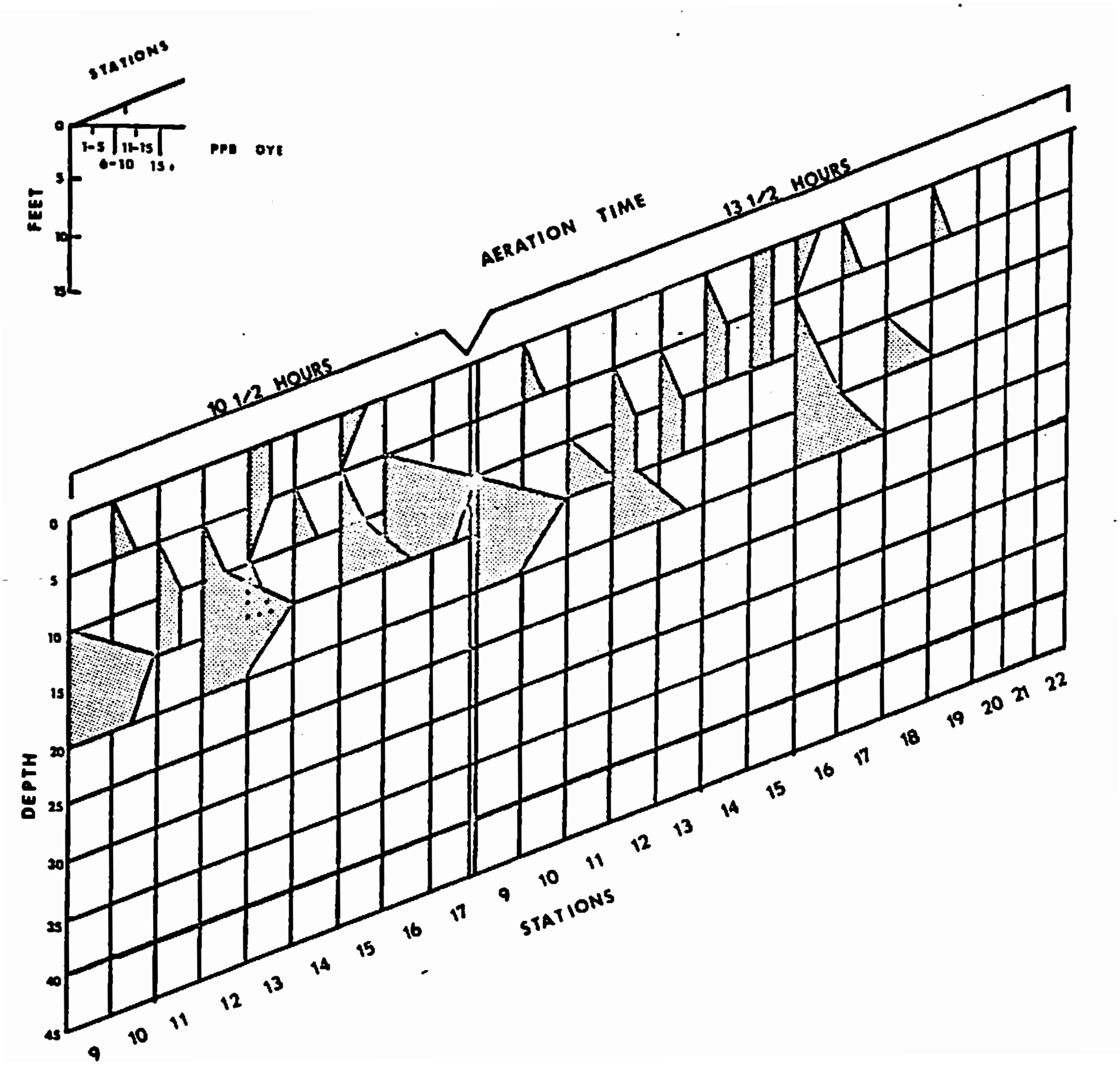

Figure 9. Dye concentrations at stations sampled 10½ hours and 13½ hours after dye release and beginning of aeration.

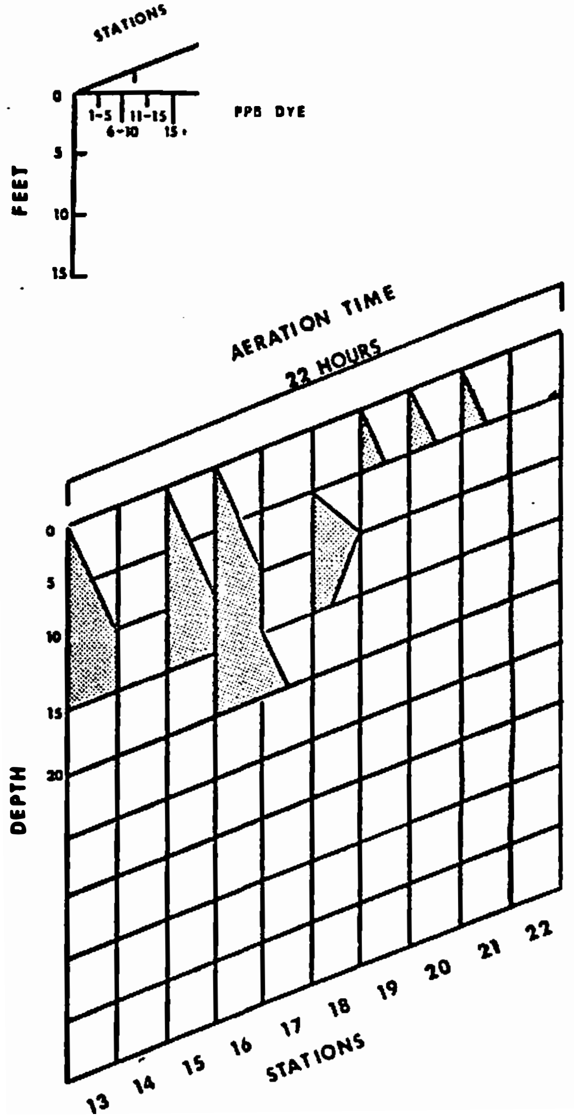

Figure 10. Dye concentrations at stations sampled 22 hours after dye release and beginning of aeration.

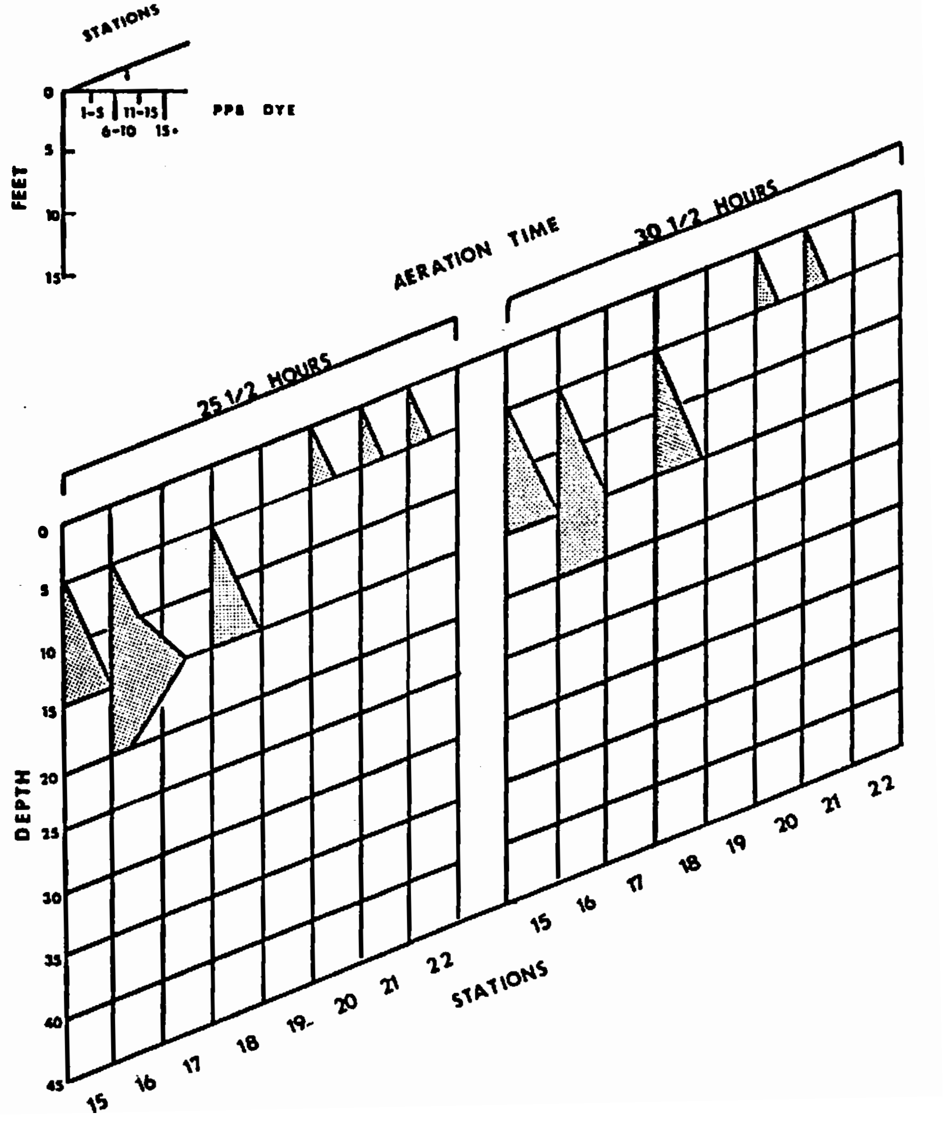

Figure 11. Dye concentrations at stations sampled 25½ hours and 30½ hours after dye release and beginning of aeration.

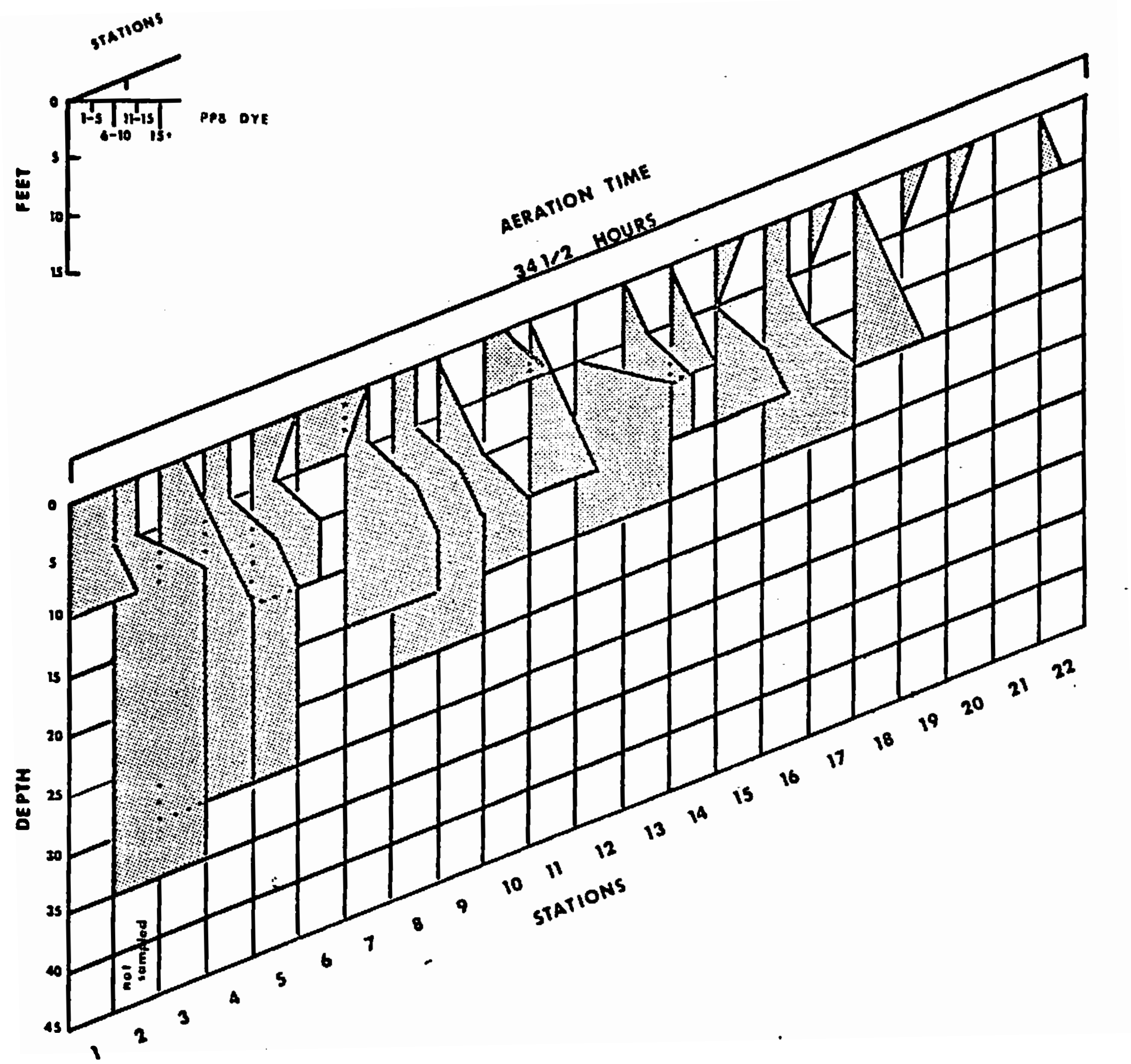

Figure 12. Dye concentrations at stations sampled 34½ hours after dye release and beginning of aeration.

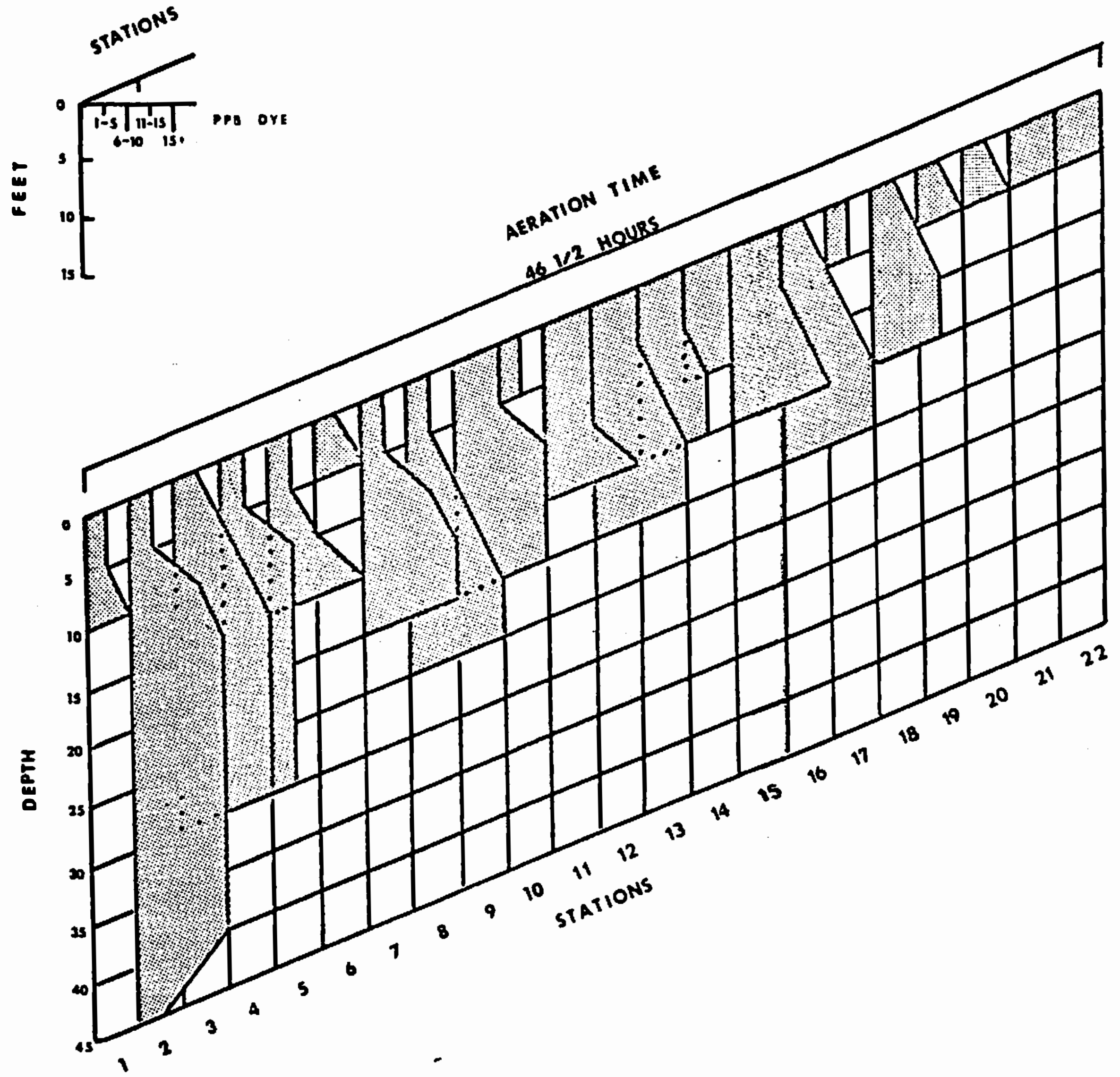

Figure 13. Dye concentrations at stations sampled 46½ hours after dye release and beginning of aeration.

horizontally away from the aeration units at this depth. Eddies apparently distribute the water upwards and downwards from the main current. Even distribution of dye appeared to result from increased intensity of eddies (Fig. 14). Density stratification, although present, was possibly weakened by the change in temperature profile, thus reducing resistance to vertical movement of water. The most probable reason the main water currents resulting from aeration occurred at the 15-foot depth was that water brought to the surface by aeration was warmed by mixing with surface water and then sank to a depth commensurate with its density. Dye was visible in "boils" over the aeration units at termination of Test IV, indicating some water lifted to the surface by rising air bubbles was continually recirculated in the area of aeration.

Approximately 186 million gallons of water, 23% of the total lake volume, were pumped by the aeration units to achieve dye distribution. By comparison, Irwin et al. (1966) reported that 11.2% of the lake volume had to be passed through a pump to mix the entire 1,260-acre foot Vesuvius Lake. Symons, Irwin, Clark and Robeck (1967, p. 11) stated: "If destratification is to be carried out by bringing cold water from the bottom as a heat sink to absorb heat from the upper layers and thereby make the lake isothermal, the volume that must be moved is the volume of cold water that is present at the start of the operation." The amount of water that has to be pumped

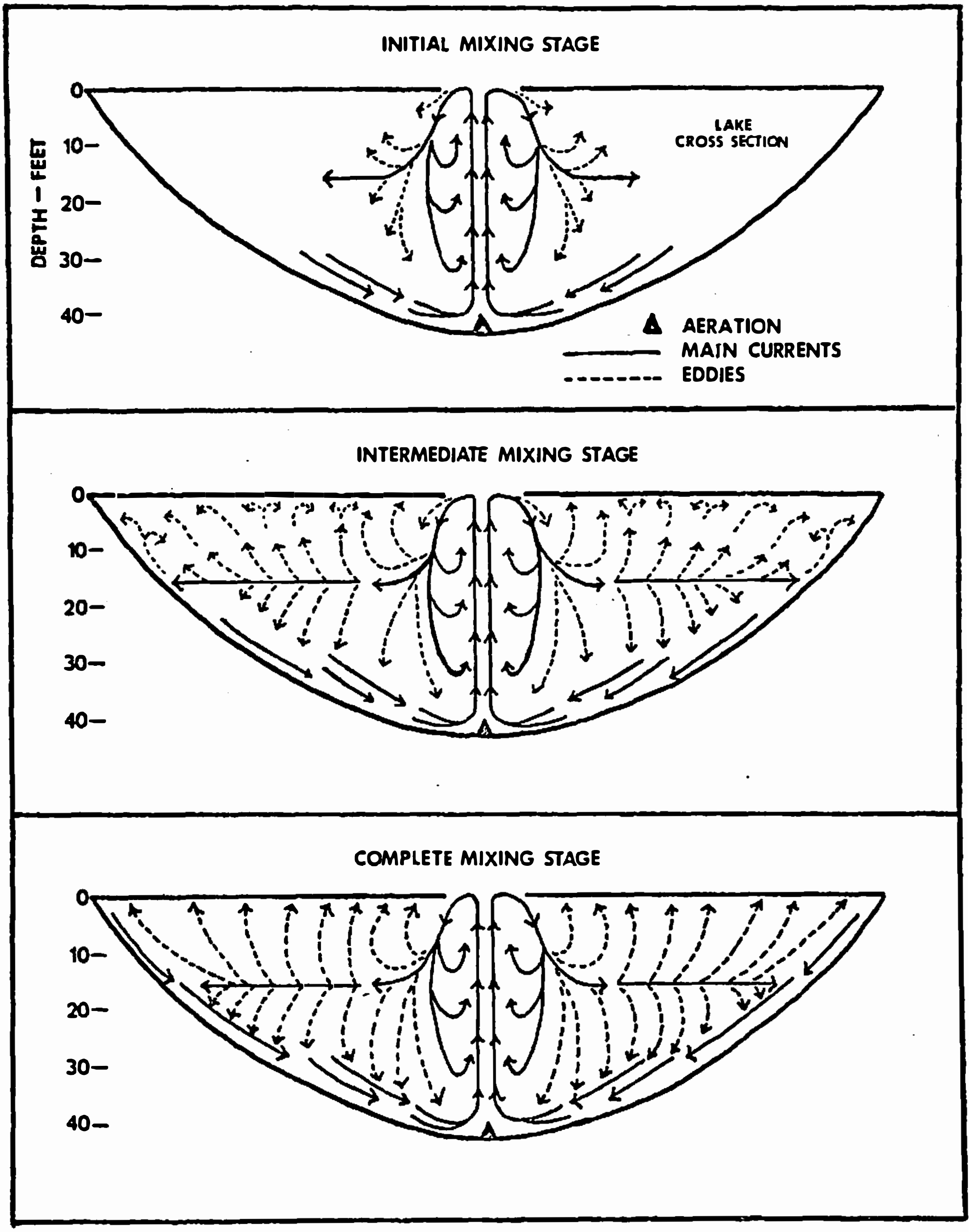

Figure 14. Interpretation of mixing currents resulting from aeration.

to achieve complete mixing varies, therefore, from lake to lake because of difference in volumes of the hypolimnion and also differs within one lake as the depth of the thermocline fluctuates.

Temperature Changes

Aeration and consequent mixing caused temperature increases in the hypolimnion and temperature decreases in the epilimnion during Tests I-IV (Figs. 15 and 16). Aeration during daylight only on 4-consecutive days resulted in modification of the thermal profile during Test III. Aeration for 24-consecutive hours at termination of Test IV was necessary to achieve desired results. The hypolimnion became progressively warmer during the preceding 3-consecutive days, but high air temperatures prevented cooling of the epilimnion as occurred during previous tests. Daylight aeration, if continued, would probably have resulted in homogenous temperatures by warming the hypolimnion, regardless of whether or not the epilimnion was cooled. This would have, however, resulted in temperatures approaching the maximum limit tolerated by trout and could have resulted in a fish kill. Symons, Irwin, Robinson and Robeck (1967, p. 1284) reported a similar condition during one of their aeration tests: "In this case, solar radiation was so strong that the surface was being reheated as quickly as the mixing device distributed this heat throughout the lake."

Continual aeration appears to be the best method of mixing Stockade Lake regardless of the inconvenience of night-time

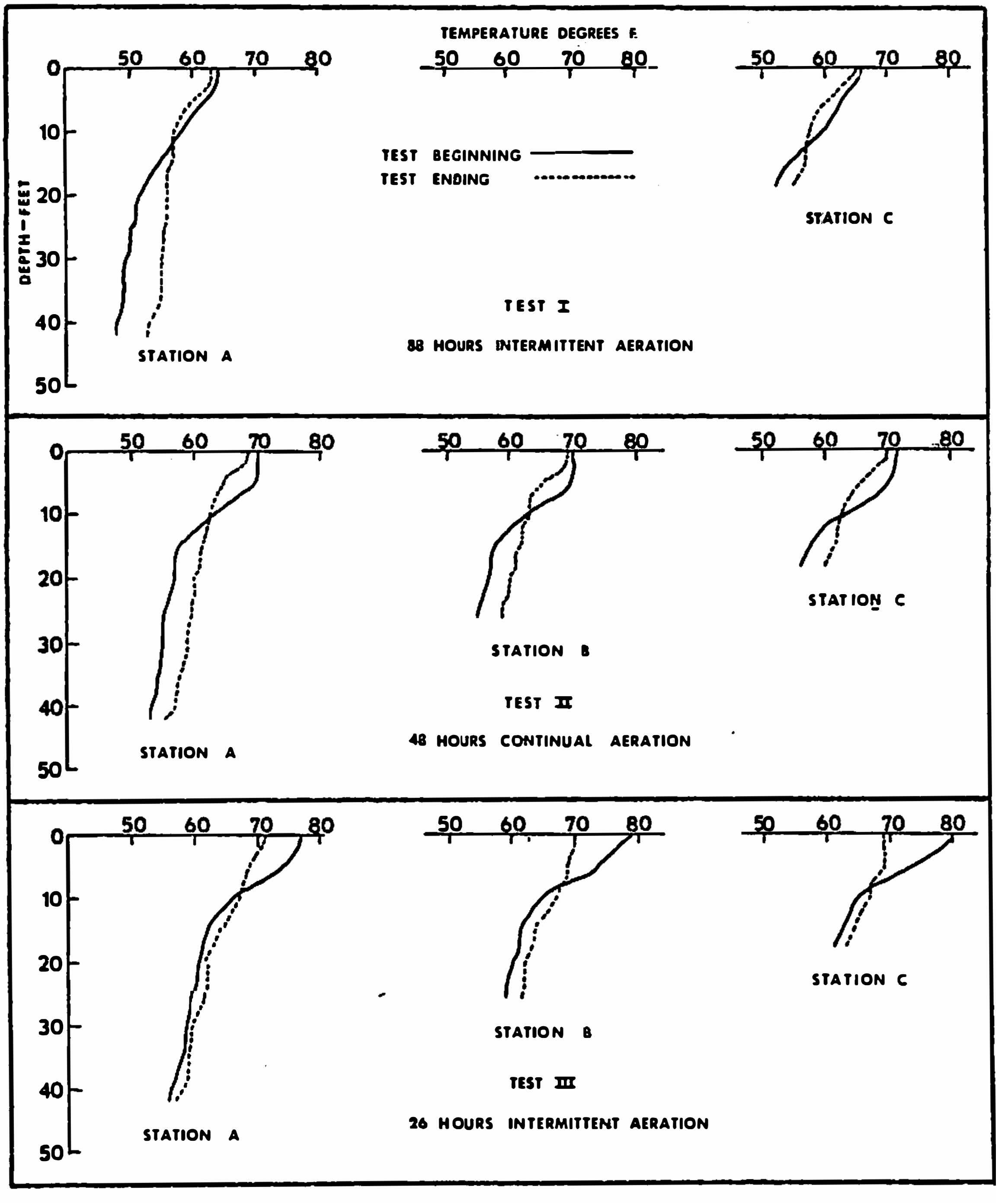

Figure 15. Temperature changes during aeration-mixing, Tests I, II and III, 1967.

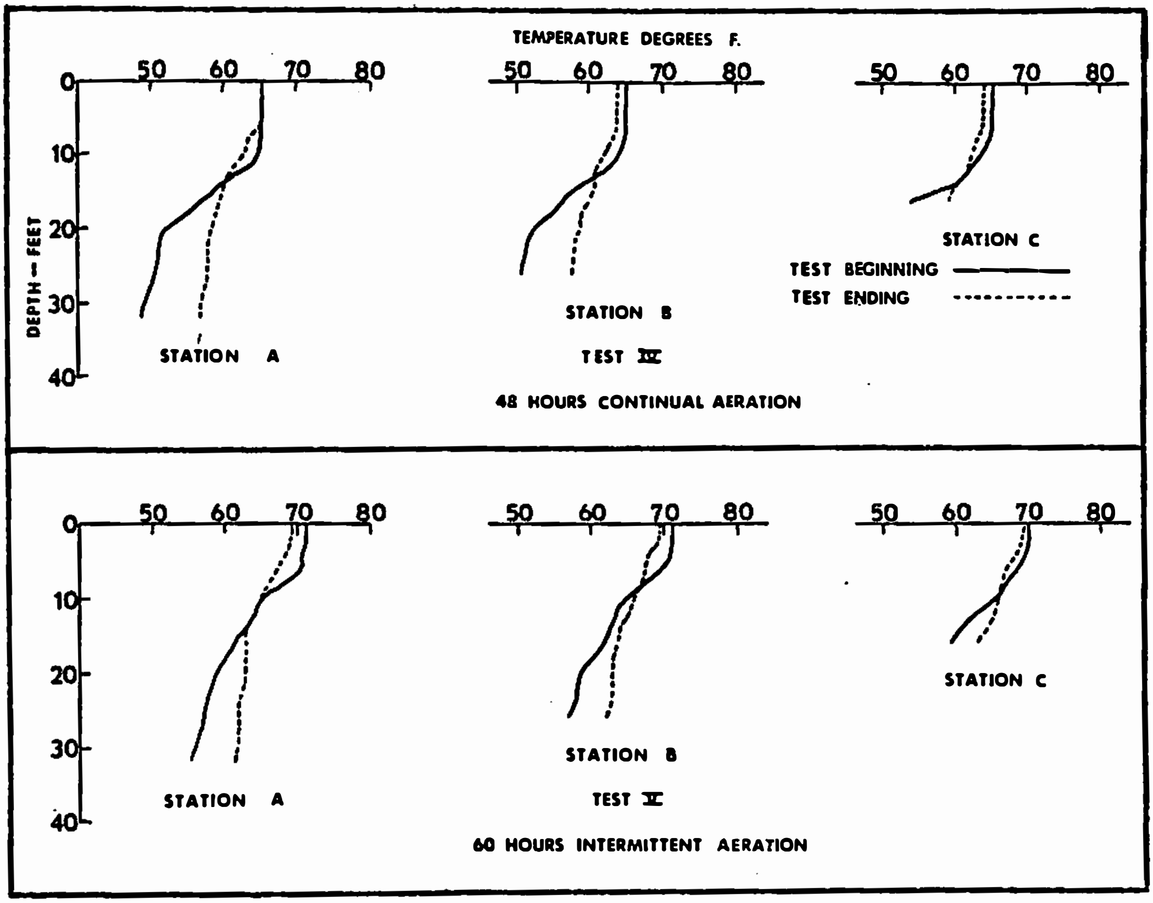

Figure 16. Temperature changes during aeration-mixing, Tests IV and V, 1963.

maintenance of the compressor because: 1) cooling of epilimnion and warming of hypolimnion waters accomplished by continual aeration is less likely to warm the lake to a point where trout life will be endangered, and 2) build-up of mixing currents with each hour of aeration would be continuous.

Thermal stratification of Stockade Lake returned to pre-aeration intensity within one week after termination of each aeration test. Water temperatures remained generally the same below the 20-foot depth after aeration, but increased in shallower water. The occurrence of restratification a short time after mixing terminated was also reported by Irwin et al. (1966), Symons, Irwin and Robeck (1967b) and Symons, Irwin, Robinson and Robeck (1967). The rate at which restratification occurred seemed dependent on weather conditions. For example, hot, clear, calm days produced a more rapid restratification rate.

Dissolved Oxygen Changes

Changes in DO resulting from aeration-mixing were inconsistent (Figs. 17 and 18). Levels of DO were not substantially increased in the hypolimnion. The BOD was probably equal to the oxygen supply rate. Irwin, Symons and Robeck (1966, p. 39) reported: "The rate at which an impoundment must be destratified is related to the rate of oxygen demand. If this rate is high, the mixing rate must be high, or dissolved oxygen will be removed from the water as fast or faster than it is added."

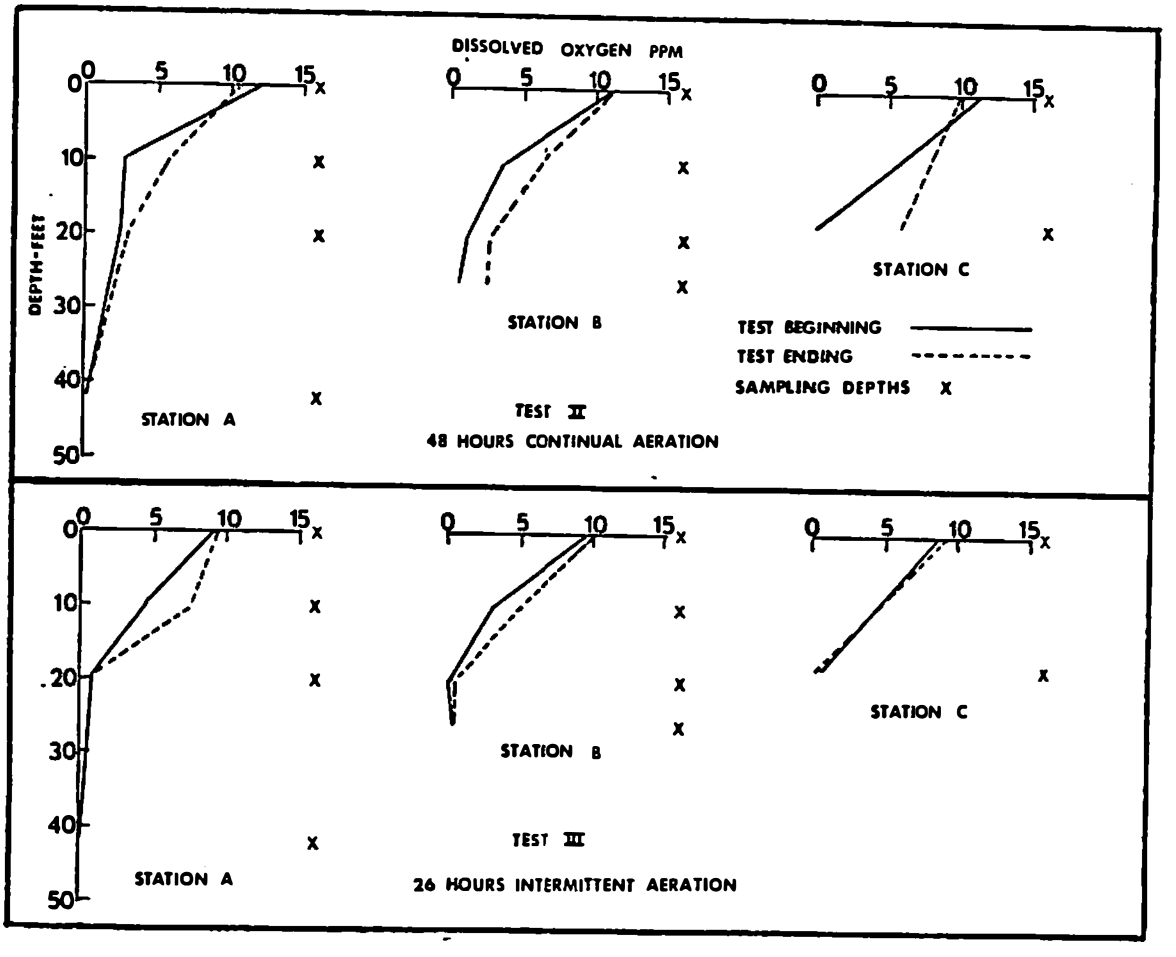

Figure 17. Dissolved oxygen changes during aeration-mixing, Tests II and III, 1967.

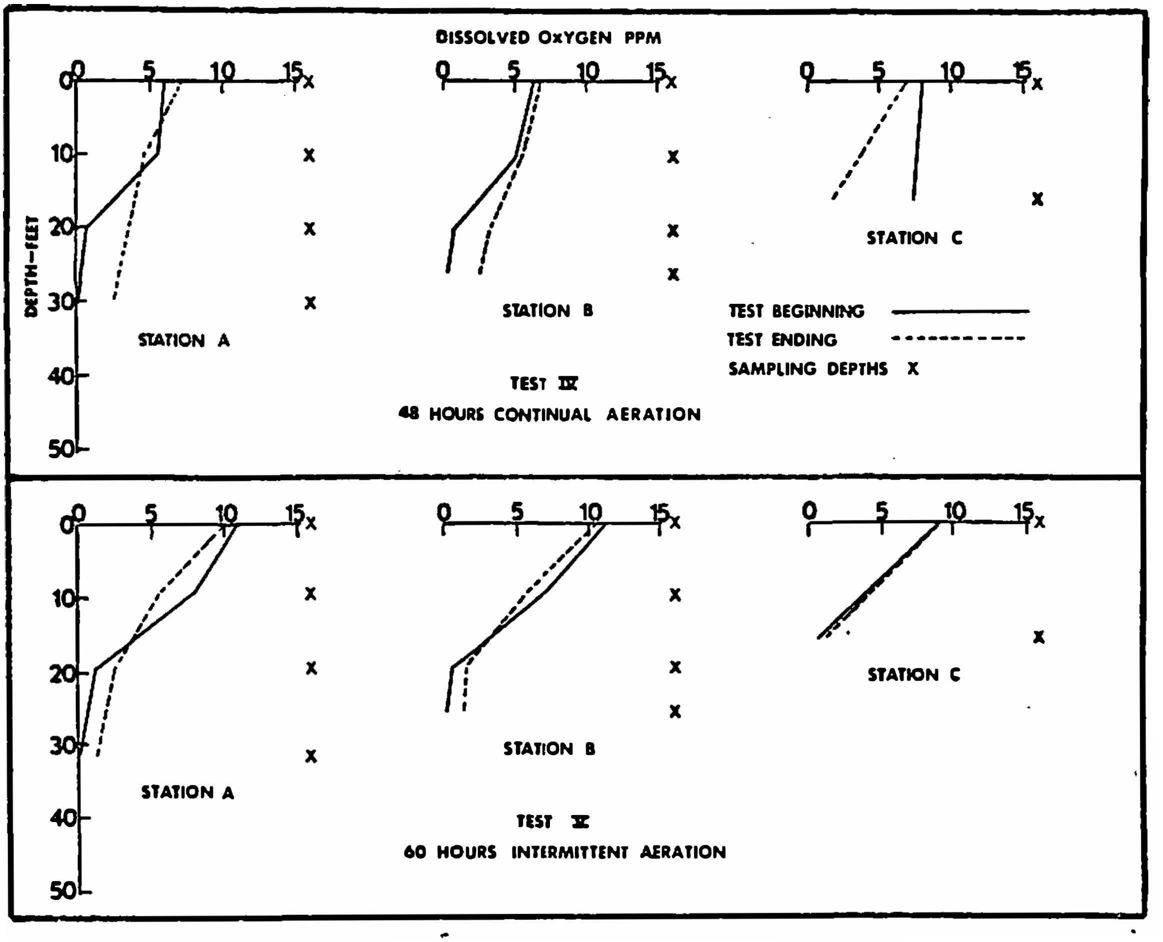

Figure 18. Dissolved oxygen changes during aeration-mixing, Tests IV and V, 1968.

The diffused-air system promotes oxygenation in two ways: 1) oxygen transfer from air bubbles and 2) moving water to the surface for aeration. Symons, Irwin, Robinson and Robeck (1967) reported oxygenation capacity of diffused air pumping is much higher than mechanical pumping, probably because the diffused-air pump was more efficient in moving water to the surface for aeration and not because of oxygen transfer from diffused-air bubbles to the water.

Redistribution of DO that already existed in Stockade Lake, and not addition by aeration, could have accounted for some DO changes that occurred during these tests. A decrease of DO in the epilimnion and an increase in the hypolimnion, as shown in Test V (Fig. 17), indicates DO redistribution resulting from mixing.

pH Changes

Aeration-mixing resulted in very little pH change. A slight increase usually occurred at the surface and a slight decrease at the bottom. Throughout the testing periods, the surface pH ranged from 8.5 to 8.9 before aeration and from 8.1 to 8.7 after. On the bottom, pH ranged from 7.0 to 7.3 before aeration and from 7.1 to 7.8 after. The largest pH increase at the bottom was 0.7 and the largest decrease at the surface was 0.3.

Carbon Dioxide Changes

Carbon dioxide changes discussed below are based on sampling at three stations (A, B and C) during Tests II-IV, a total of 12 possibilities for change. Reduction of carbon dioxide on the bottom occurred 75% of the time, the largest being 8.0 ppm. Increase in surface carbon dioxide occurred 25% of the time, decreases 25% and no changes 50%. Carbon dioxide on the surface varied from 0.0 to 8.5 ppm before aeration and from 0.0 to 5.0 ppm after. Carbon dioxide on the bottom varied from 7.5 to 14.5 ppm before aeration and from 5.5 to 11.0 ppm after.

Alkalinity Changes

No substantial or consistent changes in alkalinity occurred during these tests. Total alkalinity varied from 98 to 156 on the surface and from 102 to 136 on the bottom.

Symons, Irwin and Robeck (1967b) reported that destratification had little influence on alkalinity when compared to its behavior in a control lake.

Hydrogen Sulfide

Hydrogen sulfide analyses were conducted on surface and bottom water samples during Test I only. No hydrogen sulfide was detected.

Algal Density Changes

Visual observations of algal concentrations near the lake surface were recorded. Algal populations seemed to be reduced during each aeration test, however, they appeared to build up to pre-aeration levels within 1 week after each test.

Reductions of algal density by lake mixing have been reported by Bernhardt (1967), Dunst (1967), Ford (1963), Symons, Irwin and Robeck (1967a; 1967b), Symons, Irwin, Robinson and Robeck (1967), Wirth and Dunst (1967) and Wirth, Dunst, Uttormark and Hilsenoff (1967). Hooper et al. (1952) reported that phytoplankton numbers increased 8- to 10-fold during their pumping experiment.

Equipment Operation

Gasoline costs were the only operating expenses during the entire testing period. The compressor cost 75 cents per hour to operate at a gasoline price of 30 cents per gallon. It would cost approximately 1 dollar per hour to operate an electrical compressor with an equal air-output capacity for a 48-hour period (computed using electrical rates charged in the Black Hills area). The portability of an air compressor powered by a gasoline engine increases its practicability when considered from a wide-use viewpoint. Trailer-mounted electrical compressors are available on the commercial market, but convenient electrical hook-ups are not available at all lakes to which this aeration technique could be applied. Aeration units used in the tests on Stockade lake showed no deterioration from two summers' use. Units were placed in and removed from the lake with ease, using a winch mounted on a pontoon raft.

The most apparent disadvantage of operating an air compressor powered by a gasoline engine, compared to an electrical compressor, was periodical maintenance checks on water temperature, oil pressure, etc. that should be made at least once every 2 hours. Portability of aeration units could be improved by development of a lighter frame. Each unit weighed approximately 120 pounds.

SUMMARY AND CONCLUSIONS

Dye was distributed throughout Stockade Lake by aerating in the deepest portion, indicating that mixing currents distributed water uplifted by rising air bubbles to all portions of the lake. The four aeration units had a combined pumping rate of 4.7 mgh. Uplifted water flowed approximately 45 ft. in a radial-horizontal direction before sinking to the 15-foot depth. The main current spread throughout the lake at this depth as eddies dispersed water upwards and downwards. Distribution of dye to all portions of the lake occurred after approximately 40 hours continual aeration, during which time 23% of the lake's volume had been pumped. Similar limnological changes were produced by continual and daylight-only aeration. Lake mixing during all tests did not produce homogeneity of parameters studied and was, therefore, considered to be of a lesser magnitude than mixing which had occurred during a previous lake overturn. The lake was not completely destratified, but possibly could have been by longer periods of aeration.

The thermal profile was altered in each test by warming the hypolimnion and cooling the epilimnion.

Dissolved oxygen changes were inconsistent and not of a magnitude to increase lake space available to fish. Oxidation of reduced materials and some reduction of BOD probably occurred, thus producing at least a temporary improvement of water quality.

Changes in pH and carbon dioxide which occurred during these tests did not follow a definite pattern. Alkalinity changes were not attributed to aeration-mixing. No improvement of fish habitat was attributed to changes in these factors.

Algal density reduction, although temporary, is possibly the most important improvement in fish habitat that occurred as a result of aeration-mixing. This conclusion was based on field observations. Time and personnel available for this project did not permit quantitative analyses of algal population changes.

Stratification became more defined within one week following each aeration test and most parameters that had been altered returned to their pre-aeration status. Water temperatures below the 20-ft. depth remained essentially the same and temperatures increased above that depth. The rate of restratification is dependent on weather conditions.

Summer fish kills did not occur during the testing period. It cannot be concluded that aeration-mixing prevented fish kills. This may be suggested, however, because some conditions which attributed to a previous fish kill, high surface temperatures and dense algal blooms, were modified by this technique.

The compressor and aeration units functioned properly throughout the tests. Harmful deterioration did not occur in any aeration equipment submerged in water.

Conclusions drawn from this research are:

1. Dye distribution indicated Stockade Lake was mixed by aerating in the deepest portion of the lake.
2. Cold, bottom water was brought to the surface by rising air bubbles and then flowed a short distance on the surface in a radial-horizontal direction before sinking to some intermediate depth. The main current traveled at this depth throughout the lake, as eddies dispersed water to the surface and bottom.
3. Mixing and consequent alteration of the thermal profile was accomplished by continual or daylight aeration.
4. Mixing usually caused a decrease in epilimnetic temperatures and an increase in hypolimnetic temperatures.
5. Daylight aeration did not produce epilimnetic cooling during hot weather and may have resulted in temperatures approaching the maximum limit tolerated by trout if continued.
6. Dissolved oxygen concentrations in deeper portions of the lake were not increased to levels sufficient to support fish life.
7. Reduction or dispersal of dense algal blooms occurred during aeration-mixing.
8. Stratification returned to pre-aeration intensity within several days after aeration was terminated. The restratification rate depended on weather conditions.

9. Aeration may be applicable as a fishery management tool in thermally stratified lakes, however, the magnitude of limnological changes caused by aeration depends on factors, i.e., lake size, air temperature, biochemical oxygen demand and pumping capacity of aeration equipment.
10. Periodical monitoring of limnological parameters during aeration may be helpful in detecting changes which would be harmful to fish.

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