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PHYSICOCHEMICAL AND BIOLOGICAL CONDITIONS IN TWO OKLAHOMA RESERVOIRS UNDERGOING ARTIFICIAL DESTRATIFICATION

Prepared for the Bureau of Reclamation's
Reaeration Research Program
by the Oklahoma Water Resources Research Institute
Oklahoma State University, Stillwater

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16. ABSTRACT
The purpose of this study was to develop more efficient methods of reservoir reaeration and to determine the environmental effects of reservoir destratification. The Garton pump, a low energy, axial flow device, is designed to pump water from the surface downward to destratify and reaerate lakes and reservoirs. A 1.07-m-diameter version of the device was tested in Ham's Lake (40 ha surface area, 10 m maximum depth) near Stillwater, Okla., in 1973 and 1974, and a 1.83-m-diameter version was operated in 1975. Complete thermal destratification was obtained. A 5-m-diameter version of the Garton Pump was operated in Lake of the Arbuckles (951 ha surface area, 27 m maximum depth) near Sulphur, Okla., in 1974 and 1975. Improvements in the design resulted in substantial perturbation of physicochemical conditions of Lake of the Arbuckles in 1975. This report describes vertical variations in the two reservoirs of: (1) temperature, dissolved oxygen, and several other physicochemical parameters; (2) species composition and density of the algae populations; (3) species composition and diversity of zooplankton; (4) species composition, diversity, and density of benthic macroinvertebrates; and (5) vertical (bathymetric) distribution and growth of fish. The report also includes recommendations for further research.

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ACKNOWLEDGMENTS

This study describes observations of physicochemical data and biological conditions in two Oklahoma reservoirs from 1972 through 1975. The research was coordinated by Mr. Howard Jarrell, Associate Director of the Oklahoma Water Resources Research Institute, with research support from the Bureau of Reclamation, the Office of Water Research and Technology, the Oklahoma Water Resources Research Institute (Projects A-028, A-044, A-048, A-049, A-050, A-052, A-059, and C-5228), and from the Fish and Wildlife Service. The following principal investigators (listed first) and major personnel participated in the various phases of the study.

Pump development: James E. Garton

Dissolved oxygen, temperature, and conductivity: All groups

Other aspects of water chemistry: Dale W. Toetz, David Bowman, Brian Cole, Hong Chau, J. Fred Heitman, Glen Hoecker, Michael Scott, Tracy McCracken, Joel Shelton, Elaine Stebler, and May Yue

Algae: Dale W. Toetz, James Cooper, and Steven Halterman

Zooplankton and benthic macroinvertebrates: Jerry Wilhm, Carl Ferraris, Susan Durham, Nancy McClintock, and John Parrish

Fish: Robert C. Summerfelt and Glen Gebhart on Lake of the Arbuckles; Dale W. Toetz and J. Fred Heitman on Ham's Lake.

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INTRODUCTION

Many lakes and reservoirs stratify during summer, which may result in anoxic conditions in the hypolimnion (Hutchinson [1])[1]. Oxygen depletion in the hypolimnion creates reducing conditions and anaerobic bacterial respiration. Manganese and iron go into solution and reduced forms of nitrogen and sulfur accumulate as ammonia and sulfide, respectively. Increased expense of water treatment often results. The concentration of dissolved hydrocarbons increases, which may result in increased levels of chlorinated hydrocarbons (EPA [2]). These substances pass through filtration plants and some of them have been shown to be carcinogenic. Hypolimnetic depletion of D.O. (dissolved oxygen) may also lead to undesirable tastes and odors of the water. Anoxic conditions and the increase of certain chemicals in the hypolimnion of stratified lakes influence distribution and density of the biota and may result in fishkills.

Artificial mixing of lakes has been attempted to improve water quality and extend the vertical (bathymetric) distribution of the biota in stratified lakes. A number of studies have shown an increase of D.O. (Hooper et al. [3], Bryan [4], Hedman and Tyley [5], Irwin et al. [6], Leach and Harlin [7], Lackey [8], Malueg et al. [9], Haynes [10]). Decreases in the concentration of manganese and iron (Haynes [10], Wirth and Dunst [11]), ammonia (Leach and Harlin [7], Haynes [10], Symons et al. [12], Brezonik et al. [13]), and hydrogen sulfide (Irwin et al. [6], Leach and Harlin [7]) have been observed in the hypolimnion after artificial destratification. Changes in the biota that have been observed in artificially destratified lakes include a decrease in the biomass of blue-green algae (Malueg et al. [9], AWWA [14]) and an increase in green algae and flagellates (Robinson et al. [15]), an extension of the vertical distribution of zooplankton (Fast [16]), an invasion of the profundal zone by benthic macroinvertebrates (Calif. Dept. of Fish and Game [17]), and extension of the vertical distribution of trout (Fast [16]). In contrast, other artificial destratification studies showed little or no effects in such factors as numbers of algae species (Robinson et al. [15]) and vertical distribution patterns of zooplankton and macroinvertebrates (Lackey [8]) demonstrating the necessity of obtaining additional information. Toetz et al. [18] described the biological effects of artificial destratification in lakes.

Lakes have been destratified by mechanical pumping (Hooper et al. [3], Irwin et al. [6], Flick [19], Steichen [20]) or by using compressed air (Riddick [21], Meyer [22], Ford [23], Fast [24], Laverty and Nielson [25]). Descriptions of various pumping devices were presented by King [26] and by Toetz et al. [18].

Prior to 1971, reservoirs were generally destratified by bubbling air or pumping water from the bottom to the top. Because equipment was not available to pump the oxygen-rich surface waters to the bottom of the lake, in 1971, Garton and Quintero [66, 67] designed a downflow mechanical pump for reservoir aeration. The pump consisted of a 1.07-m crop drying fan with a rounded entrance, a cylindrical throat, and a fabric diffuser. The diffuser increased the amount of water pumped at a given power level by about 32 percent.

During the summer of 1972, the pump, hereinafter called the Garton pump, was installed in Ham's Lake, a 40-ha flood detention reservoir about 9.5 m deep (see Description of Lake). Some preliminary tests were conducted for 5 weeks and the lake was thermally destratified; however, oxygen distribution was not uniform. The pump was then turned off at the request of the operator of a caged catfish "farm" in the lake and remained off for 6 weeks. The lake then restratified and developed an anoxic hypolimnion. The lake turned over after a week of cool, cloudy weather, resulting in the death of 150 000 catfish. The pump operated for another month to oxidize the heavy organic load on the bottom of the lake.

During 1973, further pump improvements were made and Ham's Lake was again destratified. Ham's Lake was prevented from stratifying during 1974 by a Garton pump. Pumping operations lasted from May 13 to September 26. Biological studies were initiated in the two reservoirs in 1974 with support furnished by the Bureau of Reclamation and the Oklahoma Water Resources Research Institute. In 1973, it was anticipated that the Garton pump could be enlarged to keep a larger lake

[1] Numbers in brackets refer to items in the Bibliography.

continually destratified. Bureau personnel met with representatives of the Oklahoma Water Resources Research Institute to consider testing the pump in Lake of the Arbuckles, which has about 24 times the surface area, 75 times the volume, and 2.5 times the depth of Ham's Lake. Arbuckle Lake stratifies early in May and by late June, about 42 percent of the volume contains less than 2 mg/l of D.O. A grant from the Office of Water Research and Technology enabled testing a 5-m-diameter pump on the Lake of the Arbuckles. The pump was tested in 1974 from July 17 to September; however, several mechanical problems developed. Although the lake was not destratified, its thermal stability was reduced.

Prior to the summer of 1975, a 1.83-m, 746-watt prototype pump was designed and constructed for Ham's Lake. This improved version had about 2.25 times the pumping rate of the previous 1.07-m pumps.

The device on Lake of the Arbuckles was removed, the blade angle changed from 10 to 6.5°, and the speed increased to 20 r/min.

The devices were installed in the lakes in 1975 after the impoundments had stratified. Pumping duration was from June 19 to October 10 in Ham's Lake and from June 2 to September 13 in Lake of the Arbuckles. Biological sampling intensified during the summer of 1975.

The objective of this report is to describe vertical variations in the following characteristics in the two reservoirs undergoing destratification efforts: (1) temperature, dissolved oxygen, and several other physicochemical variables; (2) species composition and density of the algae populations; (3) species composition and diversity of zooplankton; (4) species composition, diversity, and density of benthic macroinvertebrates; and (5) vertical (bathymetric) distribution and growth of fish.

SUMMARY AND CONCLUSIONS

The Garton pump offers a simple, inexpensive, low energy method of improving water quality and of altering the thermal regime of lakes and their outflow waters. In 4 years' research on Ham's Lake (40 ha), the Garton pump, a large diameter, high capacity, axial flow pump of low velocity and low energy requirements, was used to alternately destratify or prevent the occurrence of summer stratification. For 2 years, the thermal regime of Lake of the Arbuckles (951 ha) was altered so that the fall turnover occurred about 1 month earlier than in previous years. This turnover occurred without visible oxygen stress on the fish. The reoxygenation of the previously anaerobic depths of Lake of the Arbuckles occurred in only 2 or 3 days after the turnover and the total oxygen content of the lake doubled within 72 hours. Use of the pump significantly increased the total heat content of both lakes.

Concern has been expressed that destratification efforts might cause a temporary reduction of D.O. to the point that oxygen stress or even mortality of fish could occur. It is the consensus of the authors that fish mortality during destratification is a hazard only under conditions of high algal biomass coupled with low light intensity, calm winds, and high BOD (biochemical oxygen demand) loading in a lake having a high ratio of volume to surface area. Lakes exhibiting these characteristics probably should be prevented from stratifying by continuous pumping from spring on through the summer rather than destratified at midsummer.

A predictive scale capable of determining the precise minimum pumping rate required to destratify a large lake has not yet been developed. Destratification of Ham's Lake occurred in approximately 14 days in 1973 with a 1.07-m pump of 373 watts which pumped about 0.76 m^3/s, but in 1975, destratification was achieved in 4 days using a 1.83-m pump of 746 watts which moved 1.7 m^3/s of water. Using a 5-m pump of 5.6 kW and approximately 13 m^3/s capacity, Lake of the Arbuckles was not completely destratified. Arbuckle has approximately 75 times the volume and 25 times the surface of Ham's Lake, while the pump used at Lake of the Arbuckles has less than 7 times the capacity of the Ham's Lake pump. A 38-m^3/s, 18.7-kW pump is now being developed and will be tested at Lake of the Arbuckles in the summer of 1977.

The average volume of Lake of the Arbuckles containing more than 2 mg/l D.O. in a 163-day interval from May 11 to October 20 was 72.9 percent in 1973, 82.7 percent in 1974, and 72.6 percent in 1975. In both 1974 and 1975, temperature differential from top to bottom was reduced and the temperature of the hypolimnion was increased. Compared with 1968-69 and 1973, Lake of the Arbuckles was more nearly orthograde with respect to D.O. and temperature in September 1974 and 1975, which indicates that the operation of the Garton pump substantially influenced physicochemical profiles.

Artificial mixing of Ham's Lake for three successive summers following the enrichment with catfish feed is apparently returning the lake to a less eutrophic state. Bloom-forming obnoxious algae were low in density while mixing was practiced. The BOD, ammonia, iron, manganese, and other reduced compounds were decreased to nominal values after mixing. At Lake of the Arbuckles, although the thermocline was either weak or absent and the temperature differential from top to bottom was only 2 to 3 °C, complete chemical uniformity did not occur until mixing of the lake in the late summer turnover.

Benthic organisms were not observed to rapidly reinvade areas from which they had been excluded because of anaerobiosis, but when summer stratification was prevented they have been observed to thrive at depths previously barren. The assemblage of benthic macroinvertebrates in both reservoirs generally was composed of a few common species and many rare species in the shallow depths, and of a few abundant species in the deeper waters. In Ham's Lake, the midge *Procladius* sp. was the most common macroinvertebrate collected at the shallow depths in the summer of 1974, while the annelid *Dero digitata* was generally the most common throughout the 1975 sampling program. Although no single species was consistently common in the shallow depths of Lake of the Arbuckles, a number of taxa were abundant during one or more time periods. The phantom midge *Chaoborus punctipennis* was generally abundant in the deeper waters of both reservoirs. The annelid *Aulodrilus pigueti* was often common in the deeper waters of Lake of the Arbuckles.

Total number of species of benthic macroinvertebrates generally decreased with depth in both reservoirs. The most abrupt decrease generally occurred between 1 and 2 m in Ham's Lake and at deeper depths in Lake of the Arbuckles. Numbers of species generally increased slightly during summer 1975 in Ham's Lake and decreased in Lake of the Arbuckles. Density of benthic macroinvertebrates was slightly greater in Lake of the Arbuckles than in Ham's Lake. No consistent pattern was noted between depth and density in either reservoir. Macroinvertebrate species diversity decreased with depth in both reservoirs. Diversity in Ham's Lake was extremely low at the bottom three depths in June 1975 prior to starting the pump and increased during the summer following pumping. No significant change in diversity was observed in Lake of the Arbuckles following pumping. Diversity of benthic macroinvertebrates provided a reasonable indicator of the limiting environment of deeper areas.

Density or diversity was not consistently related to depth in either reservoir, nor did these variables reflect the severe oxygen limitations of deeper waters in summer.

Fish rapidly invaded previously anoxic depths in Ham's Lake after lake mixing began. The growth of largemouth bass was below average compared to the state average before and during lake mixing.

In Lake of the Arbuckles, using 2-mg/l D.O. isopleth as a boundary defining the limit of suitable fish habitat, more habitat was available in 1974 than in 1973 and 1975. Operation of a compressed-air gun for 83 days, July 10 to October 10, 1973, did not disrupt stratification, and its effects were limited and very localized. Stratification in 1973 was pronounced and by midsummer (July 20) as much as 48 percent of the total volume of Lake of the Arbuckles was unsuitable for habitation by fish. In 1974, Garton's pump ran for 46 days (July 17 to August 31); not more than 39 percent of the volume of the lake contained less than 2 mg/l D.O. In 1975, the pump ran for 104 days (June 2 to September 12), and as much as 59 percent of the volume contained less than 2 mg/l D.O. The 2 mg/l isopleth moved progressively closer to the surface. Gill net catches indicated a decline in abundance of gizzard shad during 1973 through 1975 (49.98 to 17.43 percent), which coincided with an increase in abundance of white bass (3.15 to 9.4 percent), but no major change in species composition could be attributed to perturbations from efforts to destratify the reservoir. Vertical (bathymetric) distributions of gizzard shad, white crappie, freshwater drum, black bullhead, and channel catfish were influenced by physicochemical conditions of lake stratification. The MDC (mean depth of capture) of all species was substantially greater in September and October collections when the depth of the 2-mg/l D.O. isopleth deepened. In many age groups for most species, instantaneous growth rates indicated that the major portion of the growth occurred during the destratified period. In fact, the growth rate was negative for many age groups during the stratified summer period. Instantaneous growth rates were larger for most age groups of most species in the summer of 1974 than the summers of 1973 and 1975. Lowest summer growth rates for most age groups of most species studied occurred in the summer of 1975. Stratification had a negative impact on fish growth, but mechanical pumping which maintains D.O. above 2 mg/l near the bottom during the entire summer may enhance fish growth.

APPLICATION

The results of this study will be of interest to anyone involved in the subject of reservoir reaeration. Both engineers and biologists will find the results presented in this report helpful in evaluating this downflow mechanical pump and for insight on environmental effects of reservoir destratification. The results will be of particular use to those responsible for managing the water quality and fishery of Lake of the Arbuckles, Okla.

HAM'S LAKE

Description of the Lake

Ham's Lake is located in sec. 22, T. 19 N., R. 1 E., Payne County, latitude 36° N., longitude 97° W., 9.6 km west of Stillwater, Okla. (fig. 1). The dam impounds Harrington Creek, a tributary of Stillwater Creek which is a tributary to the Cimarron River. The Lake was constructed by the Soil Conservation Service, U.S. Department of Agriculture, under Public Law 566, the Upstream Flood Prevention program. It was completed in 1965 and first reached normal pool level in the spring of 1967. The surface area of the lake at the elevation of the principal spillway (287.1 m above sea level) is 40.0 ha (table 1). The area of Ham's Lake is only 4.2 percent of Lake of the Arbuckles, but most relative morphometric features of Ham's Lake are similar to those of Lake of the Arbuckles. The ratio of the surface area to its drainage basin is 1 to 37 for Ham's Lake and 1 to 34 for Lake of the Arbuckles.

The shoreline D_L (development index) is 5.0 for Ham's and 5.3 for Lake of the Arbuckles, which indicates that both lakes have similar potential for development of littoral communities in proportion to area of the lake. The two indices of depth (z_r and $\overline{z}/z_m$) indicate that Ham's Lake has a substantially larger relative depth for its size than Lake of the Arbuckles.

Although relatively shallow with an average depth of 2.9 m (fig. 2), Ham's Lake thermally stratifies naturally from May through October (Steichen [20]). By midsummer 1973, the epilimnion was about 4 m deep and was near saturation with D.O. Most of the lake's basin is above the thermocline since average depth is only 2.9 m. The thermocline extended from 4 m to the bottom. Although there was no hypolimnion, as such, D.O. depleted rapidly through the thermocline. Below 4 m, the D.O. was often zero.

Ham's Lake was used for a caged catfish farming operation during 1971 and 1972. During this time large quantities of organic matter were added to the lake in the form of uneaten feed and catfish feces. The catfish farming operation was terminated by a catastrophic fishkill during August 1972, when about 150 000 channel catfish (about 0.5 to 1.0 kg each) died at the end of a week of cloudy, cool weather. Steichen [20] reports that the reason for the fishkill was a sudden overturn. Dissolved oxygen was nearly zero throughout the water column, and ammonia and hydrogen sulfide were mixed throughout the water column. Apparently no catfish or other fish at large in the lake died from the overturn.

Pump Design and Performance

The destratifier unit used in 1975 consisted of an electric motor, a right-angle gear reducer, a floating platform, a propeller, and an orifice shroud (fig. 3).

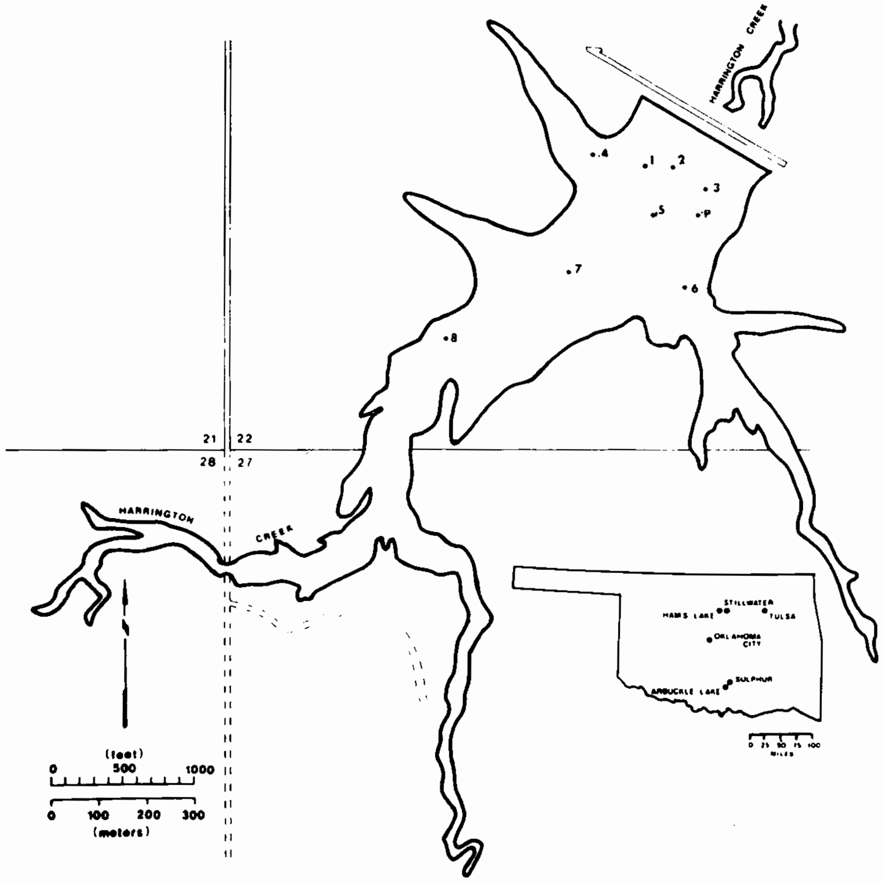

Figure 1.–Ham's Lake sampling stations and a vicinity map of Oklahoma showing Lake of the Arbuckles and Ham's Lake in relation to major cities.

Table 1.—*Comparative morphometric features of Ham's and Arbuckle Lakes*

Morphometric characteristic	Ham's Lake	Lake of the Arbuckles
Area (ha) (A_o)	40.0	951.0
Volume (m^3)	1.15×10^6	89.3×10^6
Mean depth (m) ($\bar{Z}$)	2.9	9.4
Maximum depth (m) (Z_m)	10.0	27.4
Maximum length (m)	1 153.8	11 000.0
Watershed area (drainage) (km^2)	14.7	326.0
Shoreline length (m)	11 294.0	58 232.0
Shoreline development (D_L)	5.0	5.3
Mean pool elevation (m, mean sea level)	287.1	265.8
Lake area:watershed area	1:37	1:34
Relative depth (Z_r)	1.4	0.8
Relative depth ($\bar{Z}/Z_m$)	0.29	0.34

$D_L = \dfrac{L}{2\sqrt{\pi A_o}}$, where L = length of shoreline

$Z_r = \dfrac{88.6 \times Z_m}{A}$, where A = surface area of lake

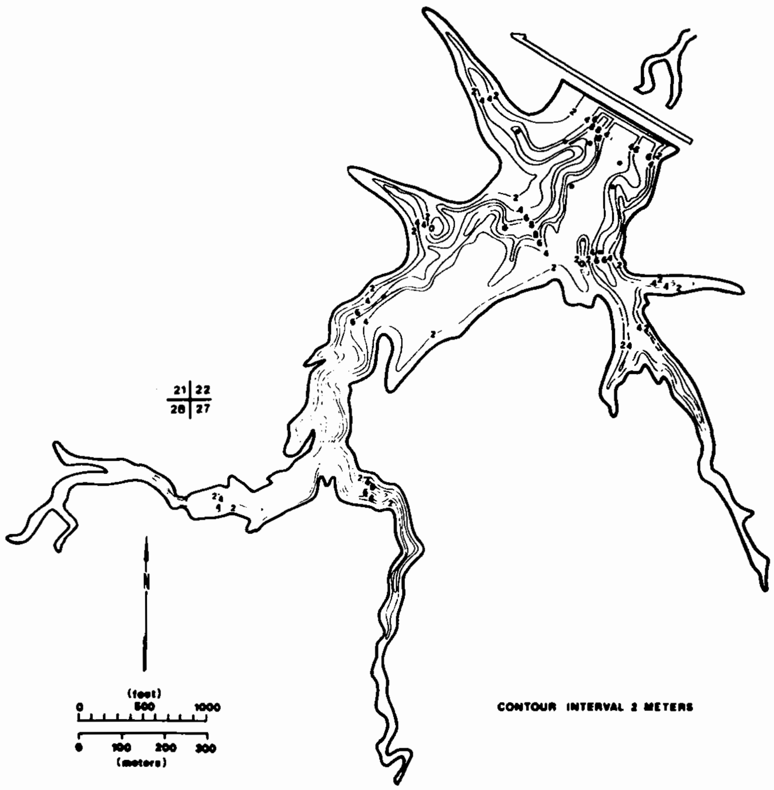

Figure 2.–Bathymetric map of Ham's Lake.

Figure 3.–General view of destratifier unit.

Keeping in mind the initial limitation, which is a maximum power requirement of 746 watts, a DCH72 Acme Windmaster fan and orifice shroud were purchased.

The six-bladed propeller had a diameter of 1.83 m and the chord angle ranged from about 60° at the hub to about 25° at the tip. The shroud was 2 m^2 and had an orifice diameter of 1.85 m.

Performance of the propeller in water was obtained by use of the fan laws and the manufacturer's stated performance in air. A raft made of redwood expanded-foam sandwich, 2 m^2, supported the pump on the lake. The raft had a flotation capacity of about 1730 kg and was held in place by anchors connected to each corner. A 120/240-volt electrical power supply was brought from shore by an underwater cable.

A more detailed description of the mechanical equipment and its design is given by Strecker [27].

Plots of temperature, D.O., and BOD_5 (5-day biochemical oxygen demand) for 1973 and 1974 are shown elsewhere (Steichen [20]) along with the data collected in 1975 to indicate the effects of the higher flow rate pump used in 1975. The pump used in 1973 and 1974 produced a flow of 0.65 m^3/s. In 1975, a new pump was designed which had a calculated flow rate of 1.58 m^3/s.

Figure 4 illustrates the temperature changes that occurred during 1973, 1974, and 1975. On June 18, the day before pumping began, there was a 10.1 °C temperature difference between the surface and the bottom. Warming of the hypolimnion waters was at an exponential rate. The coolest water at 9 m warmed at the fastest rate. After 4 days of pumping, the surface to bottom temperature difference had been reduced to 1.2 °C and the 9-m water temperature had increased 8.5 °C. The entire body of water continued warming after pumping began amd remained between 27 and 29 °C until early September. The higher flow rate pump used in 1975 destratified the lake faster and maintained a slightly lower temperature difference in the water column than pumps used in 1973 and 1974.

Since thermal destratification requires eliminating the thermocline, a plot of the density profiles (fig. 5) illustrates the effectiveness of the pump. The day before pumping started, a thermocline existed between the 4- and 7-m depths. After 1 day of pump operation, the thermocline rose to between the 1- and 2-m depths, and by the fourth day it had completely disappeared.

The surface temperature for the reservoir over the past 4 years is plotted on figure 6. The dashed line indicates when the pump was operating. These data do not indicate the cooling of the surface water occurred during destratification. Destratification was achieved by warming the bottom water in the reservoir.

The changes in D.O. were even more pronounced (fig. 7). The day before pumping began in 1975, the water below 5 m had been depleted of oxygen and the water above 4 m had in excess of 8 mg/*l*. After 1 day of pumping, the D.O. at 5 m had increased to 3.3 mg/*l* and increased at 9 m to 1.9 mg/*l*; D.O. at 3 and 4 m had been reduced to 4 mg/*l* and the water above 3 m was slightly reduced. On June 23, the first day the temperature profile was entirely uniform, D.O. ranged from 7.2 mg/*l* at the surface to 2.9 mg/*l* at the bottom. Dissolved oxygen continued to decrease in the upper waters as the D.O. increased in the lower waters until July 14, when the concentration of D.O. in the entire profile was between 5 and 6 mg/*l*. In early August, the D.O. fell briefly to 4.6 mg/*l* at 1 m and 2.5 mg/*l* at 9 m. Except for this short period, D.O. was maintained above 3 mg/*l* in the entire water column.

The pump used in 1975 pumped at a higher rate and maintained a higher D.O. level in the reservoir than the pump used in 1973 and 1974.

Physicochemical Conditions and Algae

Objectives.–The objectives of this part of the research were to describe the effects of lake mixing on water chemistry and on the abundance and taxa of algae and the biomass of chlorophyll *a*. Data on pH, alkalinity, and algal density existed before and after the outset of artificial mixing during 1973 (Steichen [20]). Additional biological and chemical parameters were monitored at Steichen's station in the deepest part of the basin, and algal density and biomass at other stations.

Methods–Sampling.–Five sampling stations (2, 4, 6, 7, and 8) were established (fig. 1). Chemical parameters were measured at station 2, which was at maximum depth near the dam. Chemical and pigment samples were taken at the surface, 5 m, and 9 m at station 2 during July and August 1974 (table 2). Temperature and D.O. were obtained at 1-m intervals using a telethermometer thermistor and galvanic oxygen probe and meter. Algae samples at each station were obtained by lowering a rubber hose 3 m below the surface, constricting the top end, and emptying the contents into a bucket. Aliquots of the same column taken at each station were pooled to obtain composite samples for the lake. This sampling program was not an effort to describe the flora during 1974, but an attempt to learn how to sample the lake reliably for the 1975 field season.

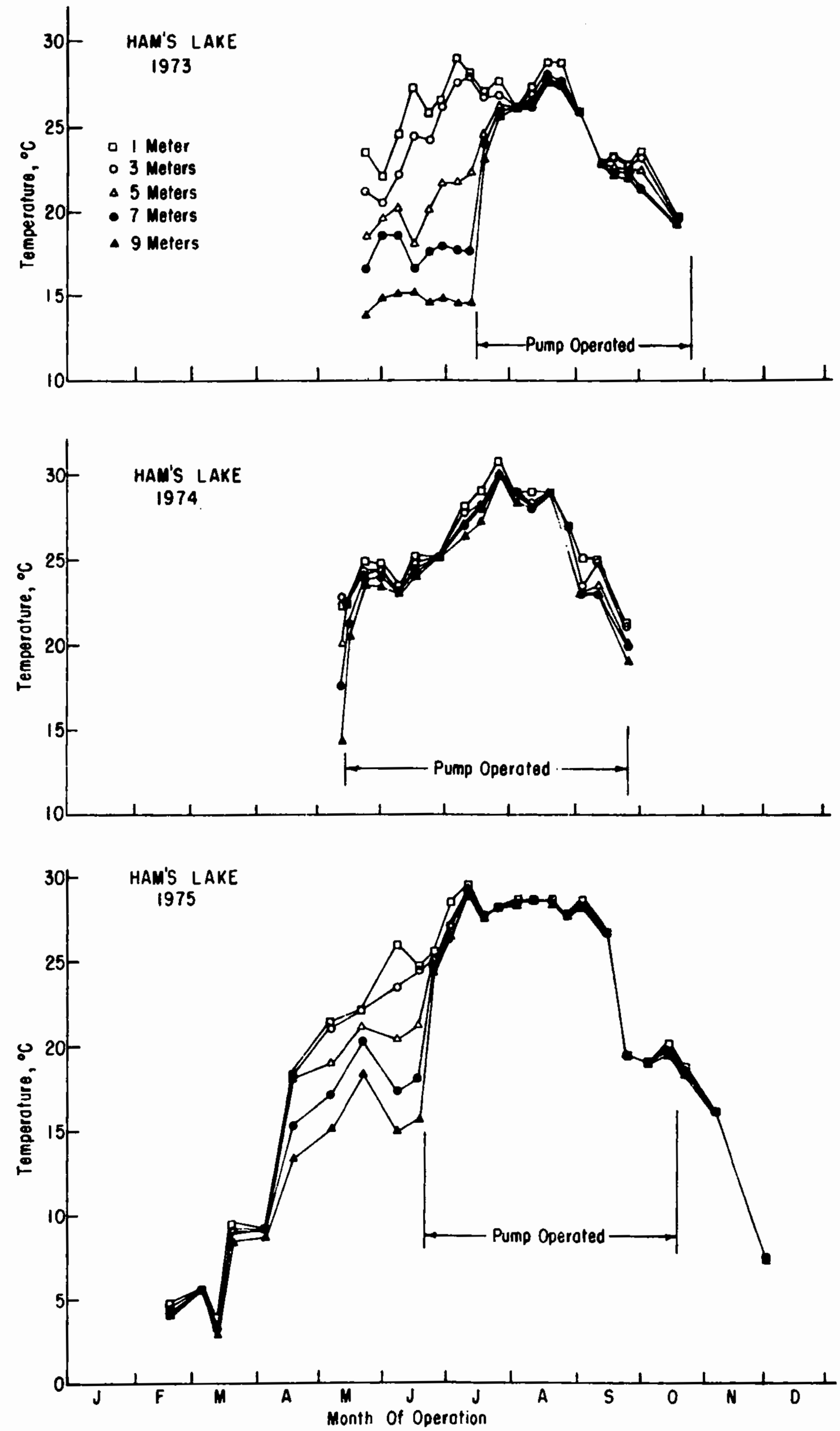

Figure 4.–Temperature versus time for Ham's Lake during 1973, 1974, and 1975.

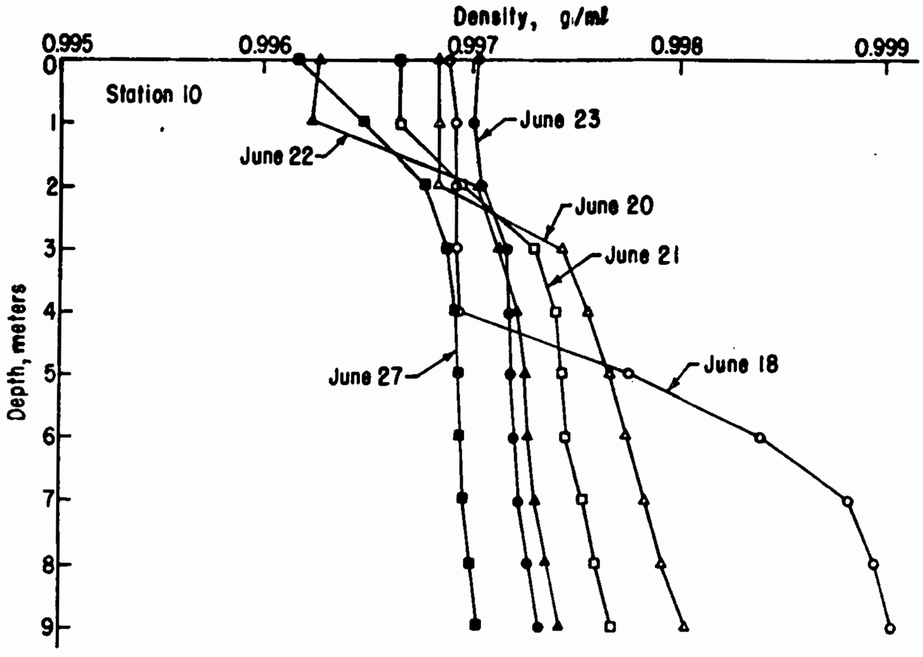

Figure 5.–Density profiles during first week of pumping (1975).

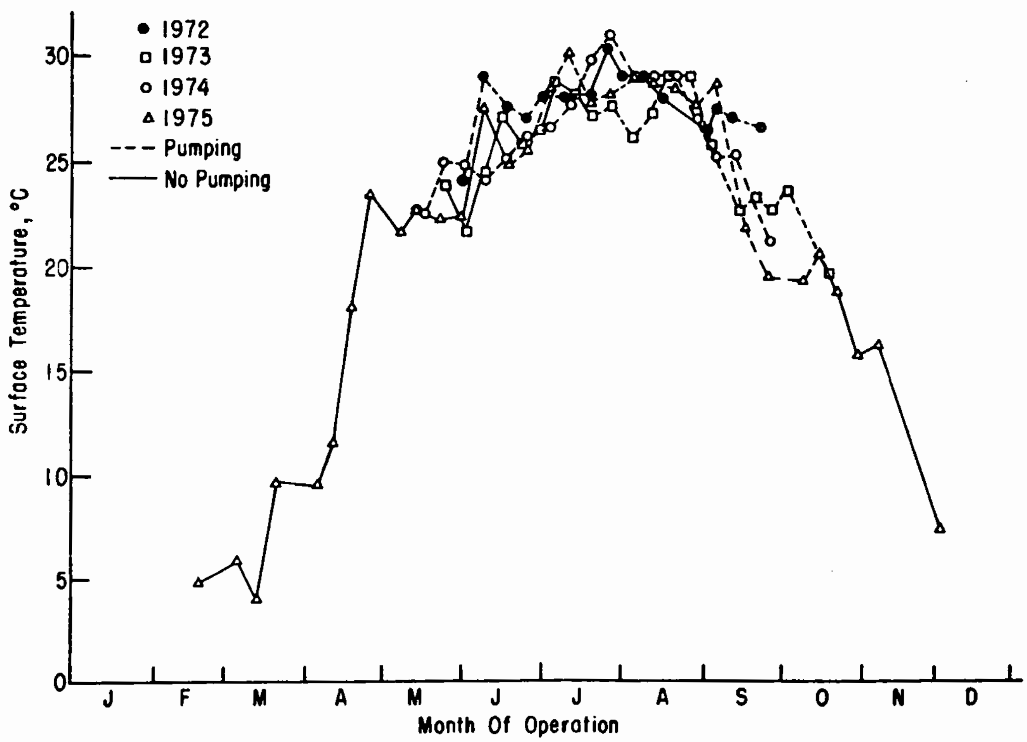

Figure 6.–Surface temperature versus time for Ham's Lake from 1972 to 1975.

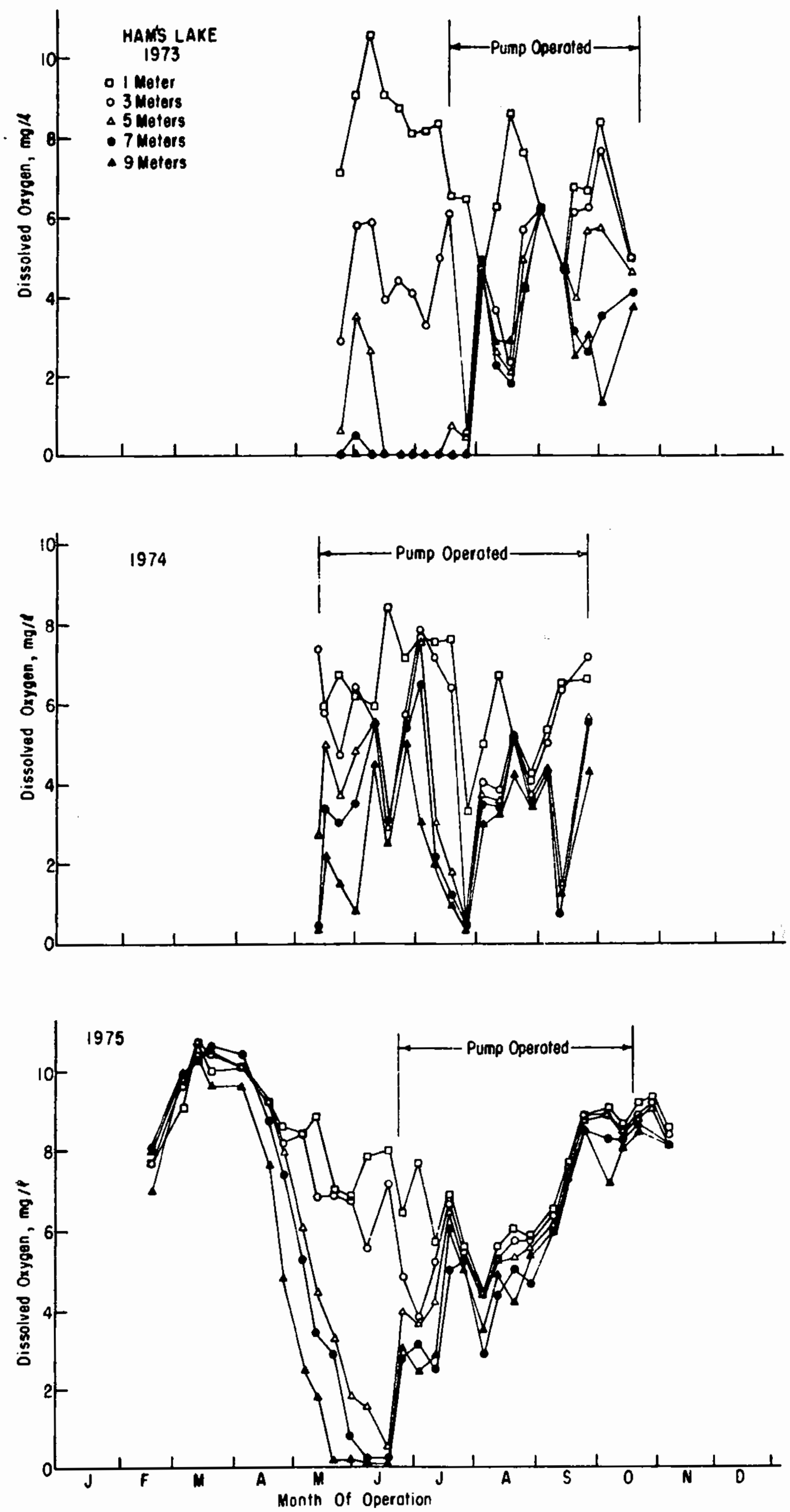

Figure 7.–D.O. versus time for Ham's Lake during 1973, 1974, and 1975.

Table 2.—*Selected water quality parameters at Ham's Lake during 1974 at station 2*

Depth	Total alkalinity		Particulate carbon		Dissolved organic carbon		Sulfide-sulphur	
	mg/ℓ		mg/ℓ		mg/ℓ		μg/ℓ	
	7/15/74	8/13/74	7/15/74	8/13/74	7/15/74	8/13/74	7/15/74	8/13/74
surface	184	124	1.88	0.73	36.6	30.6	5.8	*
5 m	186	124	1.87	0.80	26.8	36.3	13.1	*
9 m	186	120	1.80	0.87	29.2	48.8	14.0	*
	Phosphate-P		Nitrate-N		Nitrite-N		Ammonia-N	
	μg/ℓ		μg/ℓ		μg/ℓ		μg/ℓ	
	7/10/74	8/13/74	7/10/74	8/13/74	7/10/74	8/13/74	7/10/74	8/13/74
surface	*	7.83	8.39	20.19	0.54	3.70	3.12	0.32
5 m	*	4.96	7.52	15.76	0.58	4.90	7.03	4.16
9 m	*	26.62	29.71	24.87	*	4.90	13.27	6.08

* = not detected

During 1975, samples were obtained routinely between May and September every fourth day. Chemical parameters were obtained at station 2 at the surface, 4 m, and 8 m. Every 3 days phosphate, alkalinity, and pH were measured. Other chemical parameters were sampled about every other week.

Duplicate subsamples were obtained for pigments at each station with the rubber hose technique described above. Secchi disk depth was also obtained at each station as well as a sample of algae. Algae samples were obtained and handled as in 1974.

Temperature and D.O. were also obtained as above at 1-m intervals; however, supplemental D.O. data using the Winkler method were obtained to check the accuracy of the probe and meter. Lake level was measured with a permanent staff gage. Laboratory methods used for Ham's Lake samples were also used for Lake of the Arbuckles samples with some differences described below.

Results–Nutrients and phytoplankton, 1974.–Limnological data were obtained during July and August when the lake was being circulated continuously. Usually the lake was not thermally stratified, but below 5-m depth D.O. was often low (fig. 7). There were somewhat higher concentrations of reduced substances (ammonia, phosphate, and sulfide) at 9 m than at 5 m, indicative of stratified conditions (table 2). However, the reducing conditions were not extreme.

The data on algae (table 3) did not reveal high densities of *Dactylococcopsis*, a blue-green alga, as Steichen [20] described for the period when the lake was being mixed during 1973. It is likely that *Ankistrodesmus*, a green alga, was mistakenly identified as *Dactylococcopsis*. The composition of the algal flora was similar in both 1973 and 1974.

A total of 47 species of algae were identified. Diatom species were most numerous and flagellate species least numerous (table 3). A blue-green alga, *Anabaena*, was always encountered. The 1974 data were too sparse to describe seasonal changes in abundance of algae, but the algal flora was dominated by shade-tolerant diatoms and motile flagellates. No perceptible elimination of blue-green algae or flowering of green algae occurred, although the density of *Anabaena* was higher after the pump was shut down.

Nutrients and phytoplankton, 1975.–Ham's Lake was allowed to stratify normally during the spring of 1975. By May 20 the profile of D.O. was clinograde (fig. 8). The Garton pump was started on June 19; in a few days, the lake was completely mixed and remained so for the rest of the summer. However, the vertical profiles of D.O. suggest that the lake was more completely mixed on certain dates. Apparently, wind assisted the mixing process. When wind was absent, D.O. decrease occurred in deep waters.

Table 3.—*Mean density of algae as number of organisms/mℓ in samples from Ham's Lake during 1974*

	Date			
	7/18	7/28	8/13	10/17
Chlorophyta				
Coelastrum microporum	0.0	0.0	1.5	6.3
Cosmarium sp.	0.0	0.0	0.2	1.5
Closterium sp.	0.5	6.8	5.5	23.6
Kirchneriella	0.0	0.2	0.8	0.1
Pediastrum duplex	0.0	0.0	0.0	0.2
Pediastrum simplex	0.0	0.7	3.3	20.5
Scenedesmus sp.	0.0	1.0	0.8	3.2
Sphaerocystis sp.	0.0	0.0	0.2	0.0
Staurastrum sp.	0.0	0.2	0.6	1.3
Tetraedon sp.	0.0	0.2	0.9	0.0
Chrysophyta				
Achnanthes sp.	0.0	0.0	0.1	0.0
Amphipleura pellucida	0.2	0.5	0.5	0.1
Cocconeis placentula	0.0	0.2	0.6	1.0
Cyclotella Meneghiniana	6.1	11.7	58.5	23.2
Cymbella	0.5	0.0	0.6	4.3
Diploneis Smithii	0.2	0.2	0.8	0.5
Fragilaria crotonensis	0.0	0.0	0.0	0.1
Fragilaria sp.	0.0	0.2	0.1	0.0
Gomphonema angustata	0.0	0.2	0.6	0.9
Gomphonema olivaceum	0.0	0.2	0.6	0.9
Gomphonema parvulum	0.0	0.0	0.0	0.0
Gyrosigma scalproides	0.0	0.2	0.4	0.0
Melosira distans	2.5	1.0	8.2	16.5
Melosira granulata	3.0	2.2	9.0	26.7
Melosira varians	0.0	0.0	0.0	0.0
Meridion circulare	0.0	0.2	0.0	0.0
Navicula sp.	2.5	2.0	4.5	6.9
Nitzschia dissipata	0.2	1.0	1.6	1.5
Nitzschia sp.	0.0	0.0	0.2	0.0
Nitzschia sigmoidea	0.0	0.0	0.5	0.1
Nitzschia paradoxa	0.0	0.0	0.0	0.1
Nitzschia tryblionella	0.0	0.0	0.2	0.0
Pinnularia sp.	0.0	0.0	0.2	0.4
Stephanodiscus Hantzschii	0.0	0.0	3.2	0.5
Suriella ovata	0.0	0.0	0.1	0.0
Synedra ulna	0.2	0.0	1.8	3.2
Synura Adamsii	0.0	0.0	0.7	0.0
Cyanophyta				
Anabaena sp.	103.5	10.4	36.2	444.9
Dactylococcopsis	0.0	0.0	0.4	0.0
Merismopedia	0.0	0.2	0.2	0.0
Microcystis	0.0	0.0	0.4	0.0
Oscillatoria sp.	12.6	0.2	1.4	7.1
Spirulina sp.	0.0	0.0	0.1	0.0

Table 3.—*Mean density of algae as number of organisms/mℓ in samples from Ham's Lake during 1974—Continued*

	7/18	7/28	8/13	10/17
Euglenophyta				
Euglena sp.	11.1	11.7	9.4	25.7
Phacus sp.	0.0	0.0	0.5	0.8
Pyrrophyta				
Ceratium hirundinella	1.2	0.5	1.4	2.0
Glenodinium pulvisculus	0.0	0.0	0.4	0.0
Unknown				
u cells	16 112.8	5 185.0	0.0	0.0
Brown colonial spheres	19.5	18.8	44.2	6.1
Green colonial spheres	14.5	8.2	55.9	1.4

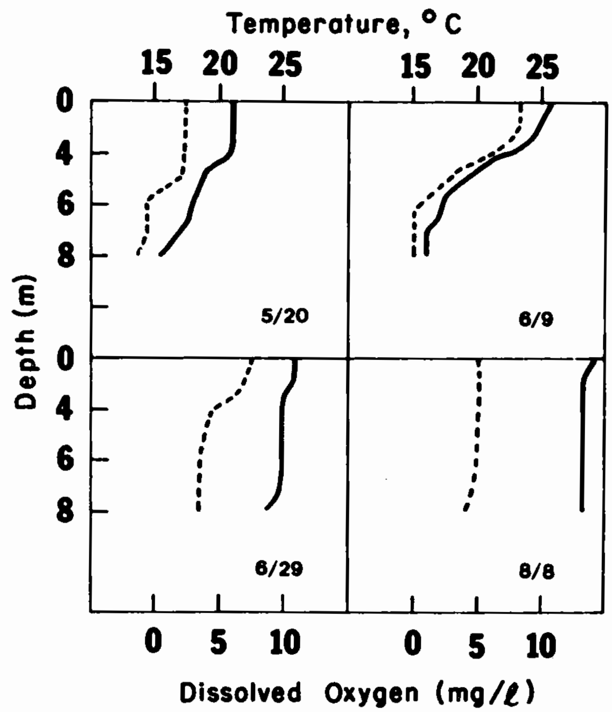

Figure 8.–Vertical distribution of temperature (solid line) and dissolved oxygen (broken line) on four dates at station 2 at Ham's Lake during 1975.

The horizontal extent of mixing was studied by comparing profiles of D.O. and temperature taken at the five stations. In general, the profiles at stations 6, 7, and 8 were similar to profiles at station 2, demonstrating that the lake was completely mixed (fig. 9). However, a comparison between stations 2 and 4 suggests that destratification did not occur at station 4. Vertical profiles of ammonia at station 4 also suggest that the lake was stratified at this point. It is likely that stratification at station 4 persisted because it is located over an old creek channel, isolated from the main body of the lake by a ridge (figs. 1 and 2).

During early May, Ham's Lake was turbid and the water level was high due to large muddy inflows from the watershed. Figure 10 shows a dramatic decrease in phosphate concentration as the lake cleared and a gradual increase in the concentration of chlorophyll *a*. By early June the standing crop of algae was probably maximum for the lake and phosphate was undetectable. Shortly after mixing began, there was an increase in chlorophyll *a* which may have resulted from an increase in algal density that occurred after an upwelling of nutrients. Nitrate and ammonia were usually greater than 0.05 mg/*l*, but phosphate was often undetectable. The small bloom lasted about 1 week and, thereafter, the concentration of chlorophyll *a* decreased to 5 to 10 mg/m³ during most of the summer.

The transparency of the water increased after mixing began (fig. 10), but then decreased during August. Unlike 1973, when the lake was also artifically mixed, surface waters were often found to have pH in excess of 8.5 and carbonate alkalinity. Artificial destratification usually decreases pH and eliminates carbonate alkalinity in the epilimnion. The most probable reason for

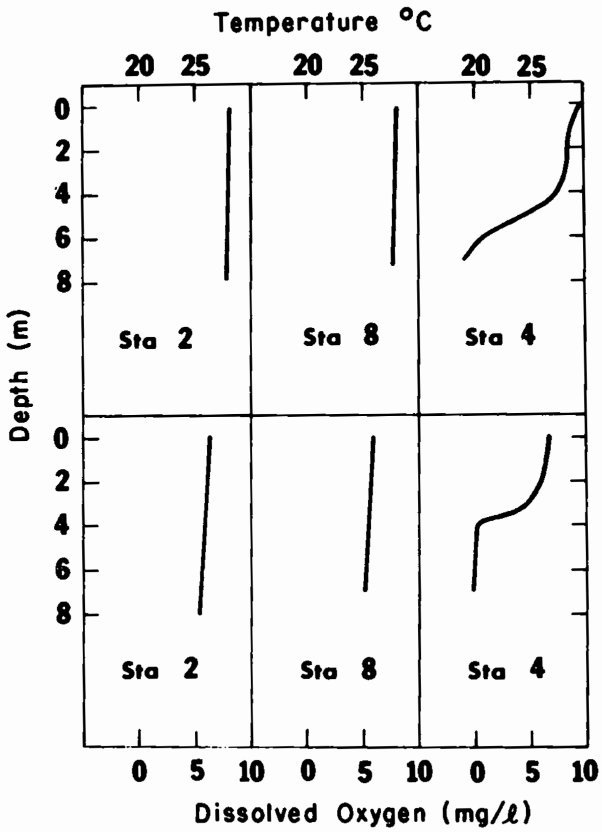

Figure 9.–Vertical distribution of temperature and dissolved oxygen at three stations at Ham's Lake on August 12, 1975.

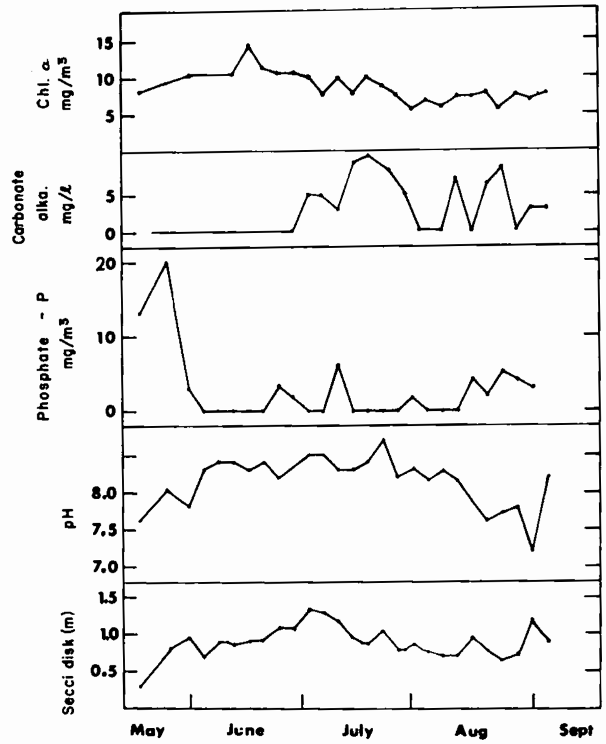

Figure 10.–Mean concentration of chlorophyll *a* in the euphotic zone, mean concentrations of carbonate and phosphate at the surface, mean pH at the surface, and mean Secchi disk transparency at five stations at Ham's Lake during 1975.

high pH and carbonate alkalinity is because of demand for carbon dioxide by the littoral hydrophytes, which were not abundant before June. High turbidity probably reduced their growth until late June. After June 13, SDT (Secchi disk transparency) ranged from 0.64 to 1.18 m. A submersible photometer was used to expand SDT to the CP (compensation point). In general, SDT times 2.5 equaled CP. Therefore, the CP in Ham's Lake ranged from 1.60 to 2.95 m after mixing began.

During 1975, the algal flora was similar to that observed during 1974. There was a relatively large population of blue-green algae at the outset of mixing in June, which increased after mixing began, only to decrease shortly thereafter to moderate densities (table 4). *Aphanizomenon* was the dominant blue-green alga in a small bloom that occurred after mixing began.

The density of the dominant species of phytoplankton increased markedly during early June, as the lake began to clear (table 4). The fact that the density of the dominant blue-green algae rose and declined in phase with other species argues against a cause and effect relationship between mixing and elimination of blue-green algae. During the period of lake mixing, blue-green algae were not a nuisance.

Apparently, Ham's Lake is becoming more oligotrophic. For example, DOC (dissolved organic carbon) and algal biomass measured as chlorophyll *a* decreased between 1974 and 1975 (table 5). Furthermore, BOD_5 has decreased since 1973. Prior to 1973, a heavy organic load accumulated in Ham's Lake from uneaten feed and catfish waste. After pumping began in 1973 and 1975, there was a dramatic decrease in BOD_5 (fig. 11) and it remained

Table 4.—*Density of dominant algae in Ham's Lake during 1975 as cells or filaments/mℓ*

Taxon	Date 05/20	06/09	06/21	07/03	07/19	08/04	08/20	10/07	10/31
Chlorophyta									
Chloroccum	32	94	176	112	140	56	40	48	94
Coelastrum	3	442	410	321	333	20	0	0	83
Pediastrum	8	47	24	56	72	56	56	59	27
Cyanophyta									
Aphanizomenon	4	670	1624	555	40	12	12	37	59
Chrysophyta									
Cyclotella	12	311	80	209	161	143	96	37	94
Melosira	178	978	965	1113	530	50	28	48	295
Euglenophyta									
Euglena	42	94	281	112	56	9	28	+	83

+ = organism seen but not enumerated.

Table 5.—*Range in concentration of dissolved organic carbon and chlorophyll "a" in Ham's Lake during July and August 1974 and 1975*

Dissolved organic carbon, mg/ℓ		Chlorophyll a, µg/ℓ		
1974 **	1975 **	1974 **	1975 *	1975 **
29.2 - 48.8	18 - 30	8.8 - 66.3	8.0 - 10.4	5.92 - 14.60
0, 5, and 9 m	0, 4, and 8 m	$\bar{x}$ = 35	$\bar{x}$ = 9.52	$\bar{x}$ = 9.02
		3 dates	4 dates	12 dates
		surface	0 - 3 m	0 - 3 m

* before mixing
** during mixing

relatively constant throughout the water column. During pumping, BOD_5 was less than 2 mg/l in the entire water column. Low values of BOD_5 indicate that small amounts of biodegradable organic matter were present in the impoundment. By maintaining aerobic conditions in the reservoir over the past 3 years, the heavy organic load apparently has been oxidized and BOD_5 has declined.

It is more difficult to assess the effect of successive years of pump operation on the density or biomass of phytoplankton because no baseline data exist for a summer when pumping has not occurred. However, the density of algae in the lake during June before mixing (June 1973) can be compared to the density of algae observed during June 1975. These data reveal that overall changes have been slight between 1973 and 1975, although certain diatoms were more numerous during 1975 (table 6). During August when lake mixing was underway, the density of dominant algae was similar in both 1973 and 1975 (table 6). The data are not directly comparable since sampling methods were different. However, it is not possible to see dramatic decline in algal density between 1973 and 1975.

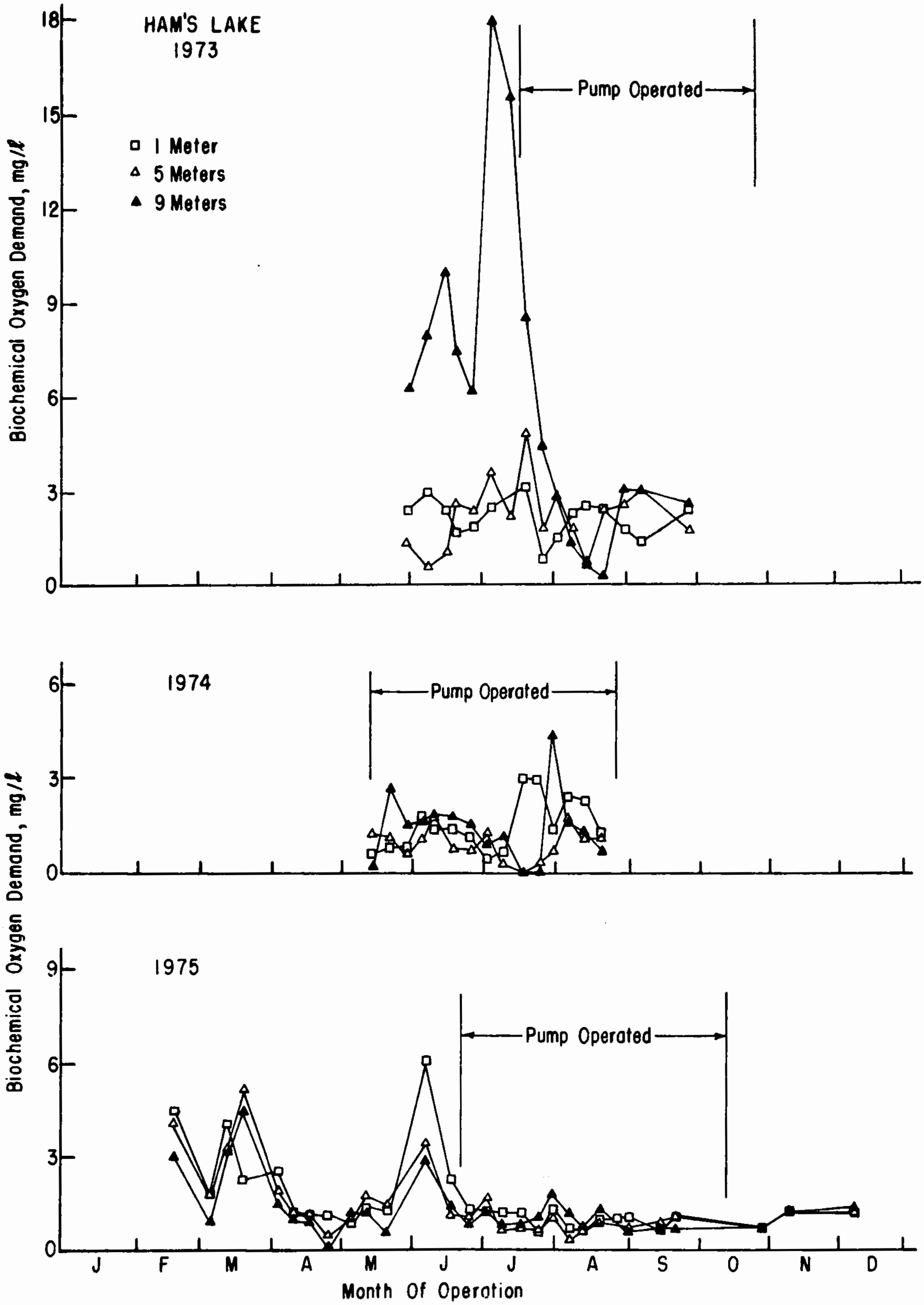

Figure 11.–BOD_5 versus time for Ham's Lake during 1973, 1974, and 1975.

Table 6.—*Range of density as cells or tricomes/mℓ of dominant algae in Ham's Lake during June and August 1973 and 1975 (Steichen [20])*

Species	June		August	
	1973	1975	1973	1975
Anabaena	30-91	737-1624	6-36	16-124
Microcystis	3-70	40-136	-0-	6-12
Euglena	36-134	94-281	3-125	9-28
Pediastrum	15-36	24-47	24-47	56
Cyclotella	3-31	80-311	12-802	56-143
Melosira	6-40	965-979	9-61	70-84

Zooplankton

Materials and methods.–Zooplankton was not collected during the 1974 sampling. During 1975, three samples each were taken with a Juday plankton trap from the surface, 2, 4, 6, and 8 m in the central pool at station 3. Samples were collected on April 12, May 21, June 12, July 2, and August 3. Sampling began 5 hours after sunrise and organisms were preserved in 5 percent formalin. In the laboratory, a sample was mixed and a 1-mℓ subsample was withdrawn and transferred to a Sedgwich-Rafter cell. All organisms in the cell were identified and counted. Additional cells were prepared until at least 200 organisms were identified. This was shown to be an adequate sample size for estimating diversity of zooplankton by Kochsiek et al. [28]. A maximum of 10 cells were analyzed for any sample. Density (d) in organisms/ℓ was calculated from the formula,

$$D = \frac{(i) \quad (c/a)}{f}$$

where:

- i = number of individuals counted,
- c = volume of concentrated samples (in milliliters),
- a = number of Sedgwich-Rafter cells analyzed, and,
- f = liters of water sampled.

Density was calculated as described in the section on benthic macroinvertebrates.

Results.–Twenty-five taxa of zooplankton were taken from Ham's Lake during the five time periods (table 7). Most species were taken from most of the depths and few species were consistently abundant. The highest density was the rotifer, *Conochilus* sp., at the surface and 2 m depths on May 21. This species was relatively abundant at these depths during the two subsequent sampling periods but rare during the first and last periods. A fairly large concentration of the cladoceran, *Ceriodaphnia lacustris*, was taken from the shallow depths on May 21 and June 12. Ostracods were relatively common at 2 m on July 2 and at 8 m on August 3. The rotifer *Keratella* sp. and the copepod, *Diaptomus pallidus*, were often common at the surface at 2 m. The copepod, *Mesocyclops edax*, and the cladoceran, *Bosmina longirostris*, exceeded 10 individuals/ℓ at the surface on June 12, and at the surface and 2 m on July 2. *Hexarthra* sp., a rotifer, was absent or rare on all dates until August 3 and tended to increase in density with depth on that date.

Total number of species ranged from 5 to 16 (table 8). The small number of species taken on April 12 was possibly influenced by low water temperatures. Although a consistent relationship was not noted between depth and number of species, as was observed for benthic macroinvertebrates, fewer species were found at 6 and 8 m on May 21 and June 12, possibly reflecting the limited oxygen concentrations (table 8). The number of species increased between June 12 and July 2 at 6 and 8 m; however, a considerable decrease occurred between July 2 and August 3.

Total density ranged from 38 to 505 individuals/ℓ (table 8). The increase in numbers of species which occurred between April 12 and May 21 was accompanied by an increase in density. An abrupt decrease in density occurred between 2 and 4 m on May 21 and between 4 and 6 m on June 12. These decreases were accompanied by concomitant

Table 7.–*Zooplankton collected in Ham's Lake from April to August 1975*

Rotifera
- Ploima
  - *Brachionus* sp.
  - *Kellicottia* sp.
  - *Keratella* sp.
  - *Lecane* sp.
  - *Monostyla* sp.
  - *Trichocerca* sp.
  - *Asplanchna* sp.
  - *Polyarthra* sp.
  - *Synchaeta* sp.
- Flosculariaceae
  - *Filinia* sp.
  - *Hexarthra* sp.
  - *Conochilus* sp.
- Unidentifiable species

Arthropoda
- Cladocera
  - *Diaphanosoma leuchtenbergianum* Fischer
  - *Daphnia ambigua* Scourfield
  - *Daphnia parvula* Fordyce
  - *Ceriodaphnia lacustris* Birge
  - *Bosmina longirostris* (O. F. Müller)
  - *Kurzia latissima* (Kurz)
  - Unidentifiable chydoridae
- Ostracoda
  - Unidentifiable species
- Copepoda
  - *Diaptomus pallidus* (Bottom)
  - *Cyclops bicuspidatus* Claus
  - *Mesocyclops edax* (S. A. Forbes)
  - Nauplii
  - Copepodites
- Diptera
  - *Chaoborus* sp.

decreases in D.O. concentration (table 8). An abrupt decrease occurred between 2 and 6 m on July 2. Although density increased at 6 and 8 m after pumping started, it decreased between July 2 and August 3. Density was relatively uniform over depth on August 3.

Species diversity ($\bar{d}$) of zooplankton ranged from 1.5 to 2.9 (table 8). Although diversity of benthic macroinvertebrates tended to decrease with depth, this pattern was not observed with zooplankton. The abrupt decrease in D.O. that occurred between 2 and 4 m on May 21 and between 4 and 6 m on June 12 was not accompanied by a decrease in diversity of zooplankton. No effects of pumping were observed in diversity of zooplankton. Minimum diversity occurred at the surface on three sampling dates, while maximum diversity occurred at 2 to 6 m on all dates except May 21.

Benthic Macroinvertebrates

Materials and methods.–Variation with depth of population of benthic macroinvertebrates was studied at the three transects over three time periods during the summer of 1974. The transects were located in the areas of stations 1, 5, and 7. Samples were taken after pumping began on May 13, 1974. On July 13, 1974, three samples each were taken from each transect with an Ekman dredge, at depths of 1, 3, 5, and 8 m. Samples were washed in No. 30 U.S. standard soil series sieve and preserved in 8 percent formalin. Time constraints necessitated reducing the number of samples during the other sampling periods, and during the collections on July 30 and August 22, 1974, the 3- and 5-m depths were combined into a single collecting

Table 8.—*Number of taxa(s), numbers/ℓ(n), and species diversity ($\bar{d}$) of zooplankton by depth in the central pool during 1975 in Ham's Lake**

Depth, m	April 12			May 21			June 12			July 2			August 3		
	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$
Surface	6	50	1.5	15	362	1.8	13	229	2.1	12	384	2.3	10	72	2.3
2	9	94	2.0	15	505	1.9	15	299	2.3	15	476	2.8	7	58	2.4
4	6	38	1.9	16	241	2.2	13	267	2.9	14	206	2.9	9	54	2.3
6	5	54	1.2	13	226	2.0	10	75	2.8	16	177	2.9	6	37	2.3
8	7	47	1.9	13	236	2.3	11	68	2.2	**13	171	2.5	** 9	98	2.2

* Values are total number of taxa, mean density, or species diversity of three Juday plankton trap samples
** Only two samples analyzed
Double vertical line designates beginning of pumping (i.e., June 19, 1975)

depth, 4.5 m. Species diversity ($\overline{d}$) of the samples was determined by the equation of Shannon and Weaver [29],

$$\overline{d} = \frac{s}{1} (n_i/n) \log_2 (n_i/n)$$

where:

n_i = number of individuals in the i'th taxon,
n = total number of individuals, and
s = total number of species.

The data collected in summer 1974 revealed that variation among depths was considerably greater than variation among stations and that considerable variation existed among replicates. In 1975, four samples were taken from each of eight depths at one transect in the area of station 1. The depths were at 1-m intervals from 1 to 8 m, and samples were taken on March 1, May 21, June 14, July 10, and July 31. The latter two samples were taken after pumping operations began on June 19. Samples were sorted and identified as described above.

Results.–Seventy-six species of benthic macroinvertebrates were collected from Ham's Lake during the study (table 9). During the preliminary study, the shallow waters were characterized by a few common species and many rare species, while the deep waters had one or two abundant species and a few rare species. Most of the dominant organisms were midges. At 1 m, midges of the genus, *Procladius*, were generally the most common invertebrate. The midge, *Tanytarsus* sp., was common at the shallow-water depth of stations 8 and 2, while the midges, *Chironomus* sp. and *Tanypus* sp., were generally common at stations 1 and 5. At the middle depths, *Procladius* sp. was generally the most common taxon, but was less abundant than at 1 m. *Chironomus* sp. and *Tanypus* sp. tended to increase in density during the summer at the middle of stations 1 and 2. The mayfly, *Hexagenia limgata*, was observed on July 13, and the phantom midge generally was not common at the middle depths. At 8 m, considerable change in dominance occurred during the summer. On July 13, *Chironomus* sp. and *Tanypus* sp. were common, especially at station 5. These species decreased in abundance and the density of *Chaoborus punctipennis* increased to extremely large numbers, especially at station 5. *Chironomus* sp. was also common at 8 m on July 30 and August 22.

Table 9.–*Benthic macroinvertebrates collected in Ham's Lake from July 1974 to July 1975*

Coelenterata
  Hydrozoa
    Hydra sp.
Platyhelminthes
  Turbellaria
    Dugesia sp.
Nematoda
    Unidentifiable species
Annelida
  Oligochaeta
    Chaetogaster sp.
    Dero digitata (Müller)
    Nais sp.
    Stylaria lacustris (Linn.)
    Aulodrilus pigueti Kowalewski
    Ilyodrilus sp.
    Limnodrilus hoffmeisteri Clap.
    L. cervix Brinkhurst
    L. claparedianus Ratzel
    L. udekemianus Clap.
    Tubifex tubifex (O.F.M.)
    Unidentifiable tubificid w/capilliform chaetae
    Unidentifiable tubificid w/out capilliform chaetae
Arthropoda
  Arachnida
    Hydracarina spp.
  Crustacea
    Unidentifiable Astacidae
    Hyalella azteca (Saussure)
  Insecta
  Ephemeroptera
    Hexagenia limbata (Serville)
    Caenis sp.
    Cloeon sp.
    Centroptilum sp.
    Unidentifiable Baetidae
  Odonata
    Gomphus sp.
    Epicordulia sp.
    Macromia sp.
    Plathemis sp.
    Somatochora sp.
    Sympetrum sp.
    Ischnura sp.
    Unidentifiable Coenagrionidae

Table 9.–*Benthic macroinvertebrates collected in Ham's Lake from July 1974 to July 1975* –Continued

Arthropoda –Continued
Megaloptera
Sialis sp.
Trichoptera
Unidentifiable Leptoceridae
Oecetis sp.
Polycentropus sp.
Molanna sp.
Coleoptera
Berosus sp.
Haliplus sp.
Diptera
Unidentifiable Ceratopogonidae
Chaoborus punctipennis (Say)
Ablabesmyia sp.
Anatopynia sp.
Coelotanypus sp.
Pentaneura sp.
Procladius sp.
Tanypus sp.
Unidentifiable Pentaneurini
Chironomus sp.
Cryptochironomus abortivus (Malloch)
Cryptochironomus sp.
Dicrotendipes sp.
Endochironomus sp.
Glyptotendipes sp.
Goeldichironomus sp.
Harnischia sp.
Lauterborniella sp.
Parachironomus sp.
Paralauterborniella sp.
Phaenopsectra sp.
Polypedilum sp.
Pseudochironomus
Stenochironomus sp.
Stictochironomus sp.
Tribelos sp.
Chironomini sp. A
Chironomini sp. B
Chironomini sp. C
Chironomini sp. F
Micropsectra sp.
Rheotanytarsus sp.
Tanytarsus sp.
Cricotopus sp.
Orthocladius sp.
Psectrocladius sp.
Chironomid pupae

Table 9.–*Benthic macroinvertebrates collected in Ham's Lake from July 1974 to July 1975* –Continued

Mollusca
Pelecypoda
Pisidium sp.
Gastropoda
Gyralus sp.
Physa sp.

Numbers of total species in the preliminary study ranged from 2 to 17 (table 10). Total number of species tended to decrease with depth. The most abrupt decrease generally occurred between 1 m and the middle depths. Total number of species collected increased slightly with time at 1 m and tended to decrease at 8 m. Variation among stations was considerably less than variation among depths.

Total density ranged from 114 to 4648 individuals/m^2 (table 10). Density of macroinvertebrates was generally greater in shallow and deep depths than at middle depths. Considerable variation in density existed among stations, but no consistent pattern was observed. Density tended to increase over time, but this was primarily due to the large numbers of *Chaoborus* at the 8-m depth.

Species diversity ($\bar{d}$) of populations of benthic macroinvertebrates ranged from 0.3 to 3.6 (table 10). Diversity tended to decrease with depth, although relatively high diversities existed at the middle depths on July 13 because of the buildup of a relatively large number of species, none of which were extremely abundant. Diversity was relatively high on July 13 at 8 m since the *Chaoborus* population had not yet increased to large numbers. No consistent pattern existed among stations, but diversity decreased slightly with time despite the increase in numbers of species reflecting the increase in numbers of several populations.

In 1975, three sets of samples were collected from station 1 before starting the pump and two after. Several trends in species composition were observed in the shallow depths. On March 1, the annelid worms, *Dero digitata, Aulodrilus piqueti,* and *Ilyodrilus* sp., were extremely abundant at 1 m. Although *D. digitata*

Table 10.—*Number of taxa(s), numbers/m² (n), and species diversity ($\bar{d}$) of benthic macroinvertebrates by station and depth during summer 1974 in Ham's Lake**

Station	Depth, m	July 13			July 30			August 22		
		s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$
1	1	12	931	2.2	12	832	2.8	16	2810	2.9
	3	8	931	1.8	—	—	—	—	—	—
	**5	10	501	2.7	6	644	1.9	9	903	2.5
	8	8	1348	2.3	6	1677	0.8	7	4648	0.5
2	1	9	614	2.2	15	1532	2.8	17	716	3.6
	3	9	615	2.8	—	—	—	—	—	—
	**5	9	759	2.7	7	816	2.0	10	773	2.6
	8	8	445	2.6	2	129	1.0	5	1047	1.6
3	1	13	1032	3.2	17	3341	2.3	16	1792	3.1
	3	9	659	1.8	—	—	—	—	—	—
	**5	7	315	2.6	3	114	1.0	10	543	2.5
	8	4	114	1.7	3	773	0.3	4	961	0.8

*Values are total number of taxa, mean diversity, or pooled diversity of three Ekman dredge hauls.
** Depth = 4.5 m on July 30 and August 22
—Samples not taken.

decreased in abundance with time,it continued to be the most common organism at 1 m, while the other two organisms were rare. *D. digitata* was also common at 2 and 3 m and tended to increase in density at 3 m. The midge, *Procladius* sp., which was the most common organism in the shallow depths in 1974, tended to decrease with time at the shallow depths in 1975, and to increase after pumping began. The biting midge, Family Ceratopogonidae, which was rare in 1974 at the 1-m depth of station 8, was common at the shallow depths, especially 1 m, in March and tended to decrease with time. The phantom midge, *Chaoborus punctipennis*, was also common at these depths in March and rare during the remaining times. The midge, *Tanytarsus* sp., which was common in 1974, was common through the June 13 samples. The mayfly, *Hexegenia limbata*, was generally more common at 2 and 3 m than at 1 m. *Sialis* sp. was more common in summer than in early samples, while the reverse was true for *Hexagenia limbata*. *Dicrotendipes* sp. was abundant at 1 m on March 1, while *Stylaria* sp. was dense at 2 m on May 21 and at 1 m on June 14. Fewer species were common at the middle depths, 4 and 5 m, than at the shallow-water depths.

In deeper areas during 1975, *Chaoborus* sp. was generally the most common invertebrate. The phantom midge was extremely abundant on March 1 and less abundant on other dates. *Dero digitata*, which was generally the most common organism in shallow water, was common in deeper waters in spring and rare in June and July. *Procladius* sp. and Ceratopogonidae exhibited a similar trend. They were relatively common on March 1, tended to decrease through the July 10 sampling, and increased on July 31.

Total number of species taken in 1975 ranged from 4 to 30 (table 11). Numbers of species tended to decrease with depth as in 1974. A marked decrease occurred between 1 and 2 m on all dates and a second abrupt decrease between 2 and 3 m on March 1. An abrupt decrease occurred between 4 and 5 m in June and July. Species numbers tended to decrease with time at 1 m and in deeper waters. At 8 m, numbers increased from 4 to 8 between the last two sampling dates.

Density ranged from 75 to 16 639 individuals/m² (table 11). The maximum was almost twice any other density value and was due largely to segmented worms. Although no consistent pattern between density and depth was observed, minimum density generally occurred in middle depths as was noted in 1974. Maximum density occurred at 1 m on the first three sampling dates. Density tended to

Table 11.—*Number of Taxa(s), numbers/m² (n), and species diversity ($\bar{d}$) of benthic macroinvertebrates by depth at station 8 during 1975 in Ham's Lake**

Depth, m	March 1			May 21			June 14			July 10			July 31		
	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$
1	29	16639	3.3	30	9240	3.0	25	6038	2.9	20	1079	3.3	—	—	—
2	20	3058	2.9	7	1259	2.0	13	605	3.0	13	2465	2.6	14	959	2.8
3	11	1357	2.6	11	2229	2.6	11	1141	2.9	15	1901	3.1	17	2382	2.3
4	5	144	2.0	10	814	2.7	11	453	3.2	11	506	3.0	10	400	2.7
5	9	1013	1.9	9	647	2.2	5	119	2.2	4	194	2.0	3	75	1.4
6	12	2908	1.6	8	496	2.8	4	635	0.5	5	205	1.5	10	593	2.6
7	7	3197	1.5	9	444	2.4	4	851	0.6	6	335	1.5	5	495	1.4
8	9	5878	1.5	7	529	2.2	5	711	0.6	4	506	0.8	8	603	2.1

*Values are total number of taxa, mean density, or pooled diversity of four Ekman dredge hauls.
—Samples not taken.
Double vertical line designates beginning of pumping (i.e., June 19, 1975).

decrease with time and the values in summer 1974 and 1975 were similar to each other.

Species diversity ($\bar{d}$) ranged from 0.5 to 3.6 (table 11), which was similar to the range observed in 1974. Diversity generally decreased with depth, reflecting the reduction in numbers of species with depth and the large populations of one or two species in deeper areas. Decrease in diversity was not marked in the spring samples; however, a large reduction was observed below 5 m on June 14. The diversity increased in the deeper waters after destratification. Significant changes in diversity over time was not observed at the shallow and middle depths.

Fish

Objectives.–The largemouth bass (*Micropterus salmoides*) is a popular sport fish. Data on its growth rate and fishing success for this species were obtained to determine effects of long-term lake mixing. In addition, the vertical distribution of fishes in the stratified and unstratified lake was studied using gill nets.

Methods.–The following age and growth data were obtained from specimens taken by angling during the summer: total length, weight, and scales. Virtually all anglers completed a survey form, since the lake had controlled access. The survey was conducted during July and August; however, since interest in angling fell off in August, only July data are used. Scales were used to determine age. Mean length of each cohort was determined at each annulus by back calculation (Lagler [30]). A third degree polynominal was used to establish the relationship between body length and scale length.

When the lake was being mixed, gill nets were used to learn how adult fish were distributed in the pelagic zone. Horizontal experimental gill nets were fished on the bottom near station 2 before and after the onset of mixing. The gill nets were 2 by 98 m and made up of 4- to 24.6-m segments, each of which had the following mesh sizes: 250, 510, 760, and 1020 mm².

Two vertical gill nets, 30 m and 24 m wide, were constructed from four panels of netting of mesh size 250, 380, 510, and 630 mm². Each panel was 1.8 m wide. These nets were fished from June 25 to July 7 near station 2, from July 8 to 27, near station 3, from July 28 to August 3 at station 4, and from August 5 to 8 at station 2.

One would expect a major energy subsidy such as wasted catfish food to be translated into greater growth during 1971 or 1972. This was apparently not the case, since there were no statistical differences between the length attained at a given age by any year-class. Nor was there any evidence of Lee's phenomenon, except for age 3 fish (table 12).

Fishermen reported satisfactory angling for largemouth bass; two fish over 3.2 kg were

Table 12.—*Mean back-calculated length, in millimeters, of largemouth bass from Ham's Lake, Okla., and comparative growth data from Oklahoma*

Year-class	n	I	II	III	IV
1974	31	126.8 (18.5)			
1973	24	127.8 (17.5)	206.4 (27.2)		
1972	23	*137.0 (16.8)	204.5 (21.8)	244.6 (22.5)	
1971	15	128.7 (14.7)	217.5 (16.7)	259.5 (25.0)	285.2 (26.4)
1970	6	131.7 (13.0)	224.8 (21.9)	277.2 (11.3)	318.7 (26.2)
1969	3	132.7 (5.1)	210.7 (20.3)	283.8 (14.1)	331.6 (25.6)
Average		130.1 (16.9)	209.9 (23.2)	256.0 (25.2)	299.4 (31.5)
Houser & Bross 1963	State average	140	246	317	378
Zweiacker 1972	Lake Carl Blackwell 1968	151	283	364	417
Zweiacker 1972	Lake Carl Blackwell 1969	148	286	371	425

* not significantly different from 1973 or 1971.

Data in parentheses are one standard deviation of the mean.

captured. Fishing for largemouth bass was generally done by one or two anglers who fished in the evening and who usually returned their catch to the lake. The rate of catch of fish larger than 300 mm total length was 0.2 fish per man-hour, which is excellent angling success. For all bass captured, the rate of catch was 1.0 per man-hour. Excellent angling in Ham's Lake may be because it is not heavily fished.

Between June 9 and 19, D.O. was depleted below 4 m to 0.05 mg/*l*, which will not support fish. Mixing began on June 17 and four days later, D.O. was present throughout the water column in sufficient amounts to support fish. Before June 19, no fish were captured at 5 to 6 m, but several fish, notably channel catfish (*Ictalurus punctatus*), were captured there afterward. In addition, several other species were captured in the deep water shortly after lake mixing began; e.g., largemouth bass, at 5 to 6 m on June 19, and at 7 to 8 m on June 19, and black bullhead (*Ictalurus melas*) at 7 to 8 m on June 29. Channel catfish were captured in several instances at 8 to 9 m after lake mixing began but not before; e.g., at 8 to 9 m on June 26 and 29. Therefore, lake mixing extended the depth distribution of fish in Ham's Lake.

Most of the fish captured in the vertical gill nets were bluegills (*Lepomis macrochirus*) and crappie (*Pomoxis* sp.), but largemouth bass were taken at 2 to 3 m on August 3 and at 1 to 2 m on June 29. Results of these collections also showed that fish rapidly invaded the previously anoxic depths.

LAKE OF THE ARBUCKLES

Description of the Lake

Lake of the Arbuckles is located in southcentral Oklahoma in Murray county, about 9.6 km southwest of Sulphur, latitude 34°26'30" N., longitude 97°01'30" W. (fig. 12). The dam impounds Rock Creek, a tributary of the Washita River which flows into Lake Texoma. The dam is located immediately below the confluence of Buckhorn and Guy Sandy Creeks. The lake was constructed by the Bureau of Reclamation to provide municipal water supply for Davis, Sulphur, and Wynnewood, and to benefit flood control, fish and wildlife, and recreation (Gomez and Brinstead [31]). To date, water has been delivered to Davis, Wynnewood, and an oil refinery. Two reservoir intake levels are available for withdrawal of municipal water, 251.8 and

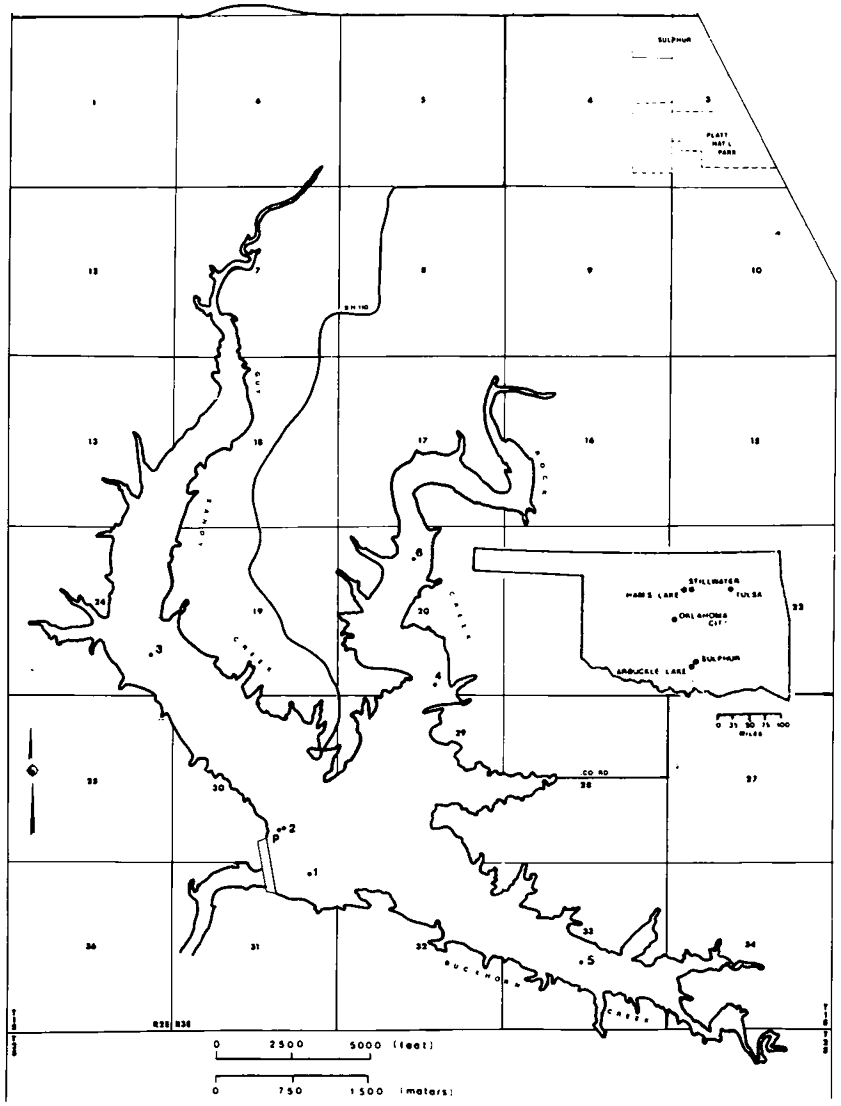

Figure 12.–Lake of the Arbuckles sampling stations and a vicinity map of Oklahoma showing Lake of the Arbuckles in relation to major cities.

259.4 m with one 14.0 and 6.4 m, respectively, below the average pool level (top of the conservation pool is 265.8 m). The lake began filling in January 1967, and filled to near the top of the conservation pool level by April 1968. Morphometry is given in table 1 and its vertical (bathymetric) profile is shown in figure 13.

The watershed receives an annual precipitation of about 960 mm. The average length of the frost-free period is 218 days. Duffer and Harlin [32] collected physical, chemical, and biological data on Lake of the Arbuckles during 1968. Their data in 1968-69 and that collected in the presented study in 1973-75 showed that the lake is thermally stratified from about mid-May to mid-October with a thermocline at a depth of about 7 m. A large volume of the lake will be below the hypolimnion and completely devoid of oxygen (anoxic) for most of the stratified interval. Lake of the Arbuckles is a warm, monomictic lake with August temperatures ranging from 30 °C in the epilimnion to 18 °C in the hypolimnion.

Pump Configuration and Performance

Lake of the Arbuckles has about 23 times the area of Ham's Lake, about 3 times the depth, and about 75 times the volume. Ham's Lake was

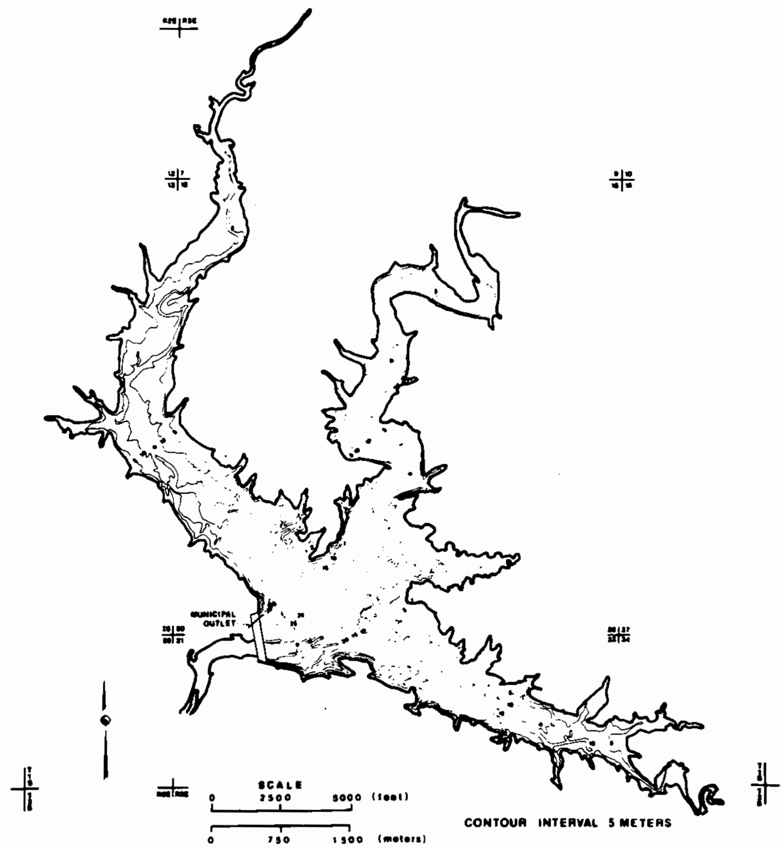

Figure 13.–Bathymetric map of Lake of the Arbuckles.

destratified in about 2 weeks with about 0.63 m^3/s.

A 5-m Curtis-Wright, variable-pitch, three-bladed propeller was installed under a 6- by 6-m redwood raft using expanded foam flotation. An industrial engine using gasoline for fuel with a 67.4 to 1 right-angle reduction gear was used for power. During 1974, the tip angle of the blades was set at 10° and operated at various speeds up to 12 r/min. At 12 r/min, the device pumped about 13.8 m^3/s of water. This was calculated using a propeller current meter traverse 2.13 m below the blade. The device was started July 17 and operated at 5 r/min for 7 days and at 9 r/min for 9 days. The speed was increased to 12 r/min on August 2 and operated until August 31. Torque and power measurements were scheduled to be made on September 2, but a wind storm producing 1.5-m waves rendered the device inoperable the night of August 31. The shaft was bent, so operation was stopped for 1974.

During the winter of 1974-75, the device was completely rebuilt with gasoline-resistant foam flotation. A wind-actuated shutoff device was used to deactivate the engine when wind speeds exceeded 15.5 m/s for 1 minute. Improved guarding of the blade was installed, the shaft was straightened, and the blade angle on the new propeller set at a 6.5° tip angle. This tip angle was calculated to produce the flow at 20 r/min which the other tip angle produced at 12 r/min.

Figure 14 shows the pump being assembled. It was decided to try a new launch procedure which was necessitated by the new guarding. Axles were installed at the lower end of the legs at each corner (fig. 15). Rubber tires and wheels were mounted on the axles. Figure 16 shows the pump in place.

Measurements were made of flow rate, rotative speed, and torque (from which the power was calculated) (fig. 17). The device pumped

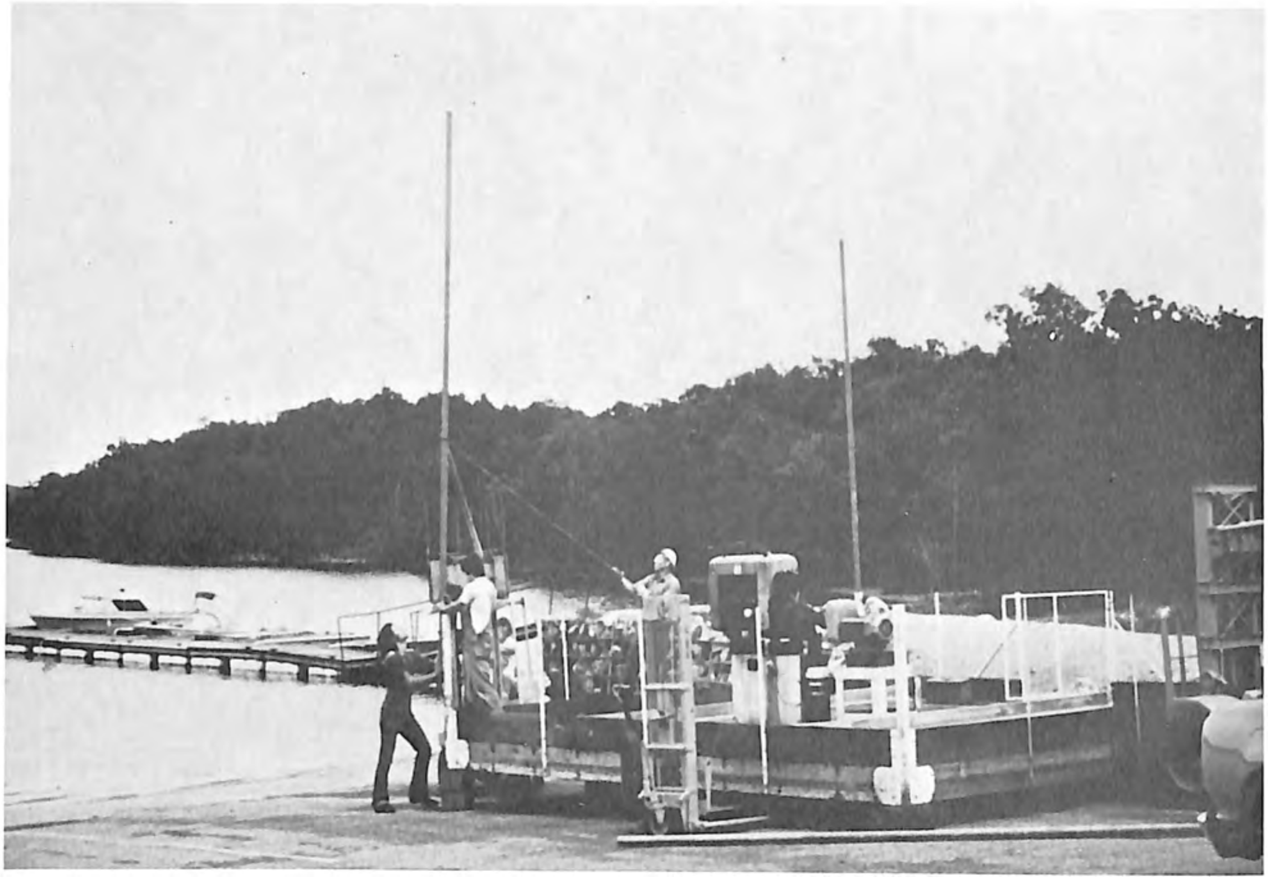

Figure 14.–The raft being assembled at Lake of the Arbuckles in 1975. Two forklifts with extensions were used to lift the raft.

13 m^3/s at 20 r/min and required 5.46 kW. At 18 r/min the flow was 11.73 m^3/s and the power required was 3.98 kW.

The pump was placed in operation on June 2 at 18 r/min and was operated until July 2, when the speed was increased to 20 r/min. The pump was operated until September 13. On that date the lake turned over and the pump was not operated again.

Physicochemical Conditions and Algae

Objectives.–The objective of this part of the research was to describe the effect of lake mixing on the vertical distribution of temperature and D.O. and to determine the degree and extent of artificial destratification on Lake of the Arbuckles. Also, changes in the vertical distribution of water quality parameters were described and the effects of lake mixing on the abundance and taxa of algae and algal biomass as measured by chlorophyll *a* were determined.

Materials and methods.–Temperature was measured at 1-m intervals with a thermistor telethermometer. The concentration of D.O. was similarly measured with a galvanic oxygen probe and meter or the Alsterberg modification of the Winkler method (APHA [33]). Generally, temperature and SDT were measured at all stations at weekly intervals during the period May to August 1973, 1974, and 1975, and at irregular intervals during the rest of the year. Transparency was measured with a 200-mm Secchi disk.

Samples for water chemistry were collected at stations 1, 5, and 6 at approximately 2-week

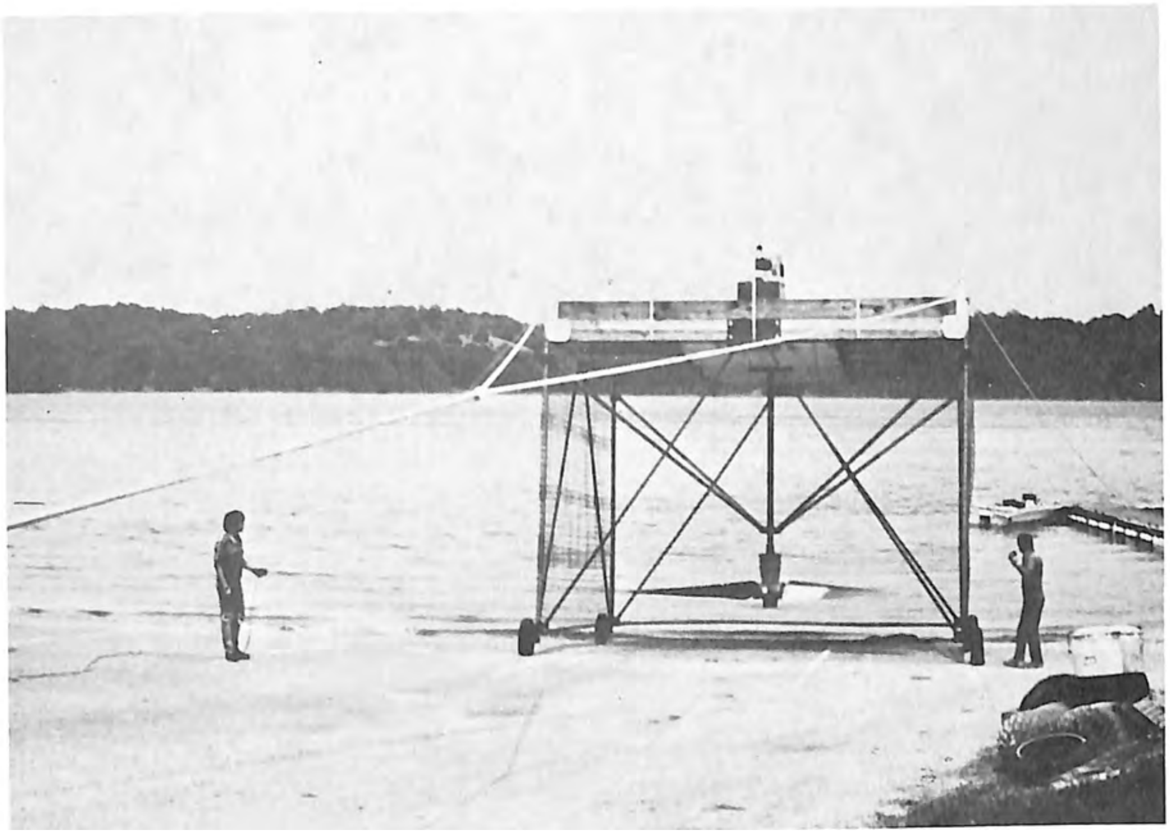

Figure 15.–The raft being rolled down the boat ramp at Lake of the Arbuckles.

Figure 16.–The raft anchored in place near the dam on Lake of the Arbuckles.

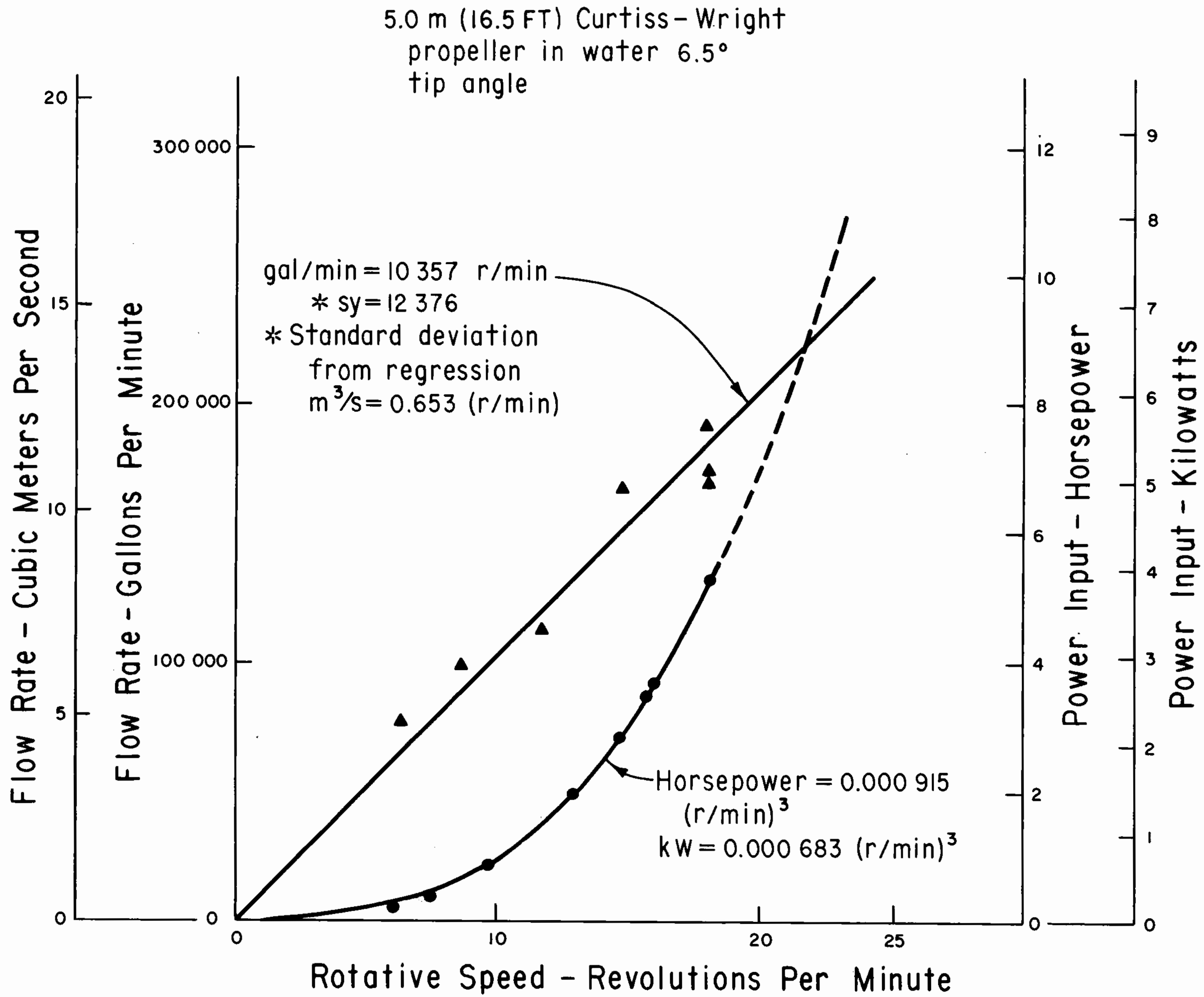

Figure 17.–Performance curves for the pump used in 1975 on Lake of the Arbuckles.

intervals from May 1 to August 23, 1973 (fig 12). Triplicate water samples for iron and manganese were taken from near the bottom at stations 1, 5, and 6. Water was collected using a Van Dorn water sampler at depths of 0, 4, 8, 12, 16, 20, and 24 m at station 1 for chemical analysis. Two composite samples of the entire water column were obtained at stations 1, 5, and 6 by pooling like aliquots of water taken with a Kemmerer bottle (or pump) at 1-m intervals. Two subsamples were taken from each composite for pigment analysis and two subsamples of 100 ml each were taken from each composite sample and preserved with 10 percent Lugol's solution.

Samples were taken during March, May, and June, twice during July, and once during August 1974. Essentially the same sampling methods were used in 1973, 1974, and 1975. During 1975, sampling was accomplished about every other week with supplemental sampling in early June just after the Garton pump began operation.

Alkalinity, BOD, and pH were measured on unfiltered lake water, using APHA procedures [33], and a Beckman and/or Corning pH meter, respectively. Water for other chemical analyses was filtered through Reeve Angel (RAF) or Gelman glass fiber filter. Usually, samples were analyzed for ammonia, sulfide, and reactive phosphate upon returning to Stillwater and for nitrate and nitrite, no more than a few days later. Samples were transported in ice water. Methods of preservation are given by Toetz [34].

Muffled RAF filters were used to retain seston for determination of PC (particulate carbon). The filtrate of water samples filtered through RAF filters for the determination of PC was used to estimate the concentration of DOC. In this report, DOC represents the difference between the concentration of total carbon and the concentration of inorganic carbon in the filtrate.

Methods for the analysis of ammonia followed Solorzano [35]. During 1974, the methods of Strickland and Parsons [36] were used for analyses of nitrate, nitrite, phosphate, PC, and sulfide.

During 1973, samples for sulfide were taken in graduated cylinders or reagent bottles with tightly fitting glass stoppers and reagents were added at Stillwater about a day later. Laboratory investigation showed only 5 to 10 percent of sulfide was lost in transit. During 1974 and 1975, reagents were added in the field.

A Varian Techtron Atomic Absorption Spectrophotometer was used to analyze for manganese. Methods for plant pigments followed Strickland and Parsons [36] using equations of Parsons and Strickland [37]. Extraction with 90 percent acetone lasted 18 to 24 hours. Enumeration of phytoplankton followed methods of McNabb [38]. The same methods were followed for samples from Ham's Lake.

Determinations of D.O. with a galvanic oxygen meter and probe were compared periodically to determinations of D.O. at the same depth using the Winkler method. Usually, the agreement was excellent. The data in this report probably have an overall accuracy of 0.50 mg DO/l, which is acceptable for field work under a wide range of climatic conditions.

Results–Effect of aero-hydraulics gun in 1973.–The profile of temperature and D.O. at the aeration device and at station 1 was essentially the same (fig. 18), although there was slightly more D.O. in the epilimnion at station 1 than at the pump station. The aeration device, therefore, had little effect on the vertical profile of temperature and D.O. in Lake of the Arbuckles. Further, no effect was exerted on temperature and D.O. profiles at stations far removed from the aerator. It was concluded that the lake stratified normally and that other aspects of water chemistry during 1973 generally reflect the effects of lake stratification on the vertical distribution of chemical species normally measured in lakes. These physical and chemical data obtained during 1973 are used below as control data to determine the effect of the Garton pump on Lake of the Arbuckles. Also used were the data of Duffer and Harlin [32] taken during 1968, when the lake stratified normally.

Effect of the Garton pump, 1974.–By early August, the Garton pump had disturbed the water

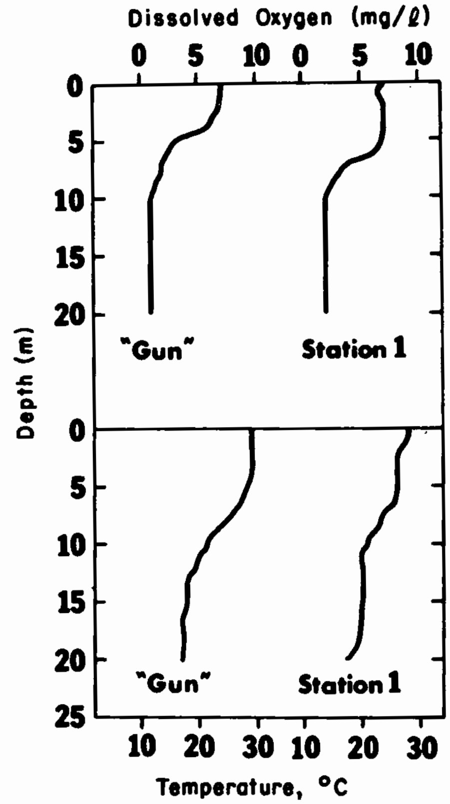

Figure 18.–Vertical distribution of dissolved oxygen and temperature at the aerohydraulics "gun" and at station 1 on July 25, 1973.

column within about 200 m of the pump (figs. 19 and 20). There was a clear increase in D.O. below the region of the thermocline, but the thermal profiles reveal little disturbance of the water column. However, during the period when measurements were made, these changes had extended only partially to station 1, and not at all to stations 5 or 6.

When the vertical profiles of temperature and D.O. are compared among 1968, 1973, and 1974, the lake as a whole stratified normally and the effects of the Garton pump operated in 1974 were relatively local. For example, the profile of temperature and D.O. at station 1 are nearly alike (fig. 21). Moreover, the stability index for the lake in 1974 was virtually the same as the stability index in 1973 (fig. 22), indicating the lake did not destratify during 1974. Thus, the Garton pump had a local effect and destratification was not observed elsewhere in the lake.

Effect of the Garton pump, 1975.– Destratification in a classical sense was not achieved during 1975, since the vertical profiles of D.O. and temperature during 1968, 1974, and 1975 were basically the same (fig. 21). However, by July 25, 1975, the difference in water temperature between the surface and 24 m at station 1 was 9° C; whereas in previous years it was 14°C in 1974 and 11°C in 1968. Therefore, the Garton pump increased the heat content of the lake. The increase in temperature at 15 m was much faster in June 1975 than in June 1974 when the lake was not being mixed. The temperature at 15 m rose 4.4°C between May 28 and June 25, but only 1.4°C between May 23 and June 20, 1974. The Garton pump was put into operation on June 2, 1975. Stability of the lake was also markedly lower in 1975 than in 1974 or 1973 (fig. 22).

Chemical stratification was maintained during 1975 in spite of almost isothermal conditions,

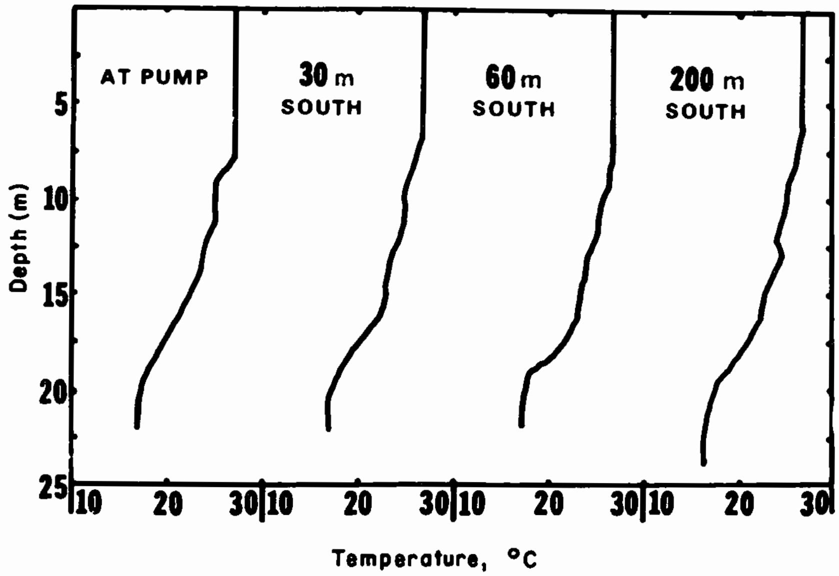

Figure 19.–The vertical distribution of temperature in the vicinity of the Garton pump during 1974.

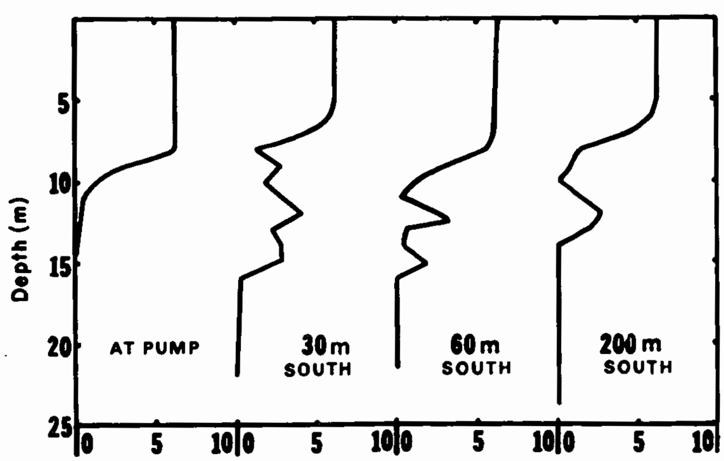

Figure 20.–The vertical distribution of dissolved oxygen in the vicinity of the Garton pump during 1974.

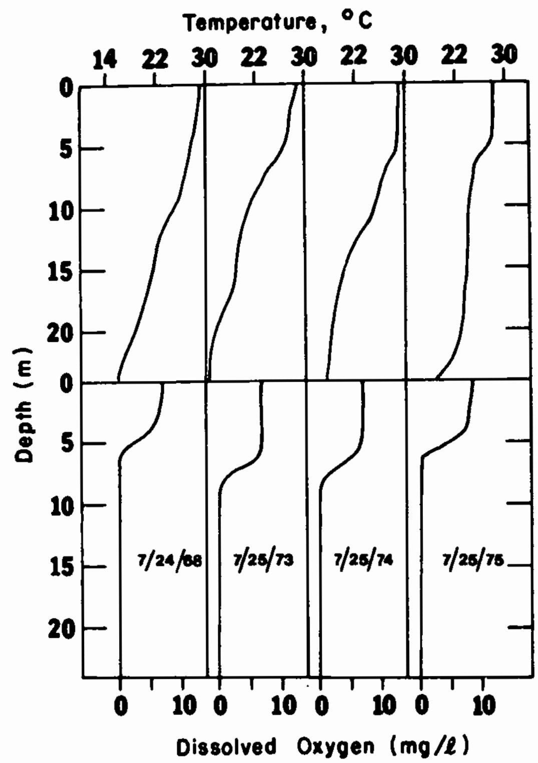

Figure 21.–Vertical distribution of temperature and dissolved oxygen at station 1 during 4 years at the same date.

probably because small differences at high water temperatures result in large density differences between strata of water. The lake became strongly stratified during July and August with a thermocline at 4 to 5 m in contrast to other years when the thermocline was deeper (fig. 21). Apparently, calm weather brought about shallow stratification in 1975.

When water temperatures decreased sufficiently in September, the lake destratified rapidly and earlier than usual. The lake was almost isothermal by September 13, 1975; whereas in 1968, the profile was mildly orthograde (fig. 23).

Surface temperatures during September 1968 were higher than during 1975, but D.O. was markedly lower (fig. 23). While the Garton pump did not destratify the lake during the summer of 1975, it did advance the fall overturn by about 1 month. The effect of the pump during September 1975 was identical to the effect observed when most lakes are destratified; i.e., the surface temperature decreases, the profile of temperature becomes isothermal, and D.O. increases in the former hypolimnion and decreases in the former epilimnion.

Operation of the Garton pump during 1975 improved water quality at the outlet. In figure 24 the concentration of D.O. is compared between the outlet and stations 1 and 2 at the depth of the outlet (6.4 m). In most cases, the outlet water contained at least 1.0 mg D.O./l more than water in the lake.

The data obtained on water chemistry during 1974 generally reflect the effects of lake stratification on the vertical distribution of most of the chemical species normally measured in lakes. These data are discussed below in a comparison between years.

Oxygen distribution index.–Garton developed an oxygen distribution index to serve the same function for D.O. that the stability index serves for temperature. It is calculated in the same way except that the weight of D.O. in the stratum is used instead of the weight of water. The D.O. distribution index gives a single number which is a measure of the D.O. distribution of the lake. The

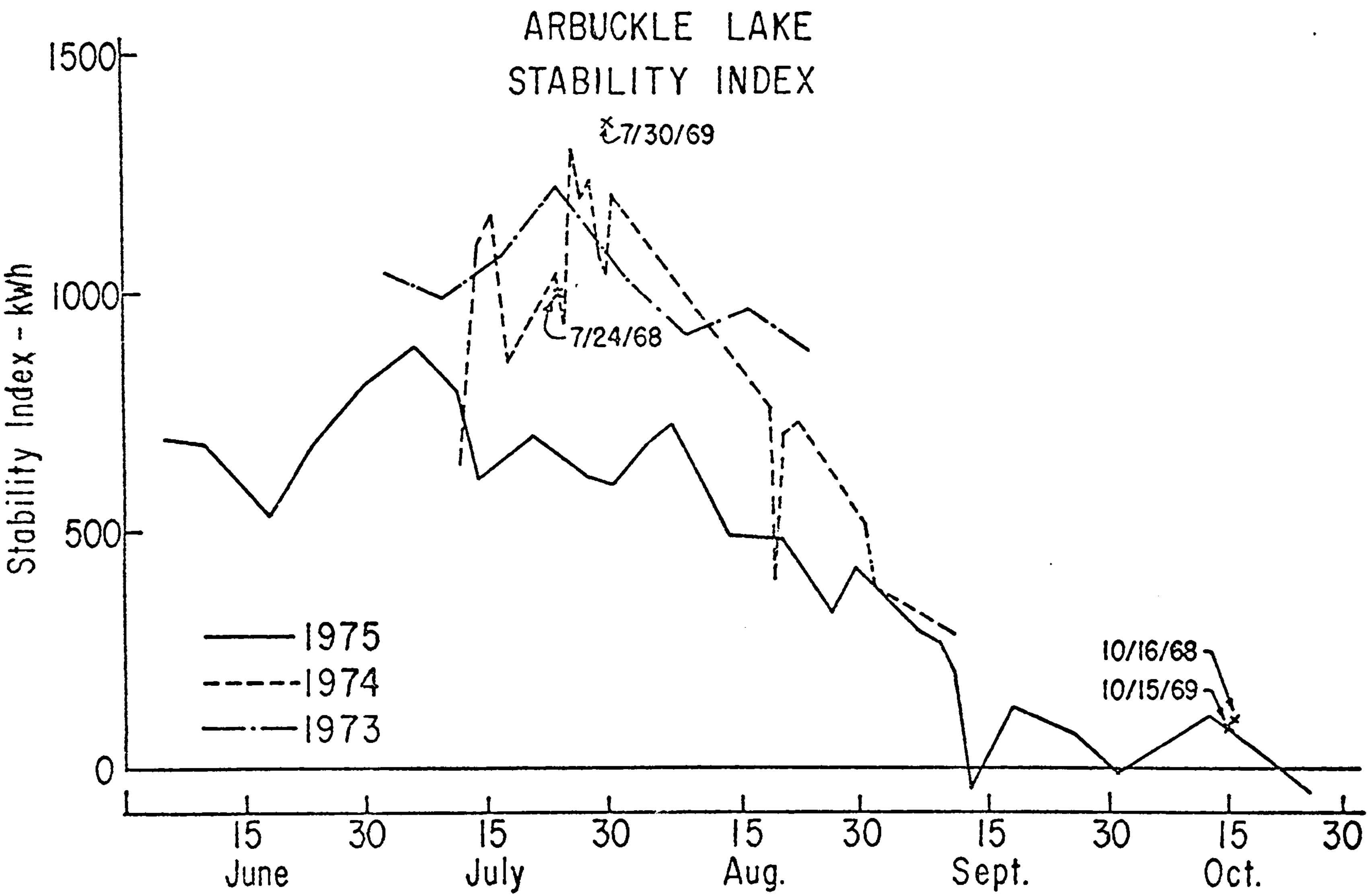

Figure 22.–Stability index on different dates for Lake of the Arbuckles.

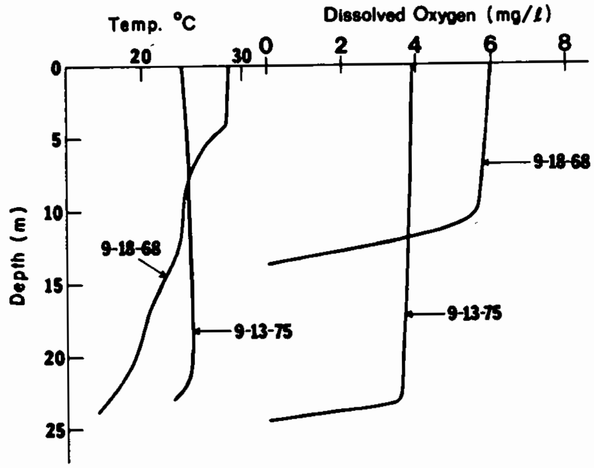

Figure 23.–Vertical distribution of temperature and dissolved oxygen at station 1 during 1968 and 1975.

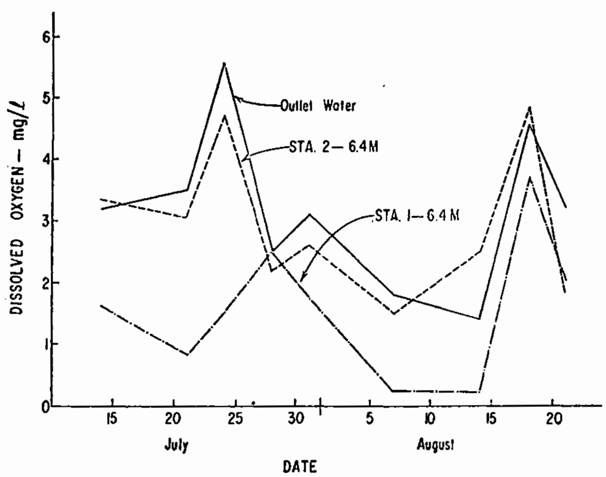

Figure 24.–Comparison of oxygen content in outlet water with oxygen content at stations 1 and 2, Lake of the Arbuckles, 1975.

total D.O. content as well as the location will have an influence on the size of the index. A value of zero indicates that the lake is completely destratified for D.O. Zero values are not usually achieved, as the values near the surface are almost always larger than the bottom values. As this is a new concept, the values of stability index versus oxygen distribution index are presented for Lake of the Arbuckles (fig. 25). An interesting observation from the curve for Lake of the Arbuckles is that the oxygen stability index changed very little, while the stability index was decreasing to about one-fourth of its maximum value. Figure 26 indicates that a lake can be

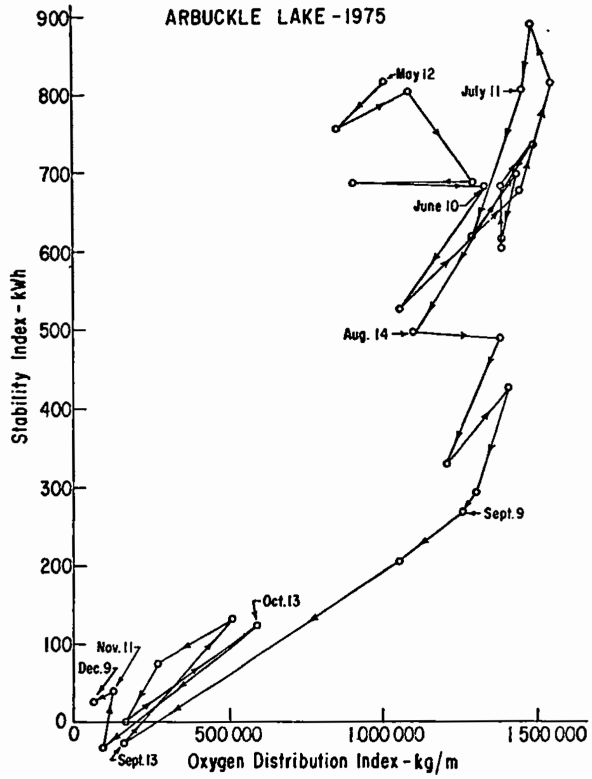

Figure 25.–Stability index versus oxygen distribution index for Lake of the Arbuckles, 1975. Note the rapid change in oxygen distribution and stability index between September 9 and 13.

weakly stratified thermally and strongly stratified for D.O. On September 7, the temperature difference between the surface and the 21-m depth was less than 2.5 °C, but the D.O. content below 5 m was essentially zero. A week later the stability index was zero, and the oxygen distribution index was a very low value. The conclusion to be reached is that anything less than total thermal destratification might not achieve chemical mixing.

Comparison between years–Dissolved oxygen at outlet depth.–Outlet depth is 6.4 m in Lake of the Arbuckles. Data on the concentration of D.O. at 5, 6, and 7 m were compared among stations in different years and among stations during the same year at about the same dates (tables 12 and 13). Comparisons are made between four dates in 1974 and five dates in 1973 and 1975.

Within the same year, no significant difference existed among stations, with one exception. During 1975, the mean concentration of D.O. at

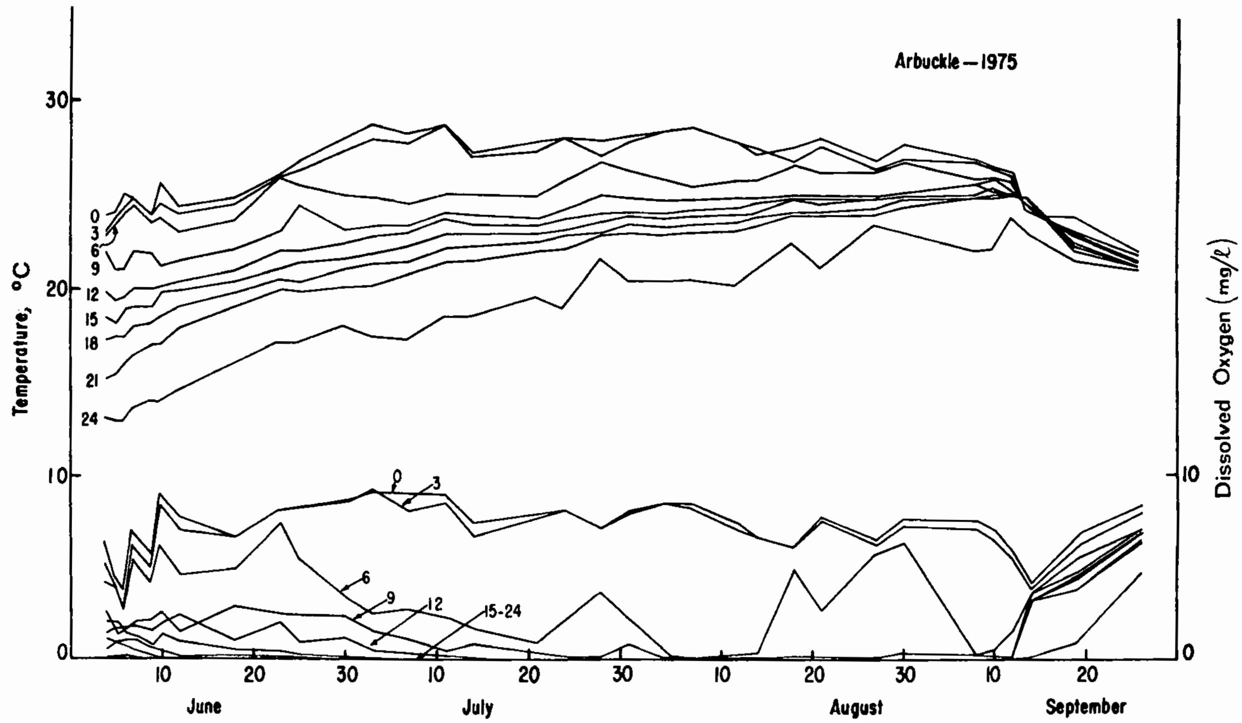

Figure 26.–Temperature and dissolved oxygen for various depths, in meters, for Lake of the Arbuckles, summer 1975.

station 6 was 2.5 mg/l which was significantly different (D > 0.05) from the mean concentration of D.O. at station 1 where the mean concentration was 1.5 mg/l (table 13). This was probably because station 6 is located in a rather isolated basin of the lake and at a considerable distance from station 1 (fig. 12).

There was a significant difference in the mean concentration of D.O. between 1975 and 1973 at a given station, but not between 1974 and 1973 (table 14). The concentration of D.O. was lower in 1975 ($\bar{x}$ = 2.2 mg/l) than in 1973 at 5, 6, and 7 m.

Comparative limnology, 1968-1975.–This discussion is limited to data collected during the summer when water quality problems are most acute. An epilimnion in Lake of the Arbuckles exists between 4 and 8 m, the exact depth shifting daily, depending apparently upon how deep wind-driven currents erode the hypolimnion. Another thermocline exists below 20 m, which effectively remains in place from May to October.

Figure 27 shows the vertical distribution of four water quality parameters that affect oxygen demand, directly or indirectly. Highest concentrations are reached at 24 m. The region of the lake below 20 m is isolated from the rest

Table 13.—*Comparisons of dissolved oxygen at 5, 6, and 7 m between station 1 and stations 5 and 6 in the same year*

Station	Year	Significant difference t = 0.05	t_{calc}
6	1973	no	0.2405
5	1973	no	0.2504
6	1974	no	0.4514
5	1974	no	1.0732
6	1975	yes	2.3571
5	1975	no	0.7227

Table 14.—*Comparisons of dissolved oxygen at 5, 6, and 7 m between years at the same station*

Station	Years	Significant difference $t = 0.05$	t_{calc}
5	1973 & 1974	no	0.8448
5	1973 & 1975	yes	4.4080
6	1973 & 1974	no	0.3311
6	1973 & 1975	yes	3.4178
1	1973 & 1974	no	0.1779
1	1973 & 1975	yes	2.5100

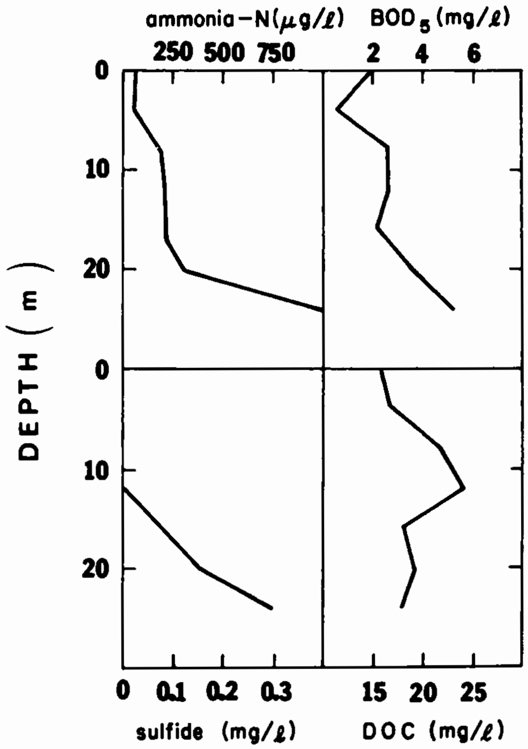

Figure 27.–Vertical distribution of ammonia, sulfide, dissolved organic carbon and 5-day BOD at station 1 at Lake of the Arbuckles on July 25, 1975.

of the lake between early May and late October, so reducing conditions at 24 m are common.

The region from 0 to 8 m is epilimnetic. The region from 12 to 20 m is often anoxic with reducing compounds. Data below 20 m are not used in this analysis, since this is usually isolated from the rest of the lake. Hereafter, the region between 12 and 20 m will be called hypolimnion I (H-I).

No significant change existed in most water quality parameters in either the epilimnion or H-I between 1973 and 1974. There was a small increase in BOD, which was probably the result of systematic analytical error during 1973. Measurements of phosphate at the concentrations encountered are at the low end of sensitivity of the method and are not likely to be significant (tables 15 and 16).

Between 1973 and 1975, no significant change occurred in the concentrations of ammonia or sulfide, respectively, either in the epilimnion or H-I (tables 15 and 16). Biochemical oxygen demand increased in both the epilimnion and H-I. The BOD_5 data collected at 8, 12, 16, and 20 m in 1975 were compared to the BOD_5 data of Duffer and Harlin [32] at the same station at comparable depths and dates during 1968 using a t-test. The mean BOD_5 in 1968 and 1975 was 2.10 and 2.82 mg/*l*, respectively; the means were not significantly different ($t = 0.78$, $n = 8$).

Manganese and nitrate were significantly higher and lower, respectively, in the epilimnion during 1975 compared to 1973. Both alkalinity and pH were lower in both the epilimnion and H-I during 1975 compared to 1973, but in all cases the differences were relatively small (table 15 and 16).

The depth of the Secchi disk was not significantly different between 1973 and 1974 at stations 1, 5, and 6 (table 17). A significant difference existed in the depth of the Secchi disk between 1973 and 1975 at station 6, but no significant difference occurred in the depth of the Secchi disk between 1973 and 1975 at stations 1 and 5 (table 17).

Table 15.—*Comparisons of water quality parameters at 0, 4, and 8 m at station 1*

Parameter	Between 1973 and 1974			
	Significant difference	t_{calc}	Means	
	t = 0.05		1973	1974
ammonia-N	no	1.13	9.1	16.4
nitrate-N	no	1.02	44.1	5.7
nitrite-N	no	0.17	3.7	4.1
total alkalinity (mg/ℓ)	no	0.76	135.0	137.1
phosphate-P	yes	2.31	1.83	6.05
BOD_5 (mg/ℓ)	no	0.80	0.75	0.96
	Between 1973 and 1975			
			1973	1975
ammonia-N	no	2.97	9.1	85.8
nitrate-N	no	0.02	44.1	6.7
nitrite-N	yes	3.30	3.7	0.5
sulfide-S	no	0.93	5.06	3.32
pH	yes	2.82	7.71	7.39
total alkalinity (mg/ℓ)	yes	3.11	135.1	126.1
manganese (mg/ℓ)	yes	2.93	0	0.07
phosphate-P	no	0.25	1.83	1.86
BOD_5 (mg/lℓ)	yes	4.04	0.75	1.97

Unless shown, units are micrograms per liter.

Table 16.—*Comparisons of water quality parameters at 12, 16, and 20 m*

Parameter	Between 1973 and 1974			
	Significant difference	t_{calc}	Means	
	t = 0.05		1973	1974
ammonia-N	no	0.75	90.9	73.2
nitrate-N	no	1.84	285.0	15.2
nitrite-N	no	0.44	9.2	7.4
total alkalinity (mg/ℓ)	no	0.71	142.9	145.5
phosphate-P	no	1.32	7.37	12.74
BOD_5 (mg/ℓ)	yes	6.78	0.47	2.29
	Between 1974 and 1975			
			1974	1975
ammonia-N	no	2.02	90.9	146.1
nitrate-N	no	1.62	285.0	18.4
nitrite-N	no	1.95	9.2	2.8
sulfide-S	no	1.50	22.61	48.09
pH	no	0.79	7.31	7.36
total alkalinity (mg/ℓ)	yes	2.64	142.9	134.3
manganese (mg/ℓ)	no	1.15	0.38	0.70
phosphate-P	no	0.33	7.37	8.53
BOD_5 (mg/ℓ)	yes	6.78	0.47	1.68

Unless shown, units are micrograms per liter.

Table 17.—*Comparisons of the depth of the Secchi disk at three stations between years*

Station	Significant difference	Between 1973 and 1974		
		t_{calc}	Mean depth, m	
	t = 0.05		1973	1974
6	no	1.64	1.57	1.20
5	no	1.56	1.75	1.39
1	no	1.31	1.87	1.53
		Between 1973 and 1975		
			1973	1975
6	yes	2.28	1.57	1.25
5	no	1.37	1.75	1.54
1	no	1.40	1.87	1.70

Algae.–Increasing the heat budget during 1975 had no effect on the biomass of algae (the standing quantity of chlorophyll *a*), figure 28. Since concentrations reported in figure 28 are for the entire water column, values are lower at station 1 where the lake is 24 m than at stations 5 and 6 where the lake is 15 and 11 m, respectively.

The dominant algal species in Lake of the Arbuckles during the summer were desmids, diatoms, phytoflagellates, and blue-green algae (tables 18 and 19). The most abundant desmid was *Pediastrum simplex; Melosira distans* the most abundant diatom during 1974. Blue-green algae were relatively more abundant during late summer of 1974 than 1975.

The algal flora was similar in composition in 1974 and 1975. No apparent significant shift in species composition can be related to lake mixing. An overall decline in algal density towards late summer was reflected in a general decline in the biomass of chlorophyll *a*.

Operation of the Garton pump in Lake of the Arbuckles did not result in an algal bloom and nuisance blue-green algae never became a problem, probably because upwelling of nutrient-rich water never occurred.

Zooplankton

Materials and methods.–Zooplankton was not collected during the 1974 sampling. During 1975, three samples each were taken with a Juday plankton trap from the surface and 4, 8, 12, 16, 20, and 24 m in the central pool at station 1. Collection times were approximately the same as for benthic macroinvertebrates except no sample was taken on January 25. Samples were preserved and analyzed as described for Ham's Lake.

Results.–Twenty-four taxa of zooplankton were taken from station 1 in Lake of the Arbuckles during the five time periods (table 20). Since the lake was not destratified during the study, the

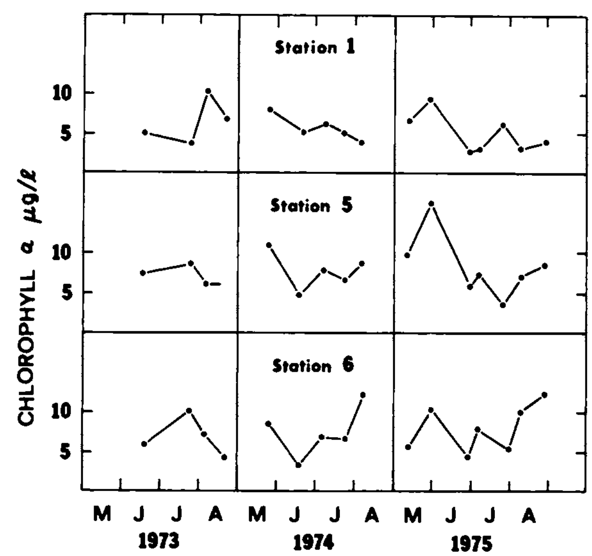

Figure 28.–Mean concentrations of chlorophyll *a* in the water column at three stations at Lake of the Arbuckles.

Table 18.—*Density of algae as numbers/mℓ in Lake of the Arbuckles during 1974*

	Date			
	5/23	6/21	7/9	7/25
Chlorophyta				
Ankistrodesmus sp	17.7	5.4	—	0.2
Closterium sp.	0.2	0.5	—	4.3
Coelastrum microporum	7.6	0.9	0.7	+
Cosmarium sp.		0.3	0.2	1.1
Kirchneriella sp.		—	—	+
Pediastrum simplex	132.4	64.1	58.4	19.0
Scenedesmus sp.	1.3	—	0.5	—
Staurastrum sp.		0.3	0.3	1.4
Tetraedon sp.		—	—	—
Chrysophyta				
Asterionella formosa	—	—	—	0.2
Caloneis amphisbaena	—	—	—	+
Caloneis bacillum	—	—	—	+
Caloneis sp.	—	—	—	0.2
Cocconeis placentula	—	0.3	—	—
Cyclotella meneghiniana	—	0.5	—	0.6
Cymbella tumida	—	—	—	—
Cymbella turgida	—	—	—	—
Cymbella ventricosa	0.1	—	—	0.2
Diatoma vulgare	—	—	0.2	—
Diploneis smithii	0.1	—	0.2	0.6
Epithemia sorex	—	—	0.2	—
Fragilaria crotenensis	—	0.3	—	+
Fragilaria sp.	—	0.3	—	+
Gomphonema augustatum	1.0	—	0.2	0.2
Gomphonema olivaceum	1.7	0.2	0.2	0.9
Gyrosigma spencerii	—	—	—	—
Mallomonas sp.	—	—	—	1.8
Melosira distans	8.0	52.0	66.2	30.6
Melosira granulata	—	0.5	0.9	1.1
Melosira varians	—	—	—	—
Navicula elginensis	—	0.3	—	—
Navicula lacustris	0.7	0.8	—	2.8
Navicula seminulum	—	—	—	—
Navicula sp.	0.2	0.2	—	—
Nitzschia acicularis	—	—	—	—
Nitzschia dissipata	+	—	0.3	3.9
Nitzschia filiformis	0.1	—	—	—
Nitzschia parvula	—	—	0.2	—
Nitzschia sigmoidea	+	—	—	0.2
Nitzschia tryblionella	+	—	—	—
Rhoicosphenia curvata	+	—	—	—
Stephanodiscus astrae	7.7	3.4	0.8	—
Surirella brightwellii	—	—	—	—
Synedra sp.	—	—	8.7	67.2
Synedra ulna	—	—	0.2	6.2

Table 18.—*Density of algae as numbers/mℓ in Lake of the Arbuckles during 1974—Continued*

	5/23	6/21	7/9	7/25
Cyanophyta				
Anabaena sp.	0.4	+	0.2	5.6
Aphanizomonon flos-aguae	—	—	—	—
Merismopedia sp.	—	—	—	—
Oscillatoria sp.	0.2	—	3.2	37.9
Euglenophyta				
Euglena sp.	—	3.5	3.7	21.3
Phacus sp.	—	—	—	1.0
Pyrrophyta				
Ceratium hirundinella	0.3	6.9	1.0	1.8
Glenodinium pulvisculus	—	—	—	0.3

trends resulted from seasonal changes. As in Ham's Lake, most taxa were present at most depths and few species were consistently numerous. The rotifer, *Conochilus* sp., was abundant at the middle depths on May 9, but was rare on all dates in subsequent samples. This species was most abundant in Ham's Lake on May 21. Although *Keratella* sp. was generally collected throughout the study at all depths, it was most common on May 22. This rotifer was collected throughout the study in Ham's Lake. A species of the genus, *Trichocerca*, was common at the surface and 2 m on May 22, and rare on other dates. This species was not taken in Ham's Lake. The cladoceran, *Bosmina longirostris*, was relatively common in the summer samples.

Number of species ranged from 3 to 15 (table 21), which was slightly lower than the range reported for Ham's Lake. As in Ham's Lake, no consistent relationship was observed between numbers of species and depth. Minimum numbers generally were collected at the surface, while maximum numbers occurred between 4 and 12 m. Numbers were generally low at 20 and 24 m. Fewer species occurred at most depths in August, while maximum numbers occurred in spring.

Density ranged from 27 to 576 organisms/l (table 21). This was similar to the range for Ham's Lake. A slight tendency existed for density to decrease with depth; however, no apparent relationship existed between density and the measured physicochemical conditions. Density tended to decrease with time and minimum density occurred at all depths in August.

Species diversity ($\bar{d}$) of zooplankton ranged from 1.2 to 3.1 (table 21). As in Ham's Lake, no relationship was observed between density and depth or between diversity and time. Minimum diversity was measured in the surface sample during three sampling periods.

Benthic Macroinvertebrates

Materials and methods.–Six samples each were taken with an Ekman dredge from 1, 5, 10, and 15 m at two transects in Lake of the Arbuckles. The two transects extended from the central pool into the Buckhorn Creek and Rock Creek arms. Six samples were taken from the 24-m depth at station 1 in 1974. Samples were processed as described for Ham's Lake. In 1975, four samples each were taken from depths of 1, 2, 4, 7, 11, 15, and 19 m in the Buckhorn Creek arm of the lake and from 24 m in the central pool. Samples were taken on January 25, May 9, June 21, and August 8. The latter two periods were after pumping operations began on May 23.

Results.–Ninety-five taxa were collected in Lake of the Arbuckles during the study (table 22). As was noted in Ham's Lake, one or two common species and many rare species were taken from

Table 19.—*Mean density of algae as number of organisms/mℓ for station 1 in Lake of the Arbuckles during 1975*

	Dates					
	5/12	6/9	6/24	7/25	8/9	8/30
Chlorophyta						
Ankistrodesmus sp.	6.6			+	2.6	6.2
Asterococcus sp.			+	+	6.2	+
Chlorococcum sp.		6.6	50.1	36.9	19.3	27.3
Closteriopsis			2.6			
Coelastrum microporum	6.6	+	6.2	7.9	2.6	
Cosmarium sp.		+		+	2.6	+
Crucigenia	+	6.6	12.3	+	8.8	6.2
Kirchneriella lunaris		+	+		6.2	6.2
Kirchneriella sp.	+		12.3	+		6.2
Pandorina					+	+
Pediastrum duplex	+					
Pediastrum simplex	6.6	6.6	12.3	7.9	2.6	+
Pediastrum tetras	+	+	2.6	7.9		
Scenedesmus sp.	6.6	15.5				
Sorastrum	+			+		+
Staurastrum		+		7.9	6.2	6.2
Tetraedron regulare		6.6	2.6	+		6.2
Tetraedron sp.		+		+	+	
Unknowns						
Flagellate	221.1	221.1	19.3	134.5	22.9	39.6
Green colonial			2.6			
Chrysophyta						
Achnanthes sp.					+	2.6
Amphora ovalis		+				2.6
Asterionella formosa		+	+			
Cocconeis				+		
Cyclotella meneghiniana	+	6.6	8.8	118.7	8.8	8.8
C. stelligera	6.6	+	2.6	7.9	12.3	2.6
Cymbella sp.	+	+				
Diatoma		+				
Dinobryon	6.6	6.6	2.6			
Diploneis smithii	6.6			+	2.6	+
Fragilaria crotonensis	168.1	31.0	27.3		+	+
Fragilaria sp.		6.6			+	+
Gyrosigma			+			
Melosira distans	15.5	22.1	8.8	+	+	2.6
Melosira granulata	322.8	31.0	19.3	+	+	+

Table 19.—*Mean density of algae as number of organisms/mℓ for station 1 in Lake of the Arbuckles during 1975—Continued*

	5/12	6/9	6/24	7/25	8/9	8/30
Chrysophyta—Continued						
Melosira italica		+				
Melosira varians						
Navicula elginensis	+	+				
Navicula pygmaea						+
Navicula sp. 1	+		+	+	+	
2	+	6.6	2.6		2.6	+
3		6.6	2.6		+	+
4	+					
5			+			
6			+			+
Nitzschia amohiba			+			
Nitzschia hungarica		+				
Nitzschia linearis						2.6
Nitzschia palea	+	6.6		+	2.6	6.2
Nitzschia parodoxa	+					
Nitzschia parvula						
Nitzschia sigmoidea						
Nitzschia tryblionella	+		+			
Nitzschia unknown 1	+	+	+	+	2.6	6.2
2	+					
Opephora						+
Pseudotetraedron		+		+	+	+
Rhoicosphenia curvata	+					
Rhopalodia		6.6	2.6			
Stephanodiscus astrea	+	19.5	+			
Stephanodiscus sp.	15.5	39.8	19.3	18.5	+	15.8
Synedra rumpens				+		
Synedra sp. 1		+		422.0	16.1	141.6
2		+		26.4	2.6	12.3
Synedra ulna		+	+	+	+	+
Euglenophyta						
Euglena sp.	6.6	+	6.2	+	2.6	
Phacus sp.		+	+	+		2.6
Pyrrophyta						
Ceratium hirundinella	+	+	+	+		
Ceratium sp.			+			
Dinoflagellate unknown 1		6.6	2.6			2.6
2			6.2	7.9		2.6
Cyanophyta						
Anabaena sp 1	395.8	57.5	8.8	36.9	12.3	15.8
sp 2	6.6	322.9	97.7	18.5	30.8	12.3
Microcystis sp 1	6.6	6.6	2.6			
2			2.6	18.5	6.2	6.2

+ observed but not enumerated.

Table 20.—*Zooplankton collected in Lake of the Arbuckles from May to August 1975*

Rotifera
- Ploima
  - *Keratella* sp.
  - *Trichocerca* sp. 1
  - *Trichocerca* sp. 2
  - *Asplanchna* sp.
  - *Polyarthra* sp.
  - *Synchaeta* sp.
- Flosculariaceae
  - *Filinia* sp.
  - *Hexarthra* sp.
  - *Conochiloides* sp.
  - *Conochilus* sp.

Arthropoda
- Cladocera
  - *Diaphanosoma leuchtenbergianum* (Fischer)
  - *Daphnia ambigua* Scourfield
  - *Daphnia parvula* Fordyce
  - *Ceriodaphnia lacustris* Birge
  - *Bosmina longirostris* (O. F. Müller)
- Ostracoda
  - Unidentifiable species
- Copepoda
  - *Diaptomus pallidus* (Bottom)
  - *Diaptomus siciloides* Lillieborg
  - *Tropocyclops prasinus* (Fischer)
  - *Cyclops bicuspidatus* Claus
  - *Mesocyclops edax* (S. A. Forbes)
  - Harpacticoid copepod
  - *Ergasilus chautauquaensis* Fellows
  - Nauplii
  - Copepodites
- Diptera
  - *Chaoborus* sp.

the 1-m depths and the deeper depths were limited to several abundant species. Tubificids were generally common at 1 m during the summer of 1974. The amphipod, *Hyalella azteca,* was the most numerous invertebrate at 1 m in the Buckhorn Creek arm on July 9. The elmid beetle, *Dubiraphia* sp., was the most abundant in the Rock Creek arm on August 7, while *Tanypus* sp. was common on August 7. At 5 m, the midge, *Tanypus* sp., was generally abundant in both arms. The benthic assemblage was dominated by the phantom midge, *Chaoborus punctipennis,* at 10 and 15 m and by the tubificid worm, *Aulodrilus pigueti,* at the 24-m depth.

Number of species in the preliminary study ranged from 2 to 19 (table 23). As in Ham's Lake, number of species tended to decrease with depth, with an abrupt decrease occurring between 1 and 5 m and generally a second sharp decrease between 5 and 10 m. More species were taken on July 9 than on August 7.

Density ranged from 321 to 6176 individuals/m² (table 23). The abundance of invertebrates was generally greater in Lake of the Arbuckles than in Ham's Lake. Density tended to increase with depth in the Rock Creek arm on both sampling dates, while the minimum occurred in the middle depths in the Buckhorn Creek arm. This same trend was observed in Ham's Lake. The 24-m depth supported a large population. Thus, the relationship between density and depth differed at the two stations.

Species diversity ($\bar{d}$) ranged from 0.1 to 3.5 in summer 1974 (table 23). Diversity was generally

Table 21.—*Number of taxa (s), numbers/ℓ (n), and species diversity ($\bar{d}$) of zooplankton by depth in the central pool during 1975 in Arbuckle Reservoir**

Depth, m	May 9			May 22			June 21			August 8		
	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$
Surface	6	39	1.3	9	210	1.8	7	84	2.6	6	30	1.8
4	13	576	1.8	12	200	2.3	12	245	3.1	13	177	3.0
8	14	362	1.9	10	84	2.0	9	127	2.7	11	74	2.7
12	14	231	1.8	15	167	2.8	10	153	2.9	8	43	2.5
16	13	242	1.6	11	142	2.3	11	208	2.8	8	76	2.8
20	9	173	1.4	10	143	2.6	10	99	2.7	3	27	1.2
24	13	178	2.2	9	145	2.4	10	135	2.9	6	35	1.9

* Values are total number of taxa, mean density, or species diversity of three Juday plankton trap samples. Double vertical line designates beginning of pumping.

Table 22.–*Benthic macroinvertebrates collected in Arbuckle Reservoir from July 1974 to July 1975*

Coelenterata
  Hydrozoa
    Hydra sp.
Platyhelminthes
  Turbellaria
    Dugesia sp.
Nematoda
    Unidentified species
Annelida
  Hirudinea
    Unidentified species
  Oligochaeta
    Chaetogaster sp.
    Dero digitata (Muller)
    Nais variabilis Piguet
    Slavinia appendictulata (d'Udekem)
    Stylaria lacustris (Linn.)
    Unidentifiable Naididae
    Aulodrilus pigueti Kowalewski
    A. pleuriseta (Piguet)
    Branchiura sowerbyi Bedd.
    Ilyodrilus templetoni (Southern)
    Limnodrilus cervix Brinkhurst
    L. claparedianus Ratzel
    L. hoffmeisteri Clap.
    L. udekemianus Clap.
    Potomothrix sp.
    Tubifex tubifex (O.F.M.)
    Tubificid sp. A
    Tubificid sp. B
    Tubificid sp. C
    Unidentifiable tubificid w/capilliform chaetae
    Unidentifiable tubificid w/out capilliform chaetae
Arthropoda
  Arachnida
    Hydracarina sp. A
    Hydracarina sp. B
    Hydracarina spp.
  Crustacea
    Hyalella azteca (Saussure)
  Insecta
   Ephemeroptera
    Hexagenia limbata (Serville)
    H. rigida
    Brachycercus sp.
    Caenis sp.

Table 22.–*Benthic macroinvertebrates collected in Arbuckle Reservoir from July 1974 to July 1975*–Continued

Arthropoda –Continued
  Odonata
    Epicordulia sp.
    Gomphus sp.
    Libellula sp.
    Ischnura sp.
    Unidentifiable Coenagrionidae
  Megaloptera
    Sialis sp.
  Coleoptera
    Dubiraphia sp.
    Haliplus sp.
    Stenelmis sp.
    Unidentifiable Elmidae
    Unidentifiable Hydroporinae
  Trichoptera
    Oecetis sp.
    Unidentifiable Leptoceridae
    Polycentropus sp.
    Psychomyiid genus A (Ross)
    Neotrichia sp.
    Orthotrichia sp.
    Unidentifiable trichopteran A
    Unidentifiable trichopteran B
  Diptera
    Bezzia sp.
    Unidentifiable Ceraptopogonidae
    Chaoborus punctipennis (Say)
    Ablabesmyia sp.
    Clinotanypus sp.
    Coelotanypus sp.
    Labrundinia sp.
    Procladius sp.
    Tanypus sp.
    Unidentified Pentaneurini
    Chironomus sp.
    Cryptochironomus sp.
    Dicrotendipes sp.
    Endochironomus sp.
    Glyptotendipes sp.
    Harnischia sp.
    Kiefferulus sp.
    Lauterborniella sp.
    Parachironomus sp.
    Paralauterborniella sp.
    Phaenopsectra sp.
    Polypedilum sp.

Table 22.–*Benthic macroinvertebrates collected in Arbuckle Reservoir from July 1974 to July 1975* –Continued

Arthropoda –Continued

Pseudochironomus sp.
Stentochironomus sp.
Stictochironomus sp.
Tribelos sp.
Cladotanytarsus sp.
Micropsectra sp.
Rheotanytarsus sp.
Tanytarsus sp.
Diamesa sp.
Chironomini sp. A
Chironomini sp. B
Chironomini sp. C
Chironomini sp. F
Cricotopus sp.
Metrionemus sp.
Orthocladius sp.
Psectrocladius sp.
Trichocladius sp.
Trissocladius sp.
Chironomid pupae

Mollusca
Pelecypoda
Pisidium sp.
Sphaerium sp.
Unidentified Unionidae
Gastropoda
Physa sp.

higher in Ham's Lake than in Lake of the Arbuckles. As observed in Ham's Lake, diversity tended to decrease with depth, although minimum diversity was observed at 10 m in the Buckhorn Creek arm on both sampling dates. These low diversities resulted from the dense population of *Chaoborus punctipennis* at 10 m. Diversity decreased with time as was observed for number of species in Lake of the Arbuckles and for diversity in Ham's Lake.

In 1975, three sets of samples were taken before pumping started on May 25 and two sets following. However, since pumping did not destratify the lake during the study period, the changes in density are due to seasonal environmental changes. Several species were present in large numbers. *Stylaria lacustris*, which was common in Ham's Lake, was extremely abundant on January 25 in Lake of the Arbuckles at 1 and 2 m and tended to decrease with time. *Hyalella axteca* was abundant at 1 m in winter and in the summer samples. The midge, *Tanytarsus* sp., also common in Ham's Lake, was generally common at the 1- and 2-m depths expect in August. At 2 m, the midge, *Chironomini* sp., reached a density of 4198 individuals/m² on January 25, while the midge, *Cladotanypus* sp., was abundant on the first two sampling dates and the segmented worm, *Tubifex tubifex*, on May 22. During the first three sampling dates, *Chironomus* sp. was abundant at 2 and 4 m and *Coelotanypus* at 2, 4, and 7 m. The midge, *Procladius* sp., which was common

Table 23.—*Number of taxa (s), numbers/m² (n), and species diversity ($\bar{d}$) of benthic macroinvertebrates by station and depth during summer 1974 in Lake of the Arbuckles**

Station	Depth, m	July 9			August 7		
		s	n	$\bar{d}$	s	n	$\bar{d}$
AD	1	16	321	3.5	15	909	3.2
	5	8	1090	2.0	11	1006	2.3
	10	8	2303	1.8	6	3213	0.3
	15	3	3135	0.5	3	6176	0.1
AE	1	19	572	3.1	14	666	3.2
	5	13	495	3.1	12	458	2.8
	10	5	3091	0.6	2	430	0.1
	15	4	3133	0.6	5	3385	0.7
A	24	4	1126	2.0	2	6327	1.9

* Values are total number of taxa, mean density, or pooled diversity of six Ekman dredge hauls.

in spring in Ham's Lake, was generally common at the middle depths in Lake of the Arbuckles except in August.

The lower depths in Lake of the Arbuckles had several extremely abundant species. The segmented worm, *Aulodrilus pigueti*, attained a density of over 19 000 individuals/m² at 24 m on May 9. This species was also common in shallower depths on May 22 and June 21. The phantom midge, *Chaoborus punctipennis*, the most common species in deeper waters of Ham's Lake, was abundant in Lake of the Arbuckles on January 22 and August 8. *A. pigueti* and *C. punctipennis* were commonly collected in deeper water in summer 1974. Although the segmented worm, *Dero digitata*, was common at several shallower depths, it reached especially larger numbers at 24 m in May and June in deeper waters. This species was also common in deeper waters in spring in Ham's Lake, but rare in June and July.

Total number of species taken at a particular depth and time in Lake of the Arbuckles during 1975 ranged from 1 to 30 (table 24), which was similar to the range reported in Ham's Lake in 1975. As was observed in the preliminary study, number of species exhibited two sharp decreases, between 2 to 4 m and 7 to 11 m on January 25. However, one significant decrease was noted on subsequent dates; between 7 and 11 m on May 9 and between 2 and 4 m on subsequent dates. Numbers decreased by 20 between 2 and 4 m on August 8. Number of species tended to decrease slightly with time, especially during the summer at the deeper depths, reflecting the almost anoxic conditions.

Density ranged from 292 to 20 689 individuals/m² (table 24). The latter number was due largely to a population of the segmented worm, *Aulodrilus pigueti*. Density was generally greater than in Ham's Lake. Density was not clearly correlated with depth. Minimum diversity occurred at the middle depths, while maximum diversity occurred at 24 m on three sampling dates. Minimum density was observed in middle depths in Ham's Lake. Density tended to decrease with time although no consistent relationship was noted. This trend was also observed in Ham's Lake.

Species diversity ($\bar{d}$) ranged from zero to 4.4, both extremes occurring on August 8 (table 24). The latter value was the highest measured during the entire study in the two lakes. Diversity tended to decrease with depth as was observed for numbers of species. Minimum diversity was measured at the 24-m depths during all time periods except August 8. Diversity was especially low below 4 m on August 8. No consistent relationship was observed between diversity and time.

Fish

Depth distribution and annual and seasonal growth rates are described for five species of fish collected from Lake of the Arbuckles, Okla., 1973 through 1975. These observations include:

1. Temporal variation in area and volume of fish habitat.

2. Annual variation in fish species composition.

3. The vertical depth distribution of those five species in relation to conditions of stratification.

4. Instantaneous growth rates of the selected species at triweekly periods over the late spring and summer and for winter and summer intervals of 1973, 1974, and 1975.

Methods and materials–Collecting sites.–Vertical distribution and growth of fish were measured at three sites (3, 4, and 5) located in each arm of the reservoir and site 2 located within 200 m of P, the location of the pump (fig. 12). Growth analysis was done by pooling data on fish from all sites.

Sampling procedures.–Fish were sampled with experimental gill nets, 45.7 m long, divided into six 7.6 m-panels with individual panel square mesh sizes of 13, 25, 28, 64, and 76 mm. Nets were fished in a horizontal position on the bottom at depths of 0 to 5 m, 5 to 10 m, and 15 to 20 m. The nets were set at the specific intervals, located with the aid of a recording ecosounder, to sample the epilimnion, metalimnion, and hypolimnion.

Table 24.—*Number of taxa (s), numbers/m² (n), and species diversity ($\bar{d}$) of benthic macroinvertebrates by depth at station AE during 1975 in Lake of the Arbuckles**

Depth, m	January 25			May 9			May 22			June 21			August 8		
	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$	s	n	$\bar{d}$
1	23	5 112	2.8	21	2 049	3.6	26	7 708	3.3	25	2 236	3.4	27	2 370	3.9
2	30	11 580	3.3	23	4 853	3.6	22	6 834	3.1	22	3 164	3.7	30	1 615	4.4
4	20	2 910	2.6	23	3 427	3.6	14	2 745	2.7	14	2 901	2.9	10	1 098	2.1
7	17	1 288	3.0	18	2 456	2.8	16	1 348	2.8	17	1 648	2.9	4	2 369	0.2
11	10	1 507	2.6	8	614	1.9	9	1 001	2.6	10	1 971	2.3	1	1 173	0.0
15	8	2 380	1.4	9	745	2.4	15	1 444	3.1	7	2 400	2.0	3	2 563	0.6
19	9	3 942	1.4	10	.1 141	2.6	12	7 407	2.3	7	292	2.2	2	1 034	0.1
24	8	1 819	0.8	5	20 689	0.4	10	7 333	1.2	7	3 497	1.1	5	3 111	1.2

* Values are total number of taxa, mean density or pooled diversity of four Ekman dredge hauls
Double vertical line designates beginning of pumping (i.e., May 25, 1975)

Each week one net was fished at each of the four depth contours at each of sites 3, 4, and 5 and three nets were fished at each of the four depths at site P (pump). Therefore, half the sampling effort took place near the pump (mixing device, i.e., experimental area) and half from elsewhere in the lake (control area). Nets were fished for 19 to 28 hours, but the catch was adjusted to express number of fish per 24 hours.

In 1973, fish collections were made for 15 continuous weeks from May 14 to August 24 and an additional collection was obtained October 18-21, 1973. In 1974, a collection was made March 10-14, but regular weekly collections began May 10 and continued through August 23, 1974. A final 1974 collection was made September 9-13, to monitor growth and distribution after the lake had destratified. In 1975, weekly collections began May 12 and continued through August 22. A collection was obtained September 22-26, after the lake had destratified.

Instantaneous growth.–Instantaneous growth rates were calculated at 3-week intervals for all age groups of five selected species. The instantaneous growth coefficient, G, was measured using the equation:

$$G = \frac{\log_e(\bar{w}_2) - \log_e(\bar{w}_1)}{\Delta t}$$

where:

$\bar{w}_1$ and $\bar{w}_2$ = mean weights of fish at time t_1 and t_2 (Chapman [39]).

The G values were also calculated for the intervals (1) between the first summer collection and the fall collection, and (2) the interval between the fall collection and the spring (i.e., the overwintering period). These G values were then examined in relation to conditions of stratification to establish a causal relationship between growth and environmental changes within the lake. The G value represents an estimate of the collective mean growth rate of the year-class; it is not a mean rate for growth of the fish in the sample, for the latter could be obtained only if marked fish were recaptured. Growth estimates of the year-class will probably be lower than means of individual fish growth for fish older than age 1 or 2 (Ricker [40]).

Bathymetric distribution.–The vertical distribution of five species adequately represented in the collection are described using weekly gill net catches at 0 to 5 m, 5 to 10 m, 10 to 15 m, and 15 to 20 m. The MDC (mean depth of capture), basically a weighted mean, was calculated from the captures of each net, assumed to be at the midpoint of each depth interval. The bathymetric distribution of each species was considered in relation to the degree of stratification. Correlation coefficients were calculated for relation between MDC and temperature at the MDC, and between MDC and D.O. at the MDC. Temperature and D.O. measurements were taken weekly at 1-m intervals at all sites using a D.O. probe and thermistor.

Results–Habitat analysis.–The literature survey by Doudoroff and Shumway [41] indicated that fish generally avoid water containing less than 2 mg/l D.O. The area and volume of suitable fish habitat in Lake of the Arbuckles was calculated weekly for each of the 3 years of study, 1973 through 1975 (table 24) using the 2-mg/l D.O. isopleth (the lake contour at which 2 mg/l D.O. was present) as the lower level of suitable fish habitat. By mid-May, Lake of the Arbuckles was thermally stratified, D.O. profiles were generally clinograde, and the lake became anoxic within 2 m below the 2-mg/l D.O. isopleth. In 1973, the percentage of the lake's volume with more than 2 mg/l D.O. declined from 100 percent on May 18 to 89 percent on May 31 (table 25). In 1974, oxygen depletion had begun as early as May 19, and depletion reduced available habitat to 81 percent of the total volume by June 3 (table 25). In 1975, 98 percent of the volume contained more than 2 mg/l D.O. on May 12, but by June 2 only 70 percent of the lake's volume contained more than 2 mg/l D.O. (table 25).

Water containing more than 2 mg/l D.O. was substantially reduced in Lake of the Arbuckles during midsummer: (1) in 1973, as much as 48 percent of the total lake volume contained

***Table 25.**—Volume of Lake of the Arbuckles with more than 2 mg/ℓ D.O. in 1975 and the area of the lake's basin overlaid with water containing more than 2 mg/ℓ D.O.*

Month, day	1973 Area, hectares*	1973 Volume, m³ × 1000	1974 Month, day	1974 Area, hectares	1974 Volume, m³ × 1000	1975 Month, day	1975 Area, hectares	1975 Volume, m³ × 1000
—	—	—	—	—	—	May 12	893(94)	87 970(98)
May 18	950(100)**	89 304(100)**	May 12	770(81)	81 600(91)	May 19	770(82)	82 067(92)
May 23	823(87)	84 928(95)	May 27	703(74)	76 049(85)	May 26	702(74)	77 466(87)
May 31	742(78)	79 778(89)	June 3	640(67)	72 049(81)	June 2	527(56)	62 187(70)
June 8	677(71)	78 715(88)	June 10	648(68)	72 660(81)	June 9	533(56)	62 618(70)
June 15	624(66)	70 827(79)	June 17	582(61)	66 957(75)	June 16	582(61)	66 930(75)
June 22	544(57)	63 510(71)	June 24	533(56)	62 644(70)	June 23	538(57)	63 051(71)
June 29	507(53)	60 481(68)	July 1	528(56)	62 211(70)	June 30	400(42)	50 633(57)
July 6	438(46)	54 257(61)	July 8	496(52)	59 615(67)	July 7	337(35)	44 128(49)
July 13	383(40)	48 937(55)	July 15	507(53)	60 480(68)	July 14	314(33)	41 735(47)
July 20	363(38)	46 841(52)	July 22	438(46)	54 258(61)	July 21	344(36)	44 727(50)
July 27	378(40)	48 338(54)	July 29	448(47)	55 287(62)	July 28	320(34)	42 332(47)
Aug. 4	438(46)	54 257(61)	Aug. 5	574(60)	66 230(74)	Aug. 4	291(31)	39 097(44)
Aug. 10	432(45)	53 742(60)	Aug. 12	671(71)	74 492(83)	Aug. 11	276(29)	37 048(41)
Aug. 17	372(39)	47 739(53)	Aug. 19	671(71)	74 492(83)	Aug. 18	366(39)	47 123(53)
Aug. 24	363(38)	46 841(52)	—	—	—	—	—	—
Aug. 31	—	—	—	—	—	—	—	—
—	—	—	Sept. 8	775(82)	81 939(92)	—	—	—
—	—	—	—	—	—	Sept. 22	940(99)	89 134(99)
Sept. 29	—	—	—	—	—	—	—	—
Oct. 7	—	—	—	—	—	—	—	—
Oct. 14	—	—	—	—	—	—	—	—
Oct. 20	950(100)	89 304(100)	—	—	—	—	—	—

* The surface area of the lake minus the surface area of a horizontal plane at the depth of the 2-mg/ℓ D.O. isopleth.

** Percent total area (951 hectares) and total volume (89 304 166 cubic meters).

less than 2 mg/l D.O. on July 20 and between July 13 and August 24, the average volume of available habitat was 55.3 percent of the total lake volume; (2) in 1974, with the Garton pump operating for 46 days between July 17 and August 31, the suitable volume of space never was less than 61 percent; and (3) in 1975, with the Garton pump operating for 104 days between June 2 and September 12, the volume of suitable habitat was as little as 41 percent and averaged only 47 percent between July 21 and August 18. By early June 1975, the lake was anoxic below about 10 m.

The volume of stored water in Lake of the Arbuckles containing more than 2 mg/l D.O. was calculated 1973 through 1975 for the 163-day interval from May 11 to October 20. During a typical year, when pumping efforts were not made to destratify the reservoir, this interval includes the period of summer stratification and spring and fall overturn. Therefore, between October 20 and May 11, 100 percent of the total lake volume should contain more than 2 mg/l D.O. Available fish habitat for the interval May 11 to October 20 was calculated by (1) interpolation from the weekly summaries (table 25) of available habitat, (2) extrapolation from the first sample each year back to May 11, and (3) extrapolation from the last sample each year to October 20.

The average volume of Lake Arbuckle with more than 2 mg/l D.O. present in the 163-day interval 1973-75 was 72.9, 82.7, and 72.7 percent, respectively, of a total of 8.93×10^6 m^3 of total lake volume. Thus, little difference existed between 1973 and 1975, but both years differed substantially from 1974.

In 1974, the pump was operated at 5 r/min (196 m^3/min) July 17-23.[2] Temperature and D.O. profiles collected July 8, 15, and 22 indicated pronounced thermal and chemical stratification for those three sample dates, and the degree of chemical stratification intensified; the 2-mg/l D.O. isopleth was at 10.6 m on July 8, 8.9 m on July 15, and 8.0 m on July 22. On July 24, the pump velocity was increased from 5 to 9 r/min (352.8 m^3/min) and maintained at that speed through August 1. Although the pumping volume increased by a factor of 1.8, after 6 days of pumping the 2-mg/l D.O. isopleth remained at 8 m. On August 2, the pumping rate was increased again by increasing the r/min from 9 to 12 (capacity from 352.8 to 470.4 m^3/min). Within 4 days the depth of the 2-mg/l D.O. isopleth dropped to 15.4 m.

In 1975, the lake stratified by May 15. The volume of water containing more than 2 mg/l D.O. between May 11 and October 20, 1975 was 72.6 percent compared with 72.9 percent in 1973. In 1975, the pump was started June 2 at 18 r/min (705.6 m^3/min) and operated at this rate for 30 days through July 1. The operation of the pump at this capacity appeared responsible for a pronounced seasonal progression in the depth of the 2-mg/l D.O. isopleth: the 2-mg/l D.O. isopleth was 20.7 m on May 28, 16.0 m on June 5, 11.7 m on June 13, 10.6 m on June 20, and 10.0 m on June 25. Although the depth of the 2-mg/l D.O. isopleth also approached the surface in 1973 (fig. 29), the action of the pump accentuated the process. On July 2, when the rotational speed was increased to 20 r/min (784.0 m^3/min) and operated at this rate through September 12, the 2-mg/l D.O. isopleth moved upward from 7.8 m on July 7 to 4.5 m on August 11. In 71 days of pumping from May 28 to August 11, the depth of the 2-mg/l D.O. isopleth decreased from 20.7 to 4.5 m. On July 8, 1974, the 2-mg/l D.O. isopleth was at 10.6 m compared with 7.8 m depth for this isopleth on July 7, 1975. The differences in depth of the 2-mg/l D.O. isopleth between 1974 and 1975 appeared to be an effect of the increased pumping capacity obtained by a higher average r/min in 1975.

Although the pump circulated more water in 1975 than 1974, the upward movement of the 2 mg/l isopleth reduced fish habitat in 1975. In 1975, the vertical temperature profile on August 18 was nearly orthograde from the surface to 22 m. In 1975, water temperature below 12 m was substantially higher than in 1973 and 1974. This increase in water temperature appears to explain the shallower depth of the 2-mg/l D.O. isopleth in 1975 compared to 1974 because of the effect of higher temperatures on bacterial metabolism. Garton's pump quite obviously

[2] One r/min corresponds to a water flow rate of 39.2 m^3/min.

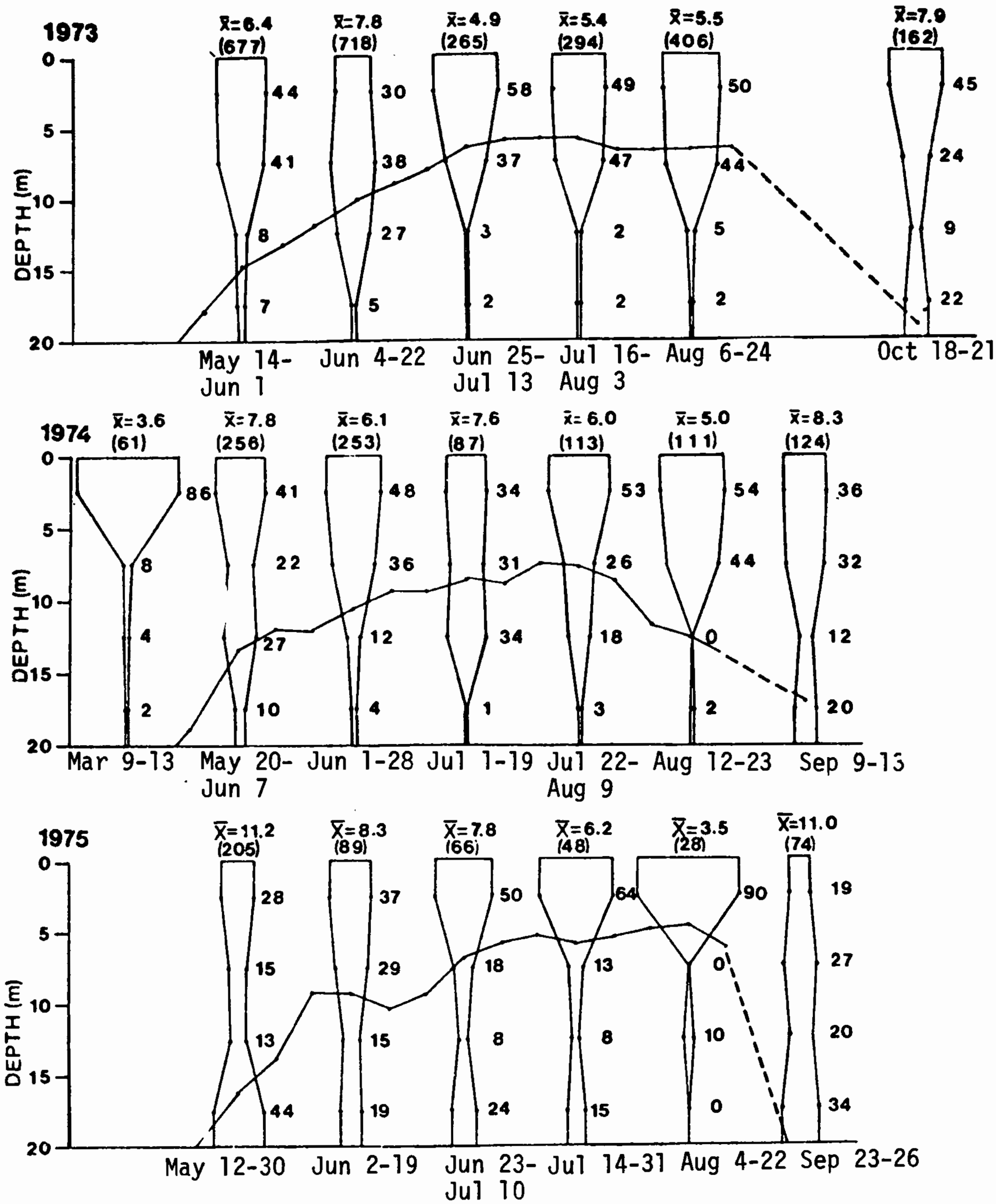

Figure 29.–Depth distribution of gizzard shad, represented by polygons that approximate the percentage (shown alongside the polygon) of fish captured at each depth interval, in relation to the 2-mg/l D.O. isopleth (curve); the $\bar{X}$ represents the MDC, and the value in ( ) the total adjusted number caught in that interval.

influenced temperature and D.O. profiles when temperature and D.O. profiles for September 12, 1974 are compared with similar profiles for September 1968-69 and 1973. Dissolved oxygen profiles (Duffer and Harlin [32]) for Lake of the Arbuckles on October 16, 1968 and October 15, 1969 indicated the 2-mg/l D.O. isopleth at 19.5 and 21.0 m, respectively, compared with a 24.4 m on September 22, 1975.

In 1973, epilimnetic surface water temperatures in Lake of the Arbuckles often exceeded what has been reported to be the preferred temperature of most species of fish (Ferguson [42]). Fish use their ability to move to cooler areas in the vicinity of the thermocline as a means of thermoregulation. Thus, during summer stratification, habitable water was reduced both because of high epilmnetic temperatures and an anoxic hypolimnion. The vertical depth distribution of certain fish were compressed into a narrow layer of water between the anoxic hypolimnion and the limiting temperatures in the upper epilimnion (Gebhart and Summerfelt [43]). It was not possible to elucidate fish depth distribution within the 0 to 5-m contour; however, gill net catches indicated that during the warmest part of midsummer, most of the fish in the 0- to 5-m contour were in the lower portion of the net.

Fish species composition.–The total number of species of fish captured was 19 in 1973 and 18 each in 1974 and 1975. In 384 gill net days of fishing each year, C/f (catch per unit of effort) declined from 13.13 fish per gill net-day in 1973 to 8.72 in 1974 and 7.61 in 1975 (table 26). A substantial part of this decline is due to the decline in C/f of gizzard shad. Without shad, the overall C/f value would be 6.57 in 1073 and 6.29 in 1975.

Determinations of instantaneous growth rates required large numbers of fish to overcome sample error caused by individual size variation. The five most numerous species captured in 1973, comprising 92.2 percent of the total catch, were gizzard shad (*Dorosoma* cepedianum), white crappie (*Pomoxis annularis*), black bullhead (*Ictalurus melas*), freshwater drum (*Aplodinotus grummines*), and channel catfish (*Ictalurus punctatus*) (table 26). These same five species predominated in the catch in 1974 and 1975, except that in 1973 channel catfish ranked fifth, but it was sixth ranking in abundance in 1974 and 1975, below white bass (*Morone chrysops*). For the sake of continuity, the five most abundant species of fishes in the 1973 catch were studied in all 3 years.

Bathymetric distribution and growth rates.–Each species exhibited a unique and characteristic growth and behavioral response to the same environmental factors; therefore, the results are presented by species.

Gizzard shad–Bathymetric distribution.–Gizzard shad were captured in all depth strata in early summer during all 3 years of study (fig. 29). In 1973, MDC declined from 6.4 m (May 14 to June 1) to 4.9 m (June 25 to July 13), corresponding to a decline in mean depth of the 2-mg/l D.O. isopleth; MDC was 5.4 m and 5.5 m in the next two intervals during July and August, but MDC went down in October to 7.9 m after the fall overturn. The 1974 and 1975 data show similar seasonal trends in MDC; however, the MDC of shad in midsummer (June 1 to August 9) was substantially greater in 1974 and 1975 than in 1973. In contrast, in the August 4-22, 1975 interval the depth of the 2-mg/l D.O. isopleth was only 4.7 m compared to 13.0 m midway in the August 12-23 interval in 1973, and 6.8 m midway through the August 6-24, 1973 interval. In the August 1975 interval, 64 to 90 percent of the catch of shad was in the 0- to 5-m depth interval. The depth distribution of gizzard shad included the entire water column after the fall overturn.

In 1974, correlation coefficients for MDC of gizzard shad and depth of the 2-, 4-, 6-, and 8-mg/l D.O. isopleths ranged from 0.22 to 0.44, but were nonsignificant at the 5-percent level. In 1975, the correlation coefficients were nonsignificant for the relation between MDC at the 2-, 6-, and 8-mg/l D.O. isopleths, but the correlation for the 4-mg/l D.O. isopleth was significant at the 1-percent level.

Instantaneous growth rates.–Instantaneous growth rates or growth coefficients (G values), were calculated at 3-week intervals during the summer and for longer intervals between summer and fall, and fall and spring for age groups III, IV, and V, which were adequately represented in the

Table 26.—*Numerical abundance, percent of total catch, and catch per gill net-day of 20 species of fishes collected by gill netting in Lake of the Arbuckles in 1973–75*

Species	1973			1974			1975		
	No.	%	C/f*	No.	%	C/f*	No.	%	C/f*
Gizzard shad	2522	49.98	6.57	1005	29.99	2.62	510	17.43	1.33
White crappie	833	16.51	2.17	977	29.16	2.54	843	28.81	2.20
Black bullhead	579	11.47	1.51	506	15.10	1.32	470	16.06	1.22
Freshwater drum	409	8.11	1.07	299	8.92	0.78	431	14.73	1.12
Channel catfish	311	6.16	0.81	176	5.25	0.46	113	3.86	0.29
White bass	159	3.15	0.41	266	7.94	0.69	277	9.47	0.72
Carp	89	1.76	0.23	32	0.95	0.08	32	1.09	0.08
Walleye	49	0.97	0.12	36	1.07	0.09	19	0.65	0.05
Largemouth bass	28	0.55	0.07	20	0.60	0.05	14	0.48	0.04
River carpsucker	23	0.46	0.06	7	0.21	0.02	28	0.96	0.07
Black crappie	22	0.44	0.06	11	0.33	0.03	9	0.31	0.02
Longnose gar	8	0.16	0.02	4	0.12	0.01	1	0.03	0.00
Flathead catfish	4	0.08	0.01	8	0.24	0.02	12	0.41	0.03
Yellow bullhead	5	0.10	0.01	0	0.00	0.00	0	0.00	0.00
Warmouth	0**	—	—	0**	—	—	26	0.89	0.07
Green sunfish	0**	—	—	0**	—	—	9	0.31	0.02
Longear	0**	—	—	0**	—	—	15	0.51	0.04
Golden redhorse	0**	0.00	0.00	0**	0.00	0.00	3	0.10	0.01
Bluegill	0**	—	—	0**	—	—	114	3.90	0.30
Blue catfish	5	0.10	0.01	4	0.12	0.01	0	0.00	0.00
Total	5046	100.00	13.13	3351	100.00	8.72	2926	100.00	7.61

* Catch per unit of effort: the catch of fish, in numbers, taken in one gill net fished for 24 hours.
** These species were collected; counts were not made due to time limitations.

collections. The G value was computed for a day as the unit of time to facilitate comparisons over intervals representing a different number of days. None of the correlation coefficients (r values in table 27) were significant ($p > 0.05$) for the relation between the G values and available habitat, represented as percentage of the lake's total volume containing more than 2 mg/l D.O. for age groups III, IV, and V gizzard shad for 1973-75 (table 27). Therefore, the correlation coefficients were not large enough to be distinguished from mere sample error. Thus, the relation between seasonal changes in G and available habitat was not apparent.

Instantaneous growth rates for age group III shads were −0.17, 0.98, and 0.71 for the summers of 1973, 1974, and 1975 (table 28).

Table 27.—*Instantaneous growth coefficient (G) for gizzard shad and mean percentage of the lake's volume containing > 2 mg/ℓ D.O., during 1973, 1974, and 1975.*

Median collection date	Interval, days	Available habitat, %	G values by age group		
			III	IV	V
1973					
5-23-73*					
	19.5	88.4	-2.00	3.89	-0.85
6-12					
	21.0	71.9	-7.31	-14.14	-5.44
7-3					
	21.0	55.8	1.20	10.98	-0.72
7-24					
	21.0	58.0	3.02	-9.85	-2.27
8-14					
	66.5	73.4	1.16	5.63	2.61
10-19-73*					
	221.5	99.2	1.58	0.54	0.34
5-29-74					
			r = -0.13**	0.06	0.26
1974					
5-29-74					
	20.0	79.9	-2.69	2.22	-3.47
6-18					
	21.0	69.8	0.82	-3.42	-0.65
7-9					
	21.0	64.2	0.06	9.60	-0.06
7-30					
	17.5	77.1	0.15	—	-3.12
8-16*					
	26.0	87.9	6.56	-0.60	2.10
9-11-74					
	252.0	99.2	1.20	1.70	—
5-21-75					
			r = 0.42	-0.30	0.14
1975					
5-21-75					
	19.5	80.7	7.42	-4.63	0.67
6-9*					
	21.5	69.4	4.68	8.40	0.22
6-30					
	21.0	49.6	0.69	-8.76	-4.17
7-21					
	19.5	45.4	0.86	8.48	14.28
8-9*					
	46.5	72.9	-3.97	1.59	-9.23
9-24-75*					
			r = 0.34	-0.10	-0.51

* The exact median collection date was between this date and the following day.
** r = correlation coefficient.

Table 28.—*Comparison of growth rates (G) and mean weight gain (g) for gizzard shad for summer (stratified) and winter (destratified) intervals, 1973–75*

Median collection date	Interval	Days	Weight gain and (G) for age groups shown		
			III	IV	V
5/23/73					
	summer	149.0	-2.0(-0.17)	29.2(1.33)	-3.8(-0.13)
10/19/73					
	winter	221.5	31.1(1.58)	20.5(0.53)	14.5(0.33)
5/29/74					
	summer	105.5	8.7(0.98)	16.8(1.40)	-14.7(-0.79)
9/11/74					
	winter	252.0	31.4(1.20)	65.1(1.69)	—
5/21/75					
	summer	128.0	7.2(0.71)	18.8(1.13)	-37.0(-1.72)
9/24/75					

The G values were also higher in the summer of 1974 for age group IV shad, but summer growth of age group V were always negative (–0.13, –0.79, and –1.72 for 1973, 1974, and 1975, respectively). In the 149-day summer interval of 1973, change in mean weight of the age III shad was –2.0 g compared to 31.1 g over the 221.5-day winter interval of 1973-74. In the summer of 1974, the mean weight gain was 8.7 g compared to 31.4 g over the winter interval of 1974-75 when the lake was destratified. The winter-summer comparison in G values of the age group III indicates larger G values for the winter interval of 1973-74 and 1974-75 than the corresponding summers. For age Group IV, the G weight gain and G values in the summer of 1973 were larger than those for the winter 1973-74; however, the winter growth in 1974-75 was better than either the summer of 1974 or 1975. The only winter growth rate measure for age group V shad was larger than any summer interval for that age group. The G value of age group V shad in the summer of 1974 (0.33) was larger than the summers in 1973 (–0.13) and 1975 (–0.79).

For age group IV, mean weight gain per fish was greater in the summer of 1973 than for the winter interval; also, the G value was larger for the summer than the winter interval. Although these data did not substantiate the summer-winter growth differences observed for fish of age group III in the 1973-74 interval, the age group IV gizzard shad did have a larger G value in the summer of 1974 than in 1973. The growth coefficient of 1.69 for age group IV shad for the 252-day overwinter interval from September 11, 1974 to May 21, 1975 was larger than that of any previous interval.

White crappie–Bathymetric distribution.–In 1973 and 1975, the first collection intervals (May 14 to June 1, 1973 and May 12-30, 1974) occurred after the lake was stratified; therefore, the 2-mg/*l* D.O. isopleth was already above the lowest depth interval of 15 to 20 m (fig. 30). In 1973 and 1975, crappie were not collected in the anoxic 15- to 20-m stratum on the first date of the collection. In 1974, when 2 mg/*l* D.O. was near the bottom during the first collection interval (March 9-13), white crappie were caught at a 15- to 20-m interval.

During 13 of the 15 collection intervals when the lake was stratified, white crappie were not collected in the 15- to 20-m depth contours; the two exceptions were the July 16 to August 3, 1973, and June 23 to July 10, 1975 intervals. In 1975, MDC of white crappie was closely correlated ($r = 0.84$, $P < 0.01$) to the depth of the 2-mg/*l* D.O. isopleth. For 1974, the correlation was 0.60, but it was not significant at the 5-percent level (Gebhart and Summerfelt [43]).

During the August 4-22, 1974 interval, when the 2-mg/*l* D.O. isopleth was about 5 m, white crappie were entirely limited to the 0- to 5-m contour. In each year after the fall overturn, when oxygen was available at all depths, the MDC of white crappie was substantially larger, indicating that fish were deeper than prior to the overturn.

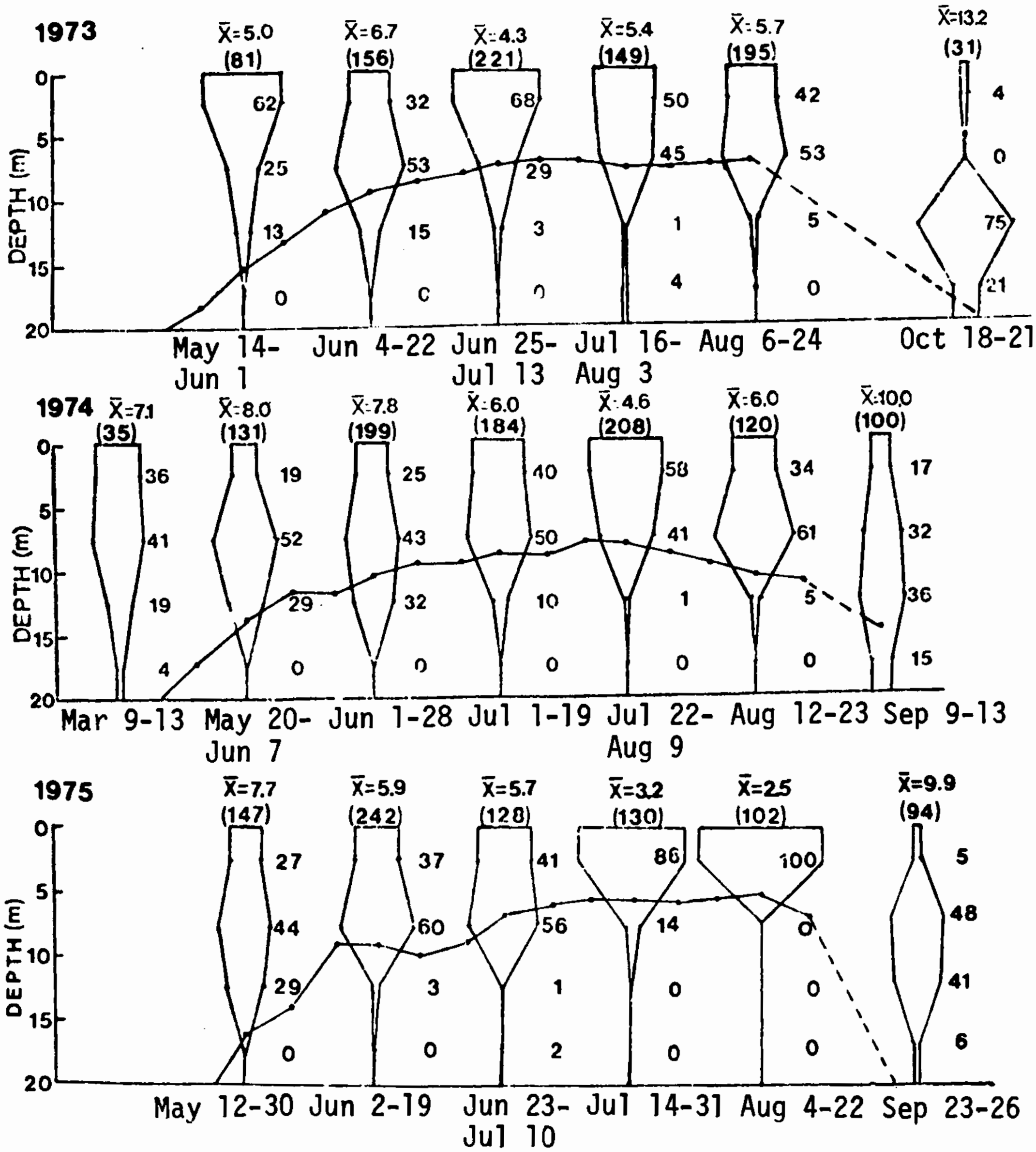

Figure 30.–Depth distribution of white crappie, represented by polygons that approximate the percentage (shown alongside the polygon) of fish captured at each depth interval, in relation to the 2-mg/l D.O. isopleth (curve); the X̄ represents the MDC, and the value in ( ) the total adjusted number caught in that interval.

Instantaneous growth rates.–The instantaneous growth rates (G values) calculated over intervals of 19.5 to 252.0 days in 1973-75 were generally positive for age group I white crappie (table 29), but substantial loss in mean weight, 22.1 g or 56 percent was observed between May 21 and June 9,1975. Age groups II and III white crappie also lost weight between these two collecting intervals. Weight loss for the 2- and 3-year-old fish might have been loss of gametes; spawning may have taken place at this time. White crappie spawn when water temperatures are about 17 to 20 °C, and on May 18 1973, the temperature profile was 20 °C through zero to 5 stratum which covers the range of depths where crappie spawn. However, it would be surprising to find age group I white crappie spawning because their sexual maturity is usually at 2 to 3 years of age Goodson [44]).

Table 29.—*Instantaneous growth coefficient (G) for white crappie and mean percentage of the lake's volume containing $>$ 2 mg/ℓ D.O. during 1973, 1974, and 1975*

Median collection date	Interval, days	Available habitat, %	G values by age group		
			I	II	III
			1973		
5-23*					
	19.5	88.4	—	7.49	-47.58
6-12					
	21.0	71.9	10.94	5.09	19.59
7-3					
	21.0	55.8	0.59	2.20	-5.77
7-24					
	21.0	58.0	7.38	-11.50	14.14
8-14					
	66.5	73.4	—	2.32	5.30
10-19*					
	221.5	99.2	0.90	—	—
5-29-74					
			r = -0.19**	0.68	0.32
			1974		
5-29					
	20.0	79.9	19.18	6.15	—
6-18					
	21.0	69.8	8.38	6.94	8.33
7-9					
	21.0	64.2	7.12	4.94	0.28
7-30					
	17.5	77.1	6.06	4.15	6.54
8-16*					
	26.0	87.9	1.98	8.76	-1.70
9-11					
	252.0	99.2	4.39	0.65	—
5-21-75					
			r = -0.27	-0.40	-0.34
			1975		
5-21					
	19.5	80.7	-29.52	-13.67	-5.44
6-9*					
	21.5	69.4	14.63	2.00	-15.23
6-30					
	21.0	49.6	25.17	-6.86	25.17
7-21					
	19.5	45.4	-11.54	4.37	—
8-9*					
	46.5	72.9	-0.58	3.58	—
8-24*					
			r = 0.43	-0.36	-0.82

* The exact median collection date was between this date and the following day.
** r = correlation coefficient.

None of the correlation coefficients, not even the −0.82 for age group III in 1975, relating G values and percentage of available habitat were significant ($P > 0.05$) (table 29).

For age group I white crappie, growth rates (G values) for summer and winter intervals indicated larger summer than winter growth (table 30). In the summer of 1973, the G value was 6.3 for 149 days, compared with 0.9 for the 221.5 days (1973-74) overwinter interval. The comparison for the summer-winter intervals 1974-75 were similar, G of 8.25 for the summer and 4.39 for the winter. The G values of age group I white crappie in 1974, summer and winter, were substantially larger than those for summer and winter intervals 1973 and summer of 1975. The G value of 0.12 for the summer 1975 was substantially less than G values of 6.3 and 8.25 for 1973 and 1974, respectively.

For age group II white crappie, G values were smaller, as expected, than those of the age group I fish. The summer-winter comparisons in 1973 are reverse of the case for the age group I white crappie; in that year, the G values for age group II fish were higher for the winter intervals than the summer intervals. However, in 1974, the summer growth rate was larger than the rate for the winter interval.

For all age groups, summer growth rates in 1974 were larger than summer growth rates in 1973 or 1975. Also, growth rates of all age groups of crappie in the summer of 1975 were lower than all previous summers (exception, noted, that the G value for age group III crappie in the summer of 1973 was lower than in 1975). Conversely, and without exception, summer growth rates of all age groups were higher in 1974 than any other summer or winter interval.

Freshwater drum–Bathymetric distribution.–The depth distribution of drum appeared highly responsive to conditions of stratification and destratification (fig. 31). The September 9-13 collection in 1974 did not contain enough drum to describe their depth distribution at that time, but when total catch was large, drum were not abundant in the lowest stratum in the midsummer collections of 1973 through 1975, or the first collection intervals in 1973 and 1975 when the reservoir already evidenced some degree of stratification and the 2-mg/l D.O. isopleth was above the bottom.

Drum showed an obvious avoidance of the anoxic 15- to 20-m interval and the catch in the 10- to 15-m interval was generally a small percentage of the total. Drum were most abundant in the 15- to 20-m depth contour after fall turnover when the D.O. content in the water

Table 30.—*Comparison of growth rates (G) and mean weight gain (g) for white crappie for summer (stratified) and winter (destratified) intervals, 1973–75*

Median collection date	Interval	Days	Weight gain and (G) for age groups shown		
			I	II	III
5/23/73					
	summer	149.0	21.7(6.30)	30.2(1.42)	2.9(0.08)
10/19/73					
	winter	221.5	19.7(0.90)*	102.0(2.06)	—
5/29/74					
	summer	105.5	42.8(8.25)	142.3(6.37)	74.2(2.93)**
9/11/74					
	winter	252.0	149.0(4.39)	51.7(0.64)	—
5/21/75					
	summer	128.0	0.8(0.12)	-24.4(-0.90)	34.3(1.54)†
9/24/75					

* Interval was 241.5 days in length
** Interval was 85.5 days in length
† Interval was 62.0 days in length

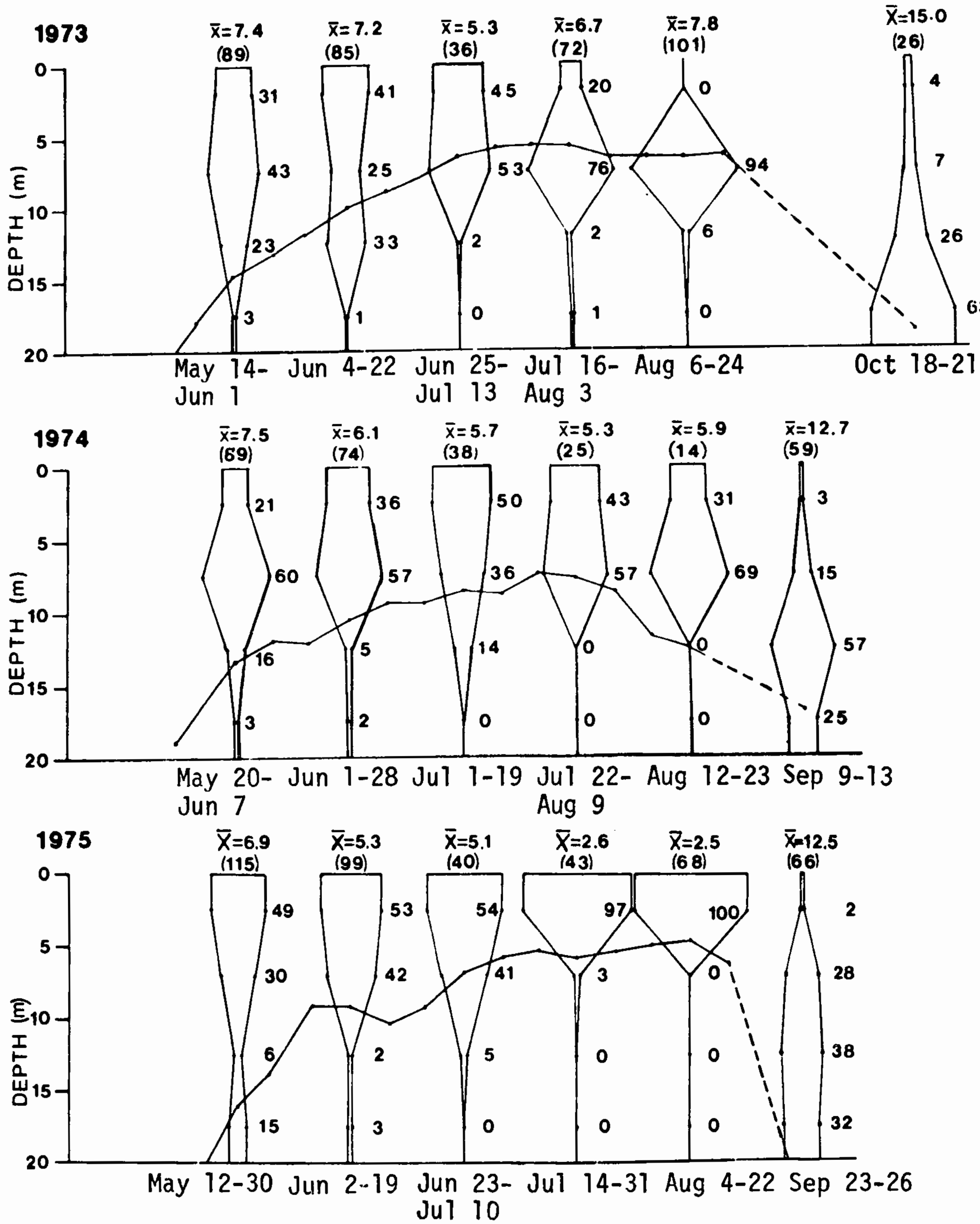

Figure 31.–Depth distribution of freshwater drum, represented by polygons that approximate the percentage (shown alongside the polygon) of fish captured at each depth interval, in relation to the 2-mg/l D.O. isopleth (curve); the $\bar{X}$ represents the MDC, and the value in () the total adjusted number caught in that interval.

in the 15- to 20-m depth interval was more than 2 mg/l. In the last 6 weeks of the summer of 1975, when the 2-mg/l D.O. isopleth was never deeper than 6 m, only one drum was captured in a net set deeper than 5 m.

In 1974, only one (the 6-mg/l D.O. isopleth) correlation coefficient was significant ($r = 0.63$, $P < 0.05$) for the relationship between mean depth of capture of drum and mean depth of the 2-, 4-, 6-, and 8-mg/l D.O. isopleths. In 1975, when D.O. depletion was more prevalent, the correlations between depth distribution of drum and D.O. isopleths were highly significant ($P < 0.01$) for the 2-, 4-, and 6-mg/l D.O. isopleths ($r = 0.87$, 0.90, and 0.85, between mean depth of capture of drum and mean depth of the 2-, 4-, 6-, and 8-mg/l D.O. isopleths. In 1975, when D.O. depletion was more prevalent, the correlations between depth distribution of drum and D.O. isopleths were highly significant ($P < 0.01$) for the 2-, 4-, and 6-mg/l D.O. isopleths ($r = 0.87$, 0.90, and 0.85, respectively) (Gebhart and Summerfelt [43]). In contrasting the results between 1974 and 1975, when drum have less habitat because of the larger volume of the anoxic hypolimnion, their distribution is closely associated with the chemocline.

Instantaneous growth rates.–Temporal variation in instantaneous growth rates of age II and III drum were irregular; negative growth occurred in many of the intervals (table 31). The mean weights, from which the instantaneous growth rates were calculated, have confidence limits which are larger than the differences between mean weights in most cases. Thus, sampling variation could be the cause of the irregular growth patterns. None of the correlation coefficients between temporal variation in percent available habitat and instantaneous growth coefficients were statistically significant, not even the –0.82 for age group III drum in 1975 (table 31).

The major portion of the growth of age II drum in 1973 and 1974 occurred between the time of the fall sample and the first sample the next summer; however, in 1975, average weight gain and rate of weight gain (G values) were larger than in the summer of 1973 and 1974. The instantaneous growth rate of age III drum was negative in the summer of 1973 (table 32). The highest summer growth rate for the age group III drum occurred in the summer of 1974; however, winter growth in 1973-74 age group III drum was larger than age III drum for the three summer intervals.

Black bullheads–Bathymetric distribution.–The MDC of the black bullhead was consistently deeper than any other species. They were captured in all depth strata during the study (fig. 32). Their obvious tolerance to low D.O. is evident by their high frequency of catch in the anoxic hypolimnion. They were not completely insensitive to anoxic conditions, however. Their MDC did decrease as the anoxic hypolimnion expanded, as illustrated in the intervals July 16 to August 3, 1973, July 22 to August 9, 1974, and the interval August 4-22, 1975 (fig. 32). As with other species, bullheads were captured at greater depths when the lake destratified and D.O. was available throughout the water column. This was especially prominent in the September 9-13, 1974 interval. In 1974, the correlations between the MDC of the black bullhead and the depth of the 2-, 4-, 6- and 8-mg/l D.O. isopleth was nonsignificant, but in 1975, the correlation was significant between the 2-, 4-, and 6-mg/l D.O. isopleths: $r = 0.65$ for the 2-mg/l, 0.70 for the 4-mg/l, and 0.78 for the 6-mg/l D.O. isopleths (Gebhart and Summerfelt [43]).

Instantaneous growth rates.–The instantaneous growth rates of black bullhead were calculated for fish collected in 1974 and 1975 for age groups II and III, which had the best representation in the total collection (table 33).

The values of G for age II black bullhead were positive in the early summer of both years, but negative in the midsummer to late summer when the lake was strongly stratified (table 33). A substantial part of the total annual growth of age II and III black bullhead in 1974 occurred between September 1973 and May 1974.

The instantaneous growth rates of age III black bullhead in 1973 and 1974 were irregular, positive growth being interspersed with negative population growth for both years of study (table 34). The confidence limits on the mean weights, from which the growth coefficients were calculated, are fairly large, indicating that sampling variation may be responsible for the

Table 31.—*Instantaneous growth coefficient (G) for freshwater drum and mean percentage of the lake's volume containing > 2 mg/ℓ D.O., during 1973, 1974, and 1975*

Median collection date	Interval, days	Available habitat, %	G values by age group	
			II	III
		1973		
5-23*				
	19.5	88.4	0.10	-5.50
6-12				
	21.0	71.9	-5.87	-0.67
7-3				
	31.0	55.8	2.83	-3.89
7-24				
	21.0	58.0	0.33	6.82
8-14				
	66.5	73.4	-2.09	-3.85
10-19*				
	221.5	99.2	1.44	0.65
5-29-74				
			r= -0.02**	-0.41
		1974		
5-29				
	20.0	79.9	4.30	-0.93
6-18				
	21.0	69.8	-0.39	-3.54
7-9				
	21.0	64.2	-4.07	-1.35
7-30				
	17.5	77.1	1.89	10.08
8-16*				
	26.0	87.9	2.07	0.44
9-11				
	252.00	99.2	0.72	—
5-21-75				
			r = 0.53	0.26
		1975		
5-21				
	19.5	80.7	-0.65	-2.33
6-9*				
	21.5	69.4	7.79	0.20
6-30				
	21.0	49.6	-12.43	1.57
7-21				
	19.5	45.4	24.73	0.86
8-9*				
	46.5	72.9	6.42	0.26
9-24*				
			r = -0.22	-0.82

* The exact median collection date was between this date and the following day.
** r = correlation coefficient.

Table 32.—*Comparison of growth rates (G) and mean weight gain (g) for freshwater drum for summer (stratified) and winter (destratified) intervals, 1973–75*

Median collection date	Interval	Days	Weight gain and (G) for age groups shown	
			II	III
5/23/73				
	summer	149.0	-34.7(-1.29)	-59.9(-1.52)
10/19/73				
	winter	221.5	61.1(1.44)	36.6(0.65)
5/29/74				
	summer	105.5	14.7(0.75)	15.4(0.63)
9/11/74				
	winter	252.0	38.2(0.71)	—
5/21/75				
	summer	128.0	99.9(5.26)	4.8(0.16)
9/24/75				

fluctuating growth rates. None of the correlation coefficients between the percent available habitat and the instantaneous growth rates were statistically significant, but all r values were negative.

The G value for age group II fish in the summer of 1974 was 3.21 compared with -1.04 in the summer of 1975 (table 34). The G value of age II and III bullheads in the winter of 1974-75 was less than the growth rate in the summer of 1974 for both age groups. For age III fish, the G value for the summer of 1974 was larger than 1975, but both were negative.

Channel catfish–Bathymetric distribution.–Channel catfish were distributed throughout most of the water column during the early summer, often occurring below the depth of the 2-mg/l D.O. isopleth (fig. 33). The MDC of channel catfish was less; therefore, the fish were closer to the surface during midsummer to late summer. Channel catfish were distributed deeper when the lake destratified in the fall, perhaps indicating that the fish show a preference for deeper water during the summer than allowed by the environmental conditions.

Instantaneous growth rates.–Temporal variation in instantaneous growth rates of channel catfish were highly variable because of small sample sizes for each individual age class. This produced wide confidence intervals and made it difficult to draw any positive conclusions from the data. For age group III channel catfish, for which adequate samples were available, variation in G values did not follow a consistent pattern in all 3 years of the study (table 35). In 1973, the growth rate was positive and fairly large except for the July sample when a substantial loss in weight occurred. The growth rate was negative during the first sampling period in 1974 and then positive for the rest of the summer. In 1975, the growth rate was positive during the first sampling period and then negative for the rest of the summer. The correlation coefficients between percent available habitat and the instantaneous growth coefficients were not statistically significant for any of the three years; the coefficients were positive in 1973 and 1975 but negative in 1974.

The seasonal growth rates for age III channel catfish indicate that the major portion of the total population growth occurs during the destratified winter period (table 36). The weight gain during the summer period was less than the winter weight gain in all cases. Instantaneous growth rate in the summer of 1974 was greater than in the summer of 1973 and 1975; the G value for 1975 was -4.0.

DISCUSSION

Pumps

The pumps used in this research are of unique design in that they are axial flow of exceptionally

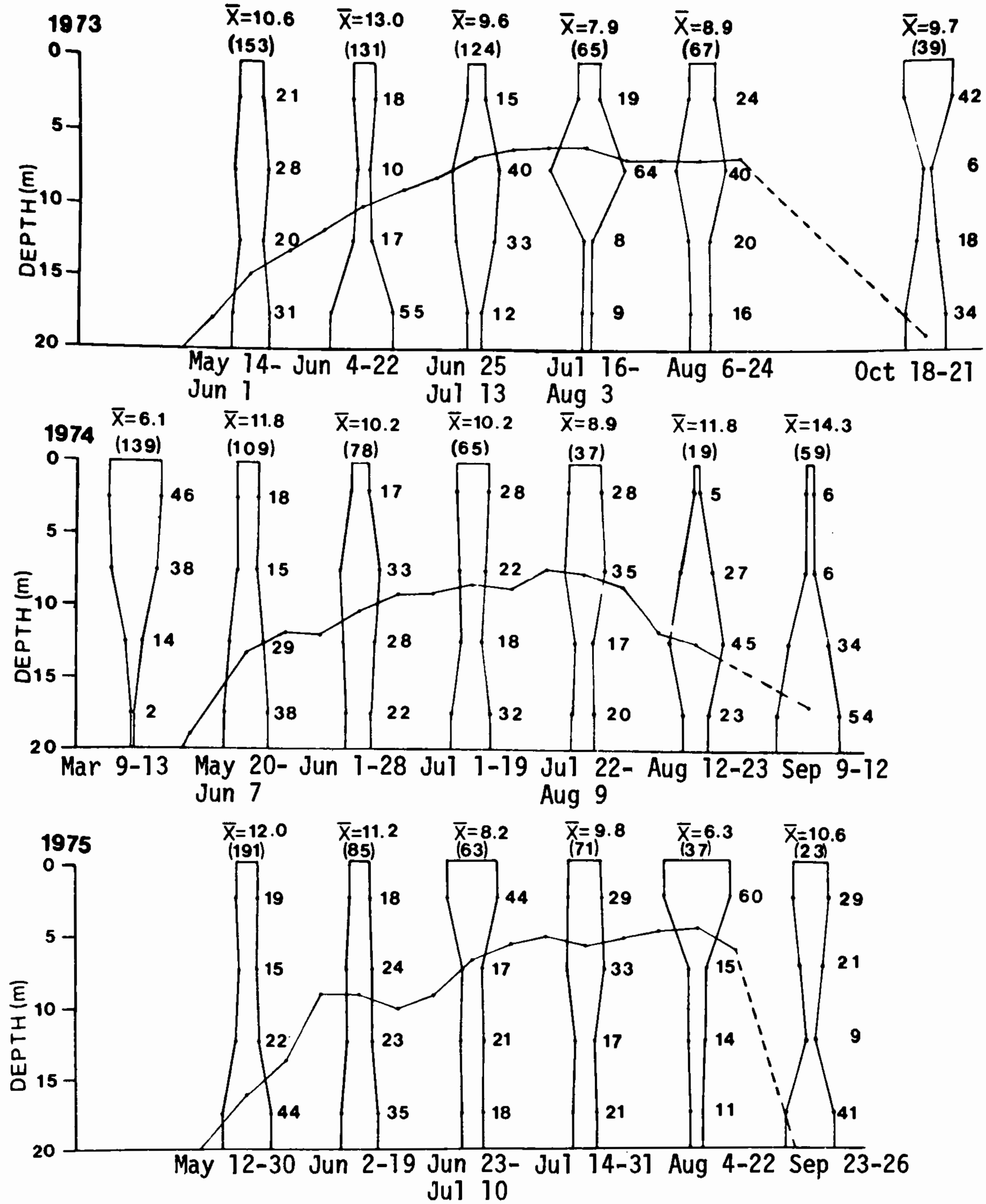

Figure 32.–Depth distribution of black bullhead, represented by polygons that approximate the percentage (shown alongside the polygon) of fish captured at each depth interval, in relation to the 2-mg/l D.O. isopleth (curve); the $\bar{X}$ represents the MDC, and the value in () the total adjusted number caught in that interval.

Table 33.—*Instantaneous growth coefficient (G) for black bullhead and mean percentage of the lake's volume containing > 2 mg/ℓ D.O., 1974 and 1975*

Median collection date	Interval, days	Available habitat, %	G values by age group	
			II	III
		1974		
5-29				
	20.0	79.9	19.70	3.03
6-18				
	21.0	69.8	9.37	-1.36
7-9				
	21.0	64.2	-0.87	17.43
7-30				
	17.5	77.1	-5.79	-11.86
8-16*				
	26.0	87.9	-5.06	-10.58
9-11				
	252.0	99.2	0.99	1.77
5-21-75				
			r = -0.13**	-0.41
		1975		
5-21				
	19.5	80.7	1.83	-0.09
6-9*				
	21.5	69.4	1.43	0.14
6-30				
	21.0	49.6	3.13	-0.55
7-21				
	19.5	45.4	-0.66	1.71
8-9*				
	46.5	72.9	-5.44	-1.23
9-24*				
			r = -0.21	-0.53

* The exact median collection date was between this date and the following day.
** r = correlation coefficient.

Table 34.—*Comparison of growth rates (G) and mean weight gain (g) for black bullhead for summer (stratified) and winter (destratified) intervals, 1974–75*

Median collection date	Interval	Days	Weight gain and (G) for age groups shown	
			II	III
5/29/74				
	summer	105.5	50.0(3.21)	-20.1(-0.79)
9/11/74				
	winter	252.0	87.0(1.61)	99.9(1.43)
5/21/75				
	summer	128.0	-29.9(-1.04)	-8.8(-0.26)
9/24/75				

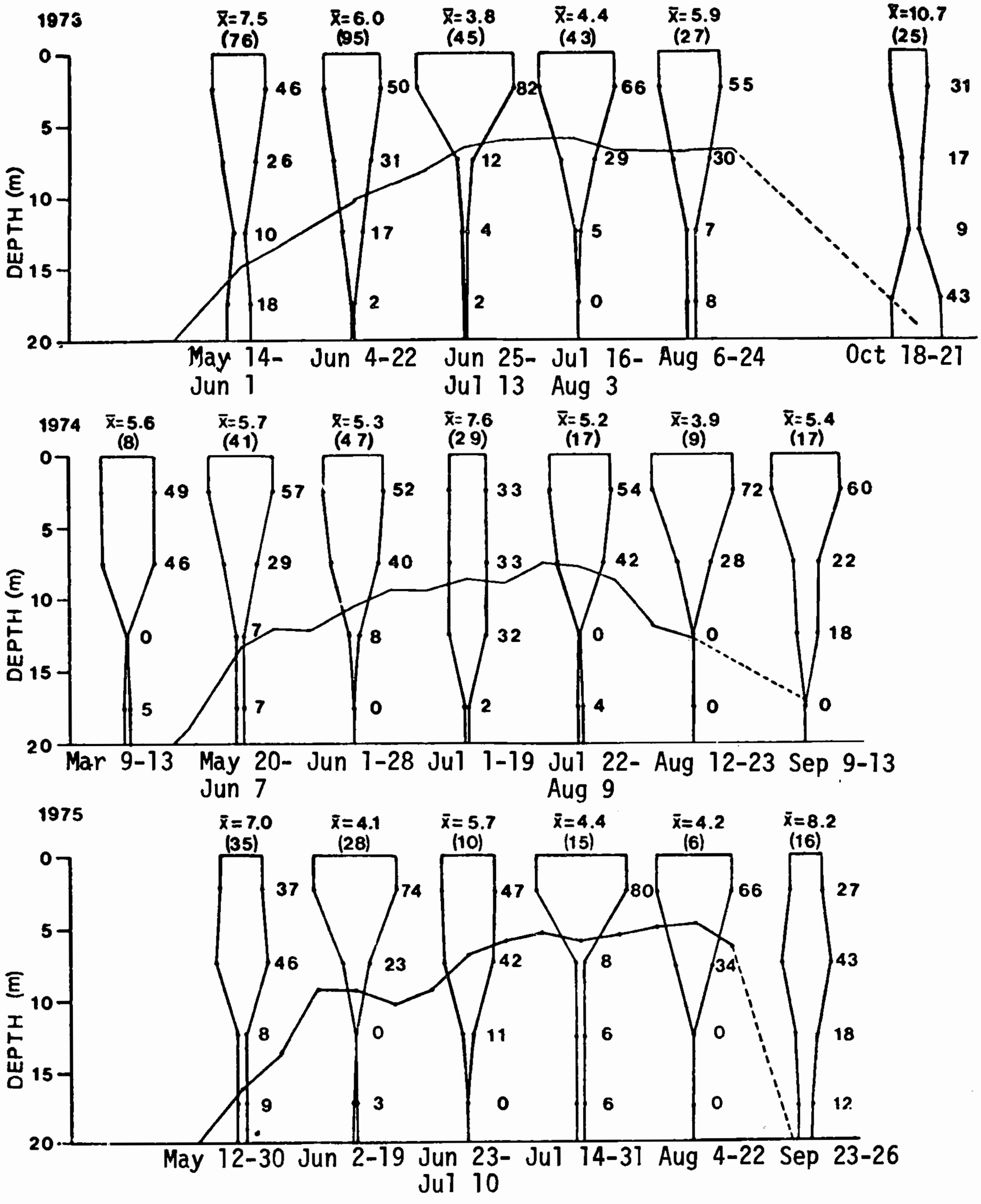

Figure 33.–Depth distribution of channel catfish, represented by polygons that approximate the percentage (shown alongside the polygon) of fish captured at each depth interval, in relation to the 2-mg/l D.O. isopleth (curve); the $\bar{X}$ represents the MDC, and the value in () the total adjusted number caught in that interval.

Table 35.—*Relationship between the instantaneous growth coefficient (G) for channel catfish and mean percentage of the lake's volume containing > 2 mg/ℓ D.O.*

Mean collection date	Interval, days	Available habitat, %	G values by age group III
	1973		
5-23*			
	19.5	88.4	11.87
6-12			
	21.0	71.9	7.76
7-3			
	21.0	55.8	-23.73
7-24			
	21.0	58.0	11.51
8-14			
	66.5	73.4	2.47
10-19*			
	221.5	99.2	—
5-29-74			
			r = 0.45**
	1974		
5-29			
	20.0	79.9	-0.66
6-18			
	21.0	69.8	2.98
7-9			
	21.0	64.2	4.88
7-30			
	17.5	77.1	2.76
8-16*			
	26.0	87.9	3.05
9-11			
	252.0	99.2	1.98
5-21-75			
			r = -0.42
	1975		
5-21			
	19.5	80.7	17.93
6-9*			
	21.5	69.4	-23.79
6-30			
	21.0	49.6	—
7-21			
	19.5	45.4	-4.03
8-9*			
	46.5	72.9	—
9-24*			
			r = 0.60

* The exact median collection date was between this date and the following day.
** r = correlation coefficient.

Table 36.—*Comparison of growth rates (G) and mean weight gain (g) for age group III channel catfish for summer (stratified) and winter (destratified) intervals, 1973–75*

Median collection date	Interval	Days	Weight gain (g)
			III
5/23/73			
	summer	82.5	21.0(1.67)
10/19/73			
	winter	288.0	169.0(2.47)
5/29/74			
	summer	105.5	90.2(2.64)
9/11/74			
	winter	252.0	240.4(1.98)
5/21/75			
	summer	128.0	-103.1(-4.00)
9/24/75			

large diameter, low r/min and low-energy to pumped-volume ratio. Two small pumps used commercial air-blowing fan blades, while a large pump utilized a surplus aircraft propeller.

The first pump was equipped with a conical diffuser skirt, and both of the two small pumps had a rounded inlet orifice shrouding the propeller. The large pump was neither shrouded nor skirted. The problem was to pump large volumes of water with a low expenditure of energy. Additionally, it was desired to pump water from the oxygen-rich epilimnion down into the oxygen-depleted hypolimnion. This would also have taken advantage of the frequent oxygen supersaturation caused by phytoplankton photosynthesis which sometimes occurs just below the surface on bright days.

Critical to design was the selection of a reduction gear capable of handling the high torque values required in the reduction of high r/min inputs into the very low r/min outputs. Other design restraints were imposed by physical laws governing the relationship between velocity and mass. The pump works against extremely low hydrostatic head and at the low r/min used, the total head losses are minimal.

The first pump had a diameter of 1.07 m and required 373 watts. It pumped 0.76 m^3/s at 44 r/min. As increased volumes of pumped water were desired, energy constraints dictated that the diameter of the pump be increased rather than the velocity. A doubling of volume pumped by doubling the velocity of the pump water column would require an eight-fold increase in energy applied. Thus, when the second model pump was designed, it had a diameter of 1.82 m which was a 70-percent increase in diameter, but gave the second pump nearly three times the swept area of the first pump. It pumped 2.4 times as much water with an expenditure of only twice the energy.

The third pump, a three-bladed aircraft propeller of 5.03-m diameter, required about 5.6 kW. This provided a swept area (area of fan) of almost 20 m^2 and pumped 13 m^3/s at 20 r/min. The ratio of water pumped per kilowatt was 2.0 m^3/s with the 1.07-m pump, 2.4 m^3/s for the 1.82-m pump, and 2.3 m^3/s for the 5-m pump. An 8.53-m pump is now under development which should deliver approximately 38 m^3/s with 18.7 kW for a ratio of 2.0 m^3/s per kilowatt.

To achieve the economy of energy desired, it was necessary to hold the initial velocity of the water pumped to the lowest value consistent with the ability of the water pumped to penetrate the thermocline and reach the bottom of the lake. As the velocity of the pumped cone of water decreases most rapidly at the turbulent interface of the pumped jet and the static adjacent water, the larger the diameter of the pump the greater the depth of the penetration of the water in the central column of the flow. Theoretical estimations are that this central column velocity would be maintained to approximately six pump diameters. Experimental results indicate that both small pumps succeeded in pumping water to the bottom of Ham's Lake at 9 m. While the limit of depth penetration has not been determined, the 5-m propeller used at Lake of the Arbuckles penetrated to 25 m, which was the depth of the bottom under the pump. The velocity of water pumped for all three models was approximately 0.7 m/s.

All pumps were mounted on rafts consisting of styrofoam flotation with a redwood frame and were anchored at all four corners. A wire mesh screen was installed for trash exclusion and swimmer safety. The concrete-filled barrels initially used to anchor the large raft proved to be inadequate to resist the high torque forces and wave action at Lake of the Arbuckles in 1974. In 1975 two mud anchors and a line to the shore were devised to supplement the concrete barrels, which proved to be adequate.

The action of the pumps apparently creates an unstable column of water extending from the pump to the bottom directly under the pump so that lake-wide density currents were established. Though not of measurable velocities at distances more than a few meters from the pump, these density currents were able to quickly establish approximately equal temperatures at equivalent depths throughout the lake. Seldom did the temperatures at like depths vary more than 1 °C, but chemical changes in the water occurred more slowly than thermal changes.

Physicochemical Conditions and Algae

The Garton pump had measurable effects on the vertical distribution of temperature and D.O. in Lake of the Arbuckles and Ham's Lake. However, mixing lakes by downflow pumping reduced epilimnetic D.O. while increasing D.O. in the former hypolimnion, apparently because lake mixing reduces the P/R (production to respiration) ratio of the community. At present, it is not possible to predict what combination of mixing speed and compensation point will produce a given P/R ratio, because the theory predicting residence time of algae in the euphotic zone is not known.

The Garton pump is considered to have great potential to improve materially the water quality in mesotrophic reservoirs such as Lake of the Arbuckles and Ham's Lake. However, the Garton pump should be used with caution on truly eutrophic lakes (chlorophyll *a* concentration $\geq$ 40 mg/m^3), especially those lakes which have a large volume of anoxic water with high BOD. To preclude the possibility of rapid destratification imposing an oxygen demand on the whole lake greater than the Garton pump can deliver, it is suggested that pumping of highly eutrophic lakes begin in the spring before a large volume of anaerobic water develops in the hypolimnion.

The Garton pump may prove useful, even in the case of eutrophic lakes, because in time, lake mixing of any sort seems to reduce eutrophy. Perhaps the best strategy would be to combine lake mixing with the Garton pump and artificial aeration for the first few years of lake renovation to assure fish survival.

A mild perturbation such as lake mixing apparently produced little measurable effects on the biota except for a redistribution of animals in response to changes in D.O. In Ham's Lake, fish growth in particular was reasonably insensitive to lake mixing, probably because fish growth is influenced by many environmental factors.

Definitive answers to ecological issues involved in lake mixing should be sought by attempting controlled experiments in the environment whenever possible; e.g., dividing a lake basin mechanically to secure true control data. However, the potential also exists to conduct long-term studies on the same environment and to use the power of relatively new statistical tools to learn the source of definitive changes in the biota. Functional aspects of ecosystem function should also be emphasized. However, this requires sophistication in analytical capability because a relatively large number of parameters need to be measured.

Zooplankton

A similar number of taxa of zooplankton were observed in the two reservoirs, 25 in Ham's Lake and 24 from Lake of the Arbuckles. Bowles [45] collected 23 taxa from Eufaula Reservoir, while 44 taxa were identified in Keystone Reservoir (Kochsiek et al. [28]). Mean density of all samples was 175 and 157 numbers/l in Ham's

Lake and Lake of the Arbuckles, which was considerably higher than that observed in Eufaula Reservoir, but within the range reported for Keystone Reservoir. Mean species diversity of all samples was 2.2 in Ham's Lake and 2.3 in Lake of the Arbuckles, which compares with the mean of 2.5 reported for Eufaula and Keystone Reservoirs.

Several seasonal trends in species composition of zooplankton were observed. Mean number of species and density over all depths were relatively low in August in both impoundments and in April in Ham's Lake. No sample was taken in April in Lake of the Arbuckles. Mean density was maximum in May in both lakes, while minimum diversity averaged over depth occurred in spring. Temperature may play a significant role in the distribution of zooplankton (Pennak [46]), and may have been responsible for the low density in April and in August. Decrease in density of zooplankton during summer was attributed to temperature by Cowell [47].

Consistent trends in species composition and diversity over depth were not observed. Mean density averaged over depth was maximum at 2 m in Ham's Lake and at 4 m in Lake of the Arbuckles. Mean density was relatively low in the bottom waters in both lakes and in the surface waters of Ham's Lake. Mean minimum diversity occurred in the surface waters. Although oxygen is generally considered to be an important limiting factor to the abundance and distribution of zooplankton, vertical variation in species composition and diversity of zooplankton and the D.O. concentration were not closely related.

Several authors have observed changes in the density and distribution of populations of zooplankton after destratification. Artificial destratification extended the vertical depth range of zooplankton in El Capitan Reservoir, Calif. (Fast [16]). Zooplankton density increased following aeration of a small lake in New Mexico (McNabb [38]). However, the vertical distributions of zooplankton were not altered significantly by destratification in a small mountain lake (Lackey [8]). Pumping did not destratify Lake of the Arbuckles. In Ham's Lake, an increase in numbers of species and density occurred at 6 and 8 m after pumping began. However, the values had decreased considerably by the second sampling period following destratification.

Benthic Macroinvertebrates

Seventy-six taxa of benthic macroinvertebrates were collected from Ham's Lake, the smaller impoundment, while 95 were taken from Lake of the Arbuckles. Sublette [48] observed 87 species in Lake Texoma, while Ransom [49] reported 25 species in four arms in Keystone Reservoir. Mean density of all samples was also less in Ham's Lake than in Lake of the Arbuckles. The means were 1887 and 3394 individuals/m^2, respectively. Density was generally less than these values in Keystone Reservoir.

Several seasonal changes in species composition and diversity of benthic macroinvertebrates were observed in the two lakes. Most of the ecological dominants in the lakes were oligochaetes and chironomid larvae. The total number of species and the density measured over all depths were less in summer than in winter and spring. Sublette [48] noted that most macroinvertebrate populations in Lake Texoma were most dense in late winter and spring; however, peak density generally occurred in August in Keystone Reservoir.

Considerable variation in species composition and diversity with depth was observed in the two lakes. Several abundant and many rare taxa were observed in the shallow depths. Although the dominant species varied between the two lakes, most were chironomid larvae and oligochaetes. Density and species diversity were relatively high in the shallow depths. Fewer species were taken from the middle depths than from the shallow depths in the two lakes, resulting in lower values of diversity. Minimum density generally occurred in middle depths. The smallest number of species and the lowest species diversity values typically existed in the deeper waters. Large populations of the phantom midge, *Chaoborus punctipennis*, in both impoundments and of the oligochaete, *Aulodrilus pigueti*, in Lake of the Arbuckles resulted in greater densities in the deep water depths than at middle depths.

The distribution of benthic macroinvertebrates is influenced by a number of environmental factors. Temperature and D.O. of the water taken near the bottom at different depths during the macroinvertebrate sampling in the two impoundments were relatively uniform in winter. In spring and summer D.O. progressively became more limiting in the deeper waters. The D.O.

content of the water adjacent to the bottom was listed as a major limiting factor by Ruttner [50]. Benthic macroinvertebrates differ in their rate of oxygen consumption (Olson and Rueger [51]) and in their ability to withstand anoxic conditions (Pennak [46], Thienemann [52], Walshe [53]). However, it is apparent that other factors besides oxygen limit the diversity of macroinvertebrates. A progressive decrease in diversity with depth occurred in both reservoirs in winter when D.O. was relatively uniform over depth.

Destratification and aeration result in changes in the density and distribution of populations of benthic macroinvertebrates. Benthic macroinvertebrates in a eutrophic lake were restricted mostly to the epilimnion prior to aeration, and certain species, especially chironomids, invaded the hypolimnion after aeration (Fast [16]). In contrast, destratification resulted in a reduction in the standing crop of chironomid larvae and oligochaetes in an oligotrophic lake. Maintaining a montane lake in a destratified condition the year around did not cause large changes in the benthic assemblage (Lackey [8]). It was not possible to evaluate changes in Lake of the Arbuckles due to pumping because the lake was not destratified. However, D.O. content increased in the bottom waters after pumping began in Ham's Lake. Numbers of taxa and species diversity tended to increase in the bottom waters of Ham's Lake after the lake destratified. However, chironomids did not rapidly invade the hypolimnion, resulting in an increase of density after aeration as was observed by Fast [16].

Fish

The Garton pump had measurable effects on the vertical distribution of temperature and D.O. in Ham's Lake and to a lesser extent on Lake of the Arbuckles. However, after achieving orthograde temperature profiles by downflow pumping, aeration apparently requires assistance from the wind. The 1975 data show that the heat content of the lake can be increased by downflow mixing, but chemical stratification occurred in spite of pumping, probably because of lack of wind assistance. There is evidence from observing D.O. isopleths in 1975 that mixing by downflow pumping during midsummer caused 2-mg/l D.O. isopleth to approach the surface; however, our findings indicate that continuous pumping each summer can substantially reduce BOD. Also, higher hypolimnetic temperatures appear to accelerate decomposition. In starting a destratificaton project in midsummer, to assure fish survival, the best strategy would be to combine lake mixing using the Garton pump along with artificial aeration.

Studies of the vertical distribution of fish have shown that a D.O. depletion or anoxia in the hypolimnion associated with stratification limits fish distribution and eliminates a substantial portion of the total lake volume from continuous occupancy during the major part of the growing season (Gebhart and Summerfelt [43], Borges [54], Byrd [55], Dendy [56], Fast [57], Mayhew [58], Sprugel [59], Summerfelt and Hover [60], Ziebell [61]).

In the present study, 2-mg/l D.O. isopleth was used as a boundary defining the limit of suitable fish habitat. Operation of a compressed-air gun for 83 days from July 10 to October 10 in 1973 did not disrupt stratification. Effects were limited and localized. As a result, stratification in 1973 was pronounced; by July 20, as much as 48 percent of the total volume of Lake of the Arbuckles contained less than 2 mg/l D.O. In 1974, Garton's pump ran for 46 days (July 17 to August 31). During this time the volume of the lake with less than 2 mg/l D.O. never exceeded 39 percent. In 1975, the pump ran for 104 days, from June 2 to September 12. In this interval, as much as 59 percent of the volume contained less than 2 mg/l D.O. The volume of the lake with more than 2 mg/l D.O. was 72.9 percent in 1973, 82.7 percent in 1974, 72.6 percent in 1975. In 1975, pumping was with a pump having a larger capacity than in 1974; also, it was operated for more days. The temperature differential from top to bottom was lowered and the temperature of the hypolimnion was increased over 1974. The volume of the lake with more than 2 mg/l D.O. was less in 1975 than in 1974. Possibly, increased bacterial respiration in 1975 may have resulted in a decrease in the oxygen concentration. Or, the increased mixing in 1975 could have transported algae cells out of the euphotic zone, thereby reducing the P/R ratio. However, neither bacterial respiration nor primary production was measured. Compared with 1968-69 and 1973, Lake of the Arbuckles was more nearly orthograde in September 1974 and 1975, which, along with observations on D.O. profiles, indicates that the operation of the Garton pump substantially influenced physicochemical profiles.

A decline in abundance of gizzard shad during 1973 through 1975, from 50.0 to 17.47 percent of the catch, coincided with an increase in abundance of white bass from 3.15 to 9.47 percent. Change in species composition was apparently not related to perturbations from the origin of Garton's pump.

Depth distributions of gizzard shad, white crappie, freshwater drum, black bullhead, and channel catfish were apparently influenced by physicochemical conditions of lake stratification. The MDC of all species was substantially greater in September and October collections when the depth of the 2-mg/l D.O. isopleth deepened.

Fish growth is highly variable, affected by food, space, temperature, and other factors (Weatherly [62]). Because artificial aeration, or destratification, is thought to influence primary and secondary biological production (Toetz, Summerfelt and Wilhm [18]), production of fishes is also affected. Gunning and LaNasa [63] have suggested that a short-term study of fish growth rate can serve as an overall indication of environmental quality. Numerous laboratory studies show that activity, growth, and production of both cold- and warm-water fishes can be restricted by the lack of suitable levels of D.O. (Doudoroff and Shumway [41]).

The effect of stratification on fish growth has been poorly documented; for warm-water fish, only the study by Mayhew [58] specifically addressed this problem. Growth checks developed on scales of certain fish at the onset of stratification indicated that their growth was retarded by the onset of stratification. Although Gerking [64] did not examine the relationship between growth rates and stratification, he did note that blue gill sunfish *(Lepomis macrochirus)* growth rates were highest in the spring, followed by progressively declining growth rates in late summer and autumn. Johnson [65] measured fish growth before and after destratification of a lake used to rear coho salmon *(Oncorhynchus kisutch).* Average fish growth decreased slightly after destratification, apparently because of an increase in smolt survival from 12.9 percent before destratification to 42.1 percent during destratification. This increased survival resulted in an increased total production of over 300 percent.

Assessment of the effect of the artificial mixing upon annual fish growth is confounded by: (1) a significant amount of natural variation between years of growth during years when no artificial efforts were made to aerate or destratify the lake, and (2) the impact of selective mortality in back-calculating growth histories of fish in previous years (Lee's phenomenon). The latter tends to indicate a larger growth occurring in the most recently back-calculated years of growth than for earlier years.

In many age groups for most species, instantaneous growth rates indicated that the major portion of the population growth occurred during the destratified overwinter period. In fact, the population growth rate during the stratified summer period was negative in many cases. This could happen if selective mortality of the larger fish of an age-class occurred over the summer, or if the average weight of the population actually decreased because of a higher anaerobic demand for energy at the high summer water temperatures of fish forced into the warmer epilimnion by occurrence of anoxic waters of the hypolimnion. Feeding efficiency of fish may decrease when they are forced to live in water which produces thermal stress and excess metabolic demand. Also, the fish may exhaust their food supply as the summer progresses and stratification shrinks the available habitat of the prey organisms. Analysis showed that stratification has a negative impact on fish growth and that artificial mixing could maintain D.O. above 2 mg/l near the bottom during the entire summer and enhance fish growth.

RECOMMENDATIONS FOR FURTHER RESEARCH

This research has given new insights into a number of questions concerning reservoir destratification and reaeration. For example, lakes can be destratified through the use of the low energy and high volume characteristics of the Garton pump. As expected, the heat content of the destratified lake is greatly increased, but the surface temperature seems to be governed principally by atmospheric conditions. At any rate, the summer warming of the total lake is quickly dissipated in autumnal cooling. Fish do use all the aerated depths of a mixed lake and probably are benefited in doing so. Reaeration reduces to nominal levels the buildup of BOD in the previously anaerobic depths and increases the total oxygen content of the lake. It alters the benthic macroinvertebrate community to permit the existence of those species with aerobic respiration requirements and seems to dampen the magnitude of algal blooms.

While the effect of reaeration will be of continuing interest to those engaged in intensive in-depth research on individual biological species or on water quality parameters, several broad areas are recommended for continuing research. These areas probably would be the most fruitful in expanding the knowledge necessary to permit wide application of this new technology. These areas are:

1. Research to establish the range of pumping rates required to destratify or to prevent the stratification of lakes. This must consider the parameters of lake morphometry, climatological regime, the quantity, quality, and temperature of stream inputs, the water release regime, and the location of outlets. The nature of the aquatic biotic community and the trophic state of the lake must also be considered.

2. Research to compare the relative efficiencies, capital cost, and logistic support requirements of a single large pump versus several smaller pumps for specific applications.

3. Development of hydrodynamic theory compatible with observed events during lake stratification and destratification. This will utilize both physical and mathematical modeling and will be complementary to No. 1.

4. Research to determine both the short-term and the long-term effects of lake destratification on:

   a. Reservoir biota

   b. Water quality (taste and odors, turbidity, effect of destratification on water treatment cost, etc.)

   c. Induced changes in nutrient cycling and its effect on the trophic state of the lake

   d. Changes in the aquatic community structure induced by lake destratification

   e. The genesis and fate of toxicants in both the reaerated and stratified state of lakes

   f. Analysis of the sediments; e.g., BOD, particle size, organic content, pH

5. Research to determine the efficacy of the Garton pump in altering the thermal and water quality characteristics of water released from reservoirs where total lake destratification is either impractical or undesirable because of cold-water fishery or industrial requirements.

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ABSTRACT

The purpose of this study was to develop more efficient methods of reservoir reaeration and to determine the environmental effects of reservoir destratification. The Garton pump, a low energy, axial flow device, is designed to pump water from the surface downward to destratify and reaerate lakes and reservoirs. A 1.07-m-diameter version of the device was tested in Ham's Lake (40 ha surface area, 10 m maximum depth) near Stillwater, Okla., in 1973 and 1974, and a 1.83-m-diameter version was operated in 1975. Complete thermal destratification was obtained. A 5-m-diameter version of the Garton Pump was operated in Lake of the Arbuckles (951 ha surface area, 27 m maximum depth) near Sulphur, Okla., in 1974 and 1975. Improvements in the design resulted in substantial perturbation of physicochemical conditions of Lake of the Arbuckles in 1975. This report describes vertical variations in the two reservoirs of: (1) temperature, dissolved oxygen, and several other physicochemical parameters; (2) species composition and density of the algae populations; (3) species composition and diversity of zooplankton; (4) species composition, diversity, and density of benthic macroinvertebrates; and (5) vertical (bathymetric) distribution and growth of fish. The report also includes recommendations for further research.

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