

PHYSICAL AND CHEMICAL ASPECTS OF THE SEDIMENTS  
OF TWO OKLAHOMA RESERVOIRS

By

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Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1976

Submitted to the Faculty of the Graduate College  
of the Oklahoma State University  
in partial fulfillment of the requirements  
for the Degree of  
MASTER OF SCIENCE  
July, 1978

*Thesis*  
*1978*  
*C619 p*  
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## PREFACE

I wish to thank my thesis adviser, Dr. Jerry Wilhm, for contributing his thought and energy to this study. Appreciation is also extended to Dr. Lester Reed for his willingness to share his knowledge, and to Dr. Robert Reed and Dr. Troy Dorris for advice and criticism of the manuscript.

Special gratitude is expressed to my husband, Robert, for his assistance in analysis and drafting and his true friendship. Also, thanks is given to my parents, Johnnie and Lavaca Collins, for their support and encouragement throughout my studies.

This project was part of a more extensive research effort to determine effect of artificial destratification on Ham's Lake and Arbuckle Lake, and was supported by the Bureau of Reclamation and the Oklahoma Water Resources Research Institute.

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## CHAPTER I

### INTRODUCTION

Bottom sediments regulate the freshwater ecosystem (Odum 1971). Metabolism of detrital and particulate organic carbon, which occurs largely in the sediments, provides stability to ecosystems (Wetzel 1975). The rate of consumption of dissolved oxygen (DO) from overlying water by undisturbed sediments can be used as an index of benthic community metabolism (Hargrave 1969). Banin et al. (1974) stated that the upper layer of lake sediment affects the cycles and balance of nutritional elements in the lake water. Sediments can play a critical role in determining the trophic status of lakes (Golterman 1966). Hargrave (1973) found that bottom sediments yield valuable information about production and mineralization in the water column. McLachlan (1969) concluded that the nature and distribution of the bottom fauna are strongly influenced by substrate characteristics.

Sediments are composed of three major fractions: (a) particulate mineral matter, (b) an inorganic component of biogenic origin, and (c) organic matter in various stages of decomposition (Wetzel 1975). Sediments of a lake or reservoir vary with depth in chemical composition and texture (Welch 1952). Wave action, autochthonous organic materials, and drift materials modify terrestrial materials in the littoral zone. The profundal zone contains sediments composed mainly of finely divided oozes. The upper layer of sediments in lakes is composed of solid



sediment and free water.

Bottom sediment is always saturated with water and is subject to little change in light or temperature except at shallow depths. DO is depleted during summer stratification in most eutrophic lakes (Hutchinson 1957). Reducing conditions and anaerobic bacterial respiration result from DO depletion in the hypolimnion (Mortimer 1941). Anoxic conditions and the resulting increase in certain chemicals impair water quality and influence the density and distribution of the biota in the hypolimnion.

Sediment influences the physical, chemical, and biological conditions of water. The role of sediments varies with the amount of mixing with the water, the biological transformations which occur between the sediments and the water, and sediment composition. Parameters which have been studied most in characterizing the sediment are: 1) sedimentation (Pennington 1974, Kirchner 1975), 2) exchange mechanisms at the mud-water interface (Mortimer 1941; Hayes, Ried, and Cameron 1958; Kamp-Nielsen 1973), 3) nutrient chemistry (Juday 1941; Frink 1969; Serruya 1971; Wildung, Schmidt, and Gahler 1974), 4) organic matter (Anderson 1939, Bordovisky 1965, Hargrave 1973), 5) DO consumption (Hayes and McAulay 1959, Edwards and Rolley 1965, Pamatmat 1971, Edberg and Hofsten 1973), and 6) particle size (Mortland 1954, Hargrave 1972, Johnson 1974, Banin et al. 1974). These processes are influenced by lake morphology and seasonal variations which change the overall thermal structure and dynamics of a lake.

The objectives of this study are to: 1) observe seasonal changes in particle size, percent oxidizable matter, P, and sedimentation rates of the sediment in two lakes during summer stratification; 2) observe

temporal variation in P and oxidizable matter of sediment exposed to aerobic and anaerobic conditions in the laboratory; and 3) determine the gross mineralogy of the lake sediments.

## CHAPTER II

### REVIEW OF LITERATURE

Characterization of lake bottom deposits is important in that it yields information about the effect of the sediment on the quality of the overlying water, the biological systems that predominate, and the source of sediment material (Ballinger and McKee 1971). Bottom deposits of lakes may be analogous to soils which have developed under humid and water-logged conditions. With appropriate modifications, the methods developed by soil scientists for assessment of agricultural soils have been used to evaluate important characteristics of sediments (Lenhard, Ross, and DuPlooy 1962).

Attempts to characterize sediments by chemical means have been largely restricted to nutrient studies. Phosphorus, organic C, and organic N content in bottom deposits of Wisconsin lakes were determined by Juday (1941). Sawyer (1954) determined the contribution of N and P from the bottom mud to overlying waters. Total C, moisture, and Kjeldahl N in Lake Tahoe sediments have been analyzed by McGauley (1963). Wrobel (1960) determined N and C content in lake bottom muds. Painter (1968) demonstrated that the top portions of the sediment are higher in P with the lower materials being stabilized. Carbon and organic N followed the same trend (Mackenthun, Keup, and Stewart 1968). Frink (1969) investigated the storage forms of N and P in the bottom sediments of a eutrophic Connecticut Lake. In an effort to understand

eutrophication processes, Serruya (1971) determined the concentration of Fe, Mn, P, N, organic C, and  $\text{CaCO}_3$  in recent sediments of Lake Kinneret, Israel.

Organic matter may be one of the most important physical and biological properties of the sediment, although the percent organic material may be low (Johnson 1974). The organic composition of sediments in lake systems has received much attention because of the overriding importance of microbial metabolism in direct mineralization of organic matter, of the amount of organic matter deposited without significant further degradation in permanent sediments, and the inorganic cycling of nutrients (Wetzel 1975). Organic matter of soils and water is primarily in the form of humic substances and aromatic polymeric compounds of partially degraded plant and animal material (Wetzel 1975). Organic matter may be transported to the bottom as precipitated dissolved or colloidal organic matter, as the rain of surface produced organic matter, or as the active transport by vertically migrating epibenthos (reviewed by Bordovisky 1965). Upon arrival at the water interface, organic matter may be oxidized, and/or buried, and/or consumed by anaerobic processes or accumulated as fossilized organic compounds (Pamatmat 1971).

On an annual basis organic matter supply is more influential on bottom community metabolism than the temperature (Hargrave 1973). Total organic matter and DO uptake may be correlated (Waksman and Hutchkiss 1938, Teal 1962, Pamatmat 1968, and Ryback 1969). The nature and quality of organic substrates have a significant effect on the extent of DO uptake (Edberg and Hofsten 1973). Hargrave (1973) demonstrated that measurements of DO uptake across an undisturbed sediment-

water interface could be used to quantify oxidizable organic matter in certain aquatic ecosystems. Mortimer (1941) stated that during the development of thermal stratification, decomposition of organic matter depletes the DO in the hypolimnion and liberated organic materials accumulate. Kato (1956) postulated that over a period of time the amount of reduced substances formed in the sediment as a result of anaerobic metabolism is related to the amount of organic matter in the sediment.

Various relationships have been found to exist between organic matter and other lake properties. Chironomid faunal biomass was found to be positively correlated with the organic C in the profundal zone and inversely associated with the quantity of coarse sand in the littoral zone of Lake Kariba, Central Africa (McLachlan and McLachlan 1971). Sediments containing different amounts of organic material support various types and numbers of benthic alga flora (Lund 1962). Mackereth (1971) reported that in lake sediments a high organic content is associated with a high percentage of interstitial water. In soils and sediments, Hg has a strong affinity for organic matter (Lindberg and Harriss 1974). Hayes and Anthony (1958) suggested that polar C compounds are predominantly sorbed by clay particles. The amount of C sorbed is related to the clay surface area determined by grain size. These clay-organic associations may include carbohydrates (Bader, Hood, and Smith 1960; Lynch, Wright and Cotnoir 1956). Clay minerals could act as organic sinks (Hendricks 1971).

Many physical and chemical properties of soils are highly correlated with the specific surface area (Mortland 1954, Morin and Jacobs 1964, Banin and Amiel 1969). Organic C increases with increasing clay

content and also with decreasing grain size (Bordovisky 1965, Thomas 1969, Longbottom 1970). An inverse relation between detritus particle size and DO consumption was demonstrated by Odum and de la Cruz (1967) and Fenchel (1970). Hargrave (1972) found a linear inverse relationship between particle diameter and DO uptake. Oppenheimer (1960) reviewed the relationship between decomposition of sedimenting organic matter and particle size. The amount of organic matter in a range of sediments from the North Kent coast varies inversely with median particle diameter (Longbottom 1970). Driscoll (1975) suggested that low pH values over fine-grained, organic-rich sediments may reflect the reduction of increasingly abundant complex organic compounds and the resultant increase in organic acids in bottom water.

Substrate characteristics have a significant influence on the nature of the bottom fauna. Percival and Whitehead (1929) recognized that sediment samples could be categorized into well defined groups according to the occurrence of certain animals. An association exists among chironomid larvae, organic matter, and particle size (Wene 1940). Sublette (1957) in a study of Lake Texoma, Texas, found that the character of the substrate influences the distribution of bottom fauna. Each principal substrate type showed qualitative and quantitative differences. The choice of settling site by chironomid larvae is influenced by particle size and substrate texture (McLachlan 1969). A highly significant and negative correlation exists between bacterial numbers and mean grain size (McLachlan 1969). The correlation of organics with mean grain size indicates that grain surface area may be a controlling factor on microorganism abundance (Hargrave 1972).

Lake sediments are composed of seston which has undergone microbial

and chemical transformations. According to Stoke's Law, particles of a given density sediment through water at a rate directly proportional to the square of their radii. Particulate organic C moves with water and may ultimately be deposited at the bottom of static water. Dissolved organic C may sediment if it is associated with inorganic particulate matter (Wetzel 1975). Qualitative and quantitative assessment of seston can provide additional insight into the functions of sediments in the aquatic system.

Sedimentation of material to the profundal zone of a lake reflects two simultaneous processes. Fresh organic matter is supplied by phytoplankton and macrophyte production, while mixing processes redistribute and resuspend material previously sedimented (Lastein 1976). Jónasson, Lastein, and Rebsdorf (1974) reported that periods of maximum sediment capture occur during summer and autumn overturn when no thermocline exists and temperature and oxygen are uniform. Processes which may affect seasonal change in seston composition include production within the lake, stratification, destratification, and rainfall (Pennington 1974).

Kirchner (1975) stated that sediment traps could be used to estimate loss of materials from the trophogenic zone or accumulation of materials in the sediment. Soluble nutrient compounds and elements may be transported to the sediments by settleable matter (McKee et al. 1970). Circulating seston and surface mud can be analyzed to determine whether the organic components of the sediment are from primary production within the lake or from the organic fraction of the soils on the catchment (Pennington 1974). In studies of the movement, deposition, and redeposition of different sizes of pollen grains, Davis and

Brubaker (1973) demonstrated horizontal differential sedimentation of particulate matter.

Sediments are intermittent sources of nutrients and can play a critical role in determining the trophic status of lakes (Serruya 1971; Wildung, Schmidt, and Gahler 1974). The exchange of nutrients between the mud and water of lakes is governed by the seasonal processes of oxidation and reduction at the bottom (Mortimer 1941). Increases in solubility accompanying reduction at the mud surface provide for accumulation of nutrients in the water. Phosphorus is of major ecological interest because of its important role in biological metabolism and the relatively small amounts in the hydrosphere.

Greater than 90% of the P of lake water is organically bound. Most sediment P is inorganic, originating in the watershed, and phosphate sorbed onto clays and ferric hydroxides (Wetzel 1975). Orthophosphate is the only significant form of inorganic P.

Phosphorous is in a much higher concentration in the sediment than in the water (Olsen 1958, 1964; Holden 1961). Contents of P and several other elements usually increase with increases in depth of the overlying water column (Frink 1967; Delfino, Bortleson, and Lee 1969; Williams et al. 1970). Phosphorus may be preferentially associated with fine textured, low density particles which tend to settle slowly from the water column and to be transported to deep-water areas (Seyers, Harris, and Armstrong 1973). Processes by which P fixation in the sediment may occur include adsorption, chemical binding to short range order iron complexes (Shulka et al. 1971), and transformation of calcium carbonate to apatite (Stumm and Leckie 1970). Li et al. (1972) found a substantial part of sediment P to be exchangeable and mobile.



Phosphates emanate from the deeper anaerobic layers of benthic deposits toward the surface during aerobic conditions (Filloos and Swanson 1975). Phosphates are released into the overlying water when conditions become anaerobic and the ferric complexes break down. Established factors affecting phosphate exchange are pH, redox potential, and sorption and diffusion (Kamp-Nielsen 1973). Phosphorus release from the sediments may be accelerated by turbulence (Zicker, Berger, and Hasler 1956), metabolic activities of benthic organisms (Hutchinson and Wollack 1940), and biological activity of surface waters (Wildung, Schmidt, and Gahler 1974).

The seasonal distribution of P in lakes is variable. Much more variable vertical distributions of P exist in lakes exhibiting a strongly clinograde DO curve during stratification. Generally, P content increases in the lower hypolimnion, especially in the latter phase of thermal stratification (Wetzel 1975).

## CHAPTER III

### DESCRIPTION OF STUDY AREAS

#### Ham's Lake

Ham's Lake, a Soil Conservation project, was built in 1965 as a flood detention reservoir (Fig. 1). The lake is located 8 km W of Stillwater, Oklahoma, in Payne County, and drains approximately 1484 ha of loamy upland. At the principal spillway elevation of 287 m above sea level, the lake surface area is 40 ha and the volume is 115 ha-m. The maximum depth is approximately 9.5 m and the pool is about 1.3 km in length.

Ham's Lake stratifies thermally and chemically in summer. During summer the epilimnion is supersaturated, but DO is depleted within 3 to 4 m (Steichen 1974). Destratification attempts were made at Ham's Lake during the summers of 1972 - 1975. A Garton pump, a 1.07 m crop drying fan with a rounded entrance, a cylindrical throat, and a fabric diffuser, was installed to mechanically mix the water (Garton 1976a). Studies were initiated in 1974 to measure vertical distributions in physicochemical variables; species composition and diversity of zooplankton, algae populations, and benthic macroinvertebrates; and distribution and growth of fish.

Sampling stations used in the present study are shown in Fig. 1; numbers in parentheses designate depth in meters. Sediment and water samples were taken at stations 2(8) and 5(8) in the central pool; 6(2)

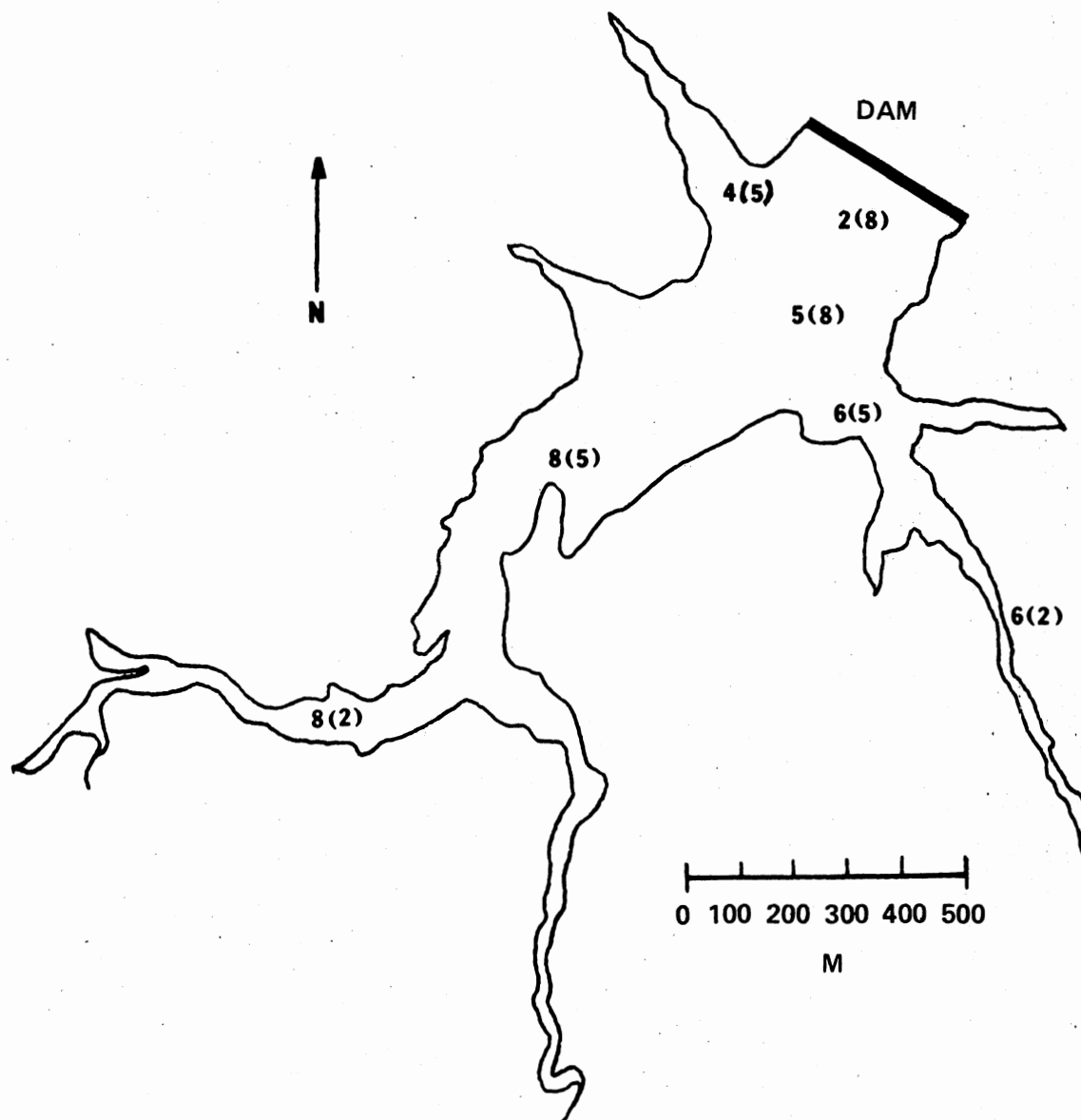


Fig. 1. Ham's Lake showing sampling stations. (Numbers in parentheses denote depth in meters.)

and 8(2) in the channels of inflowing creeks; and 4(5) which is separated from the main body of the lake by the dam of a farm pond which was submerged when Ham's Lake was filled. Sediment traps were placed at 6(5), 8(5), 2(8), 5(8), and 4(5).

#### Arbuckle Lake

Arbuckle Lake was impounded in 1967 to serve for municipal water supply, flood control, fish and wildlife, and recreation (Gomez and Grinsted 1973). The lake is located about 9.5 km SW of Sulphur in Murray County, Oklahoma, and has a drainage area of 326 km<sup>2</sup>. The surface area is about 950 ha and the volume is 8930 ha-m. Maximum depth of the lake is over 26 m and the pool is almost 11 km in length. The lake stratifies early in May and by late June about 42% of the volume contains less than 2 mg/l DO (Garton 1976b). Destratification attempts were made with a Garton pump during the summers of 1974 and 1975. Although the lake was not destratified, the thermal stability was reduced. Biological sampling, similar to that at Ham's Lake, was conducted during this period.

Sediment and water samples were taken at Stations 1(26) and 2(24) in the central pool and 3(2), 3(15) in Guy Sandy Creek, 4(2), 4(15) in Rock Creek, and 5(2), 5(15) in Buckhorn Creek. Sediment traps were placed in the same locations, except at 8 m instead of 2 m stations in the creeks (Fig. 2).

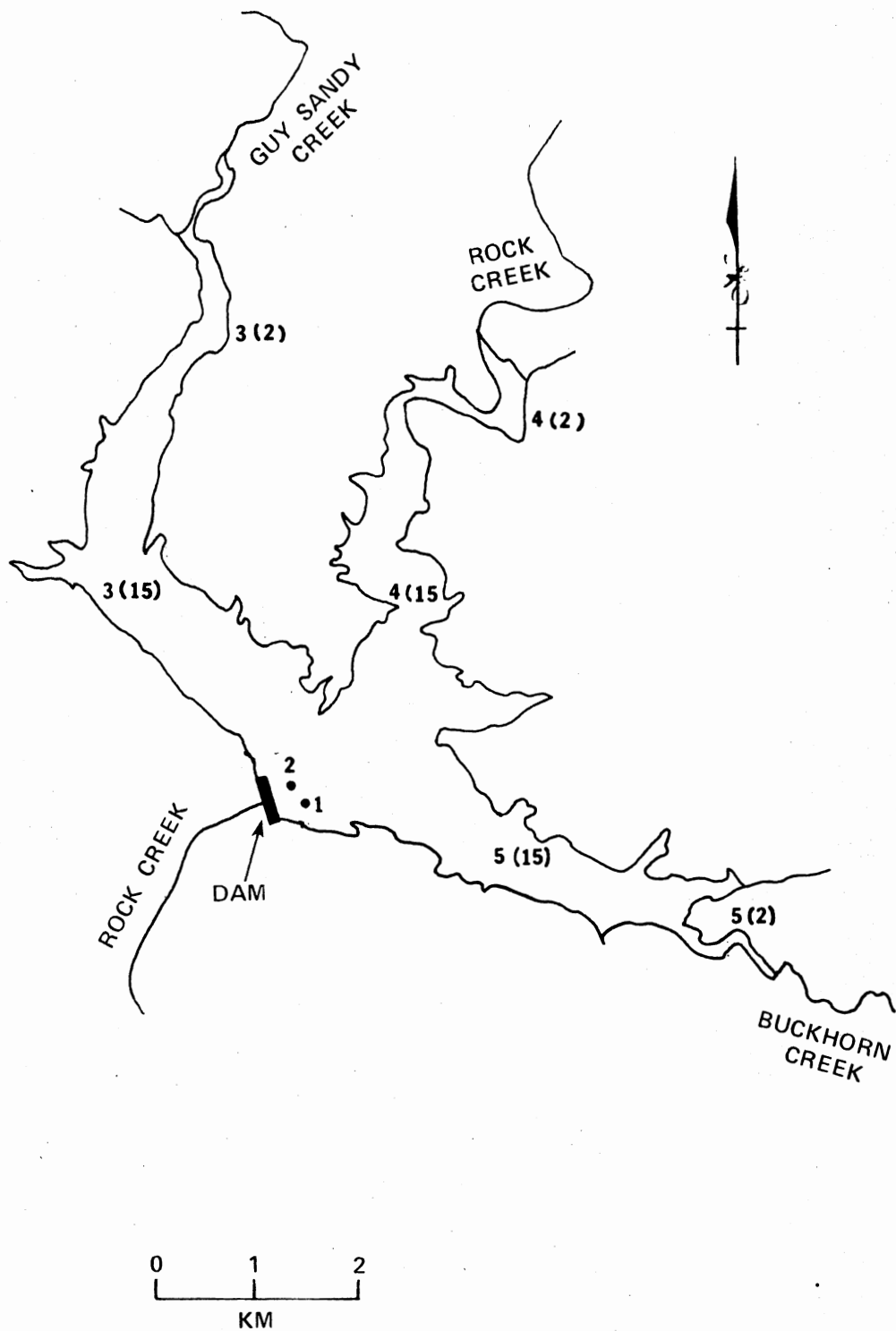


Fig. 2. Arbuckle Lake showing sampling stations. (Numbers in parentheses denote depth in meters.)

## CHAPTER IV

### METHODS

#### Ham's Lake

Particle size was determined for four replicate samples taken with an Ekman dredge at each site on 17 April, 15 June, 1 August, and 18 October. For hydrometer analysis, the top 1-2 cm of sediment from the samples were oven dried at 60° C, ground to size 60 mesh, and sieved to remove leaf litter. A mixture of 25 g of sediment and 50 ml distilled water was brought to a pH of 9 by adding a 2% solution of sodium carbonate-sodium bicarbonate ( $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3$ ). The mixture was transferred to a dispersal cup. After dispersal with a Hamilton Beach mixing machine, samples were transferred to a 1000 ml cylinder and placed in a constant temperature room. The samples were stirred and hydrometer readings followed at intervals of 0.5, 1, 3, 10, 20, 120, and 720 min (ASTM 1977).

Percentages of soil in suspension were calculated by (ASTM 1977):

$$P = (R_a/W) \times 100$$

where:

- a = correction factor to be applied to the reading of 152H hydrometer
- P = percentage of soil remaining in suspension at the level at which the hydrometer measures the density of the suspension,
- R = hydrometer reading with composite correction applied
- W = oven-dry mass of soil in a total test sample represented by mass of soil dispersed (g),
- G = specific gravity of the soil particles, and

$G_1$  = specific gravity of the liquid in which soil particles are suspended.

Diameter of soil particles was calculated by Stoke's Law:

$$D = [30\eta/980(G - G_1)] \times L/T$$

where:

D = diameter of particle (mm)  
 $\eta$  = viscosity (i.e., water) in g/sec-cm  
 L = distance from the suspension to the level at which the density of the suspension is being measured (cm)  
 T = interval of time from beginning of sedimentation to the taking of the reading (min),  
 G = specific gravity of soil particles, and  
 $G_1$  = specific gravity of suspending medium.

Organic C content was determined for four replicate sediment samples collected at the same stations and times as those used for particle size. Sediment was obtained by pushing a polyethylene tube, 2.54 cm in diameter, into an Ekman grab sample. The cores were sealed with cork stoppers, placed on ice, and frozen at the laboratory until analyzed. A 0.25 g sample from the top 2 cm of the core, which had been over dried at 60° C, was analyzed for organic matter by the Schollenberger method, an oxidation procedure (Black 1968), according to the equation:

$$\frac{(\text{meq } K_2Cr_2O_7 - \text{meq } FeSO_4) \times 0.003 \times 100}{\text{grams water-free soil}} \times (f)$$

where f = correction factor.

Rate of sedimentation was estimated for sediment collected in traps suspended 1 m from the bottom from 5 July to 4 August and from 4 August to 26 October. The traps were constructed of two 3.7 X 8.8 cm cedar boards, 60 cm long, bolted together at right angles. Eight 500 ml Nalgene collecting bottles with a 43 mm mouth opening were attached to grooves in the boards on each trap. Four were placed right

side up and four upside down. After exposure, samples were oven dried at 100° C for 1 h. The weight of the aufwuchs in the upside down bottle was subtracted from the weight of the corresponding upright bottle to obtain the sediment weight free of biomass contributed by attached organisms. Samples were ashed at 550° C for 1 h and reweighed.

Phosphorus content of the sediment was determined for four replicate samples collected on 4 May, 3 June, 8 August, and 26 October at the same stations and by the same method as those for organic matter content. Sediment from 1, 5, and 10 cm sections of each sample was muffled at 550° C for 1 h and analyzed for particulate P by the method of Stainton, Capet, and Armstrong (1974).

Soluble reactive P was estimated for three replicate samples collected from the surface, middle, and bottom of the water column with a Van Dorn water sampler at the same stations and times used for sediment P. Samples were analyzed for  $PO_4$ -P by the method of Murphy and Reilly (1962).

A crude identification of the clay minerals present in the sediment at each lake station was made by means of X-ray diffraction. A slurry was made with the fraction of the sediment less than 2  $\mu$  in particle size. The slurry was distributed on a ceramic slide and allowed to dry at room temperature. A diffractogram was obtained by scanning at 2° 2 $\theta$  per minute.

For both lakes, comparisons of particle size, organic matter, and P among stations and sampling dates were made with an analysis of variance (AOV). An AOV was also used for comparisons of sedimentation rate and P and organic matter in the aerobic-anaerobic study.



## Arbuckle Lake

The same parameters were measured at Arbuckle Lake as in Ham's with four replications each for organic matter and particle size. Phosphorus of the sediment water was determined for three replications at each station. Collections were made on 12 May, 15 June, 18 July, 20 August, and 18 October. Sedimentation traps were submerged from 29 June to 27 July, 27 July to 20 October.

Differences in organic matter and P content were determined in lake sediments which were subjected to aerobic and anaerobic conditions in the laboratory. Organic matter and P were determined for 21 replicate sediment samples collected 12 May from stations 1(26), 3(15), 4(15), and 5(15) by the same method as those for organic matter. Seven of the 21 samples were analyzed immediately. Sediment P was measured by the method of Stainton, Capet, and Armstrong (1974). Organic matter was analyzed by loss on ignition, a gravimetric procedure in which samples are oven-dried at 100<sup>o</sup> C and ashed at 550<sup>o</sup> C for 1 h each (Dean 1974). Water above seven of the sediment cores from each station was aerated and the remaining seven cores were placed in a glass cylinder that was sealed and vacuum pumped to obtain anaerobic conditions. After 2 months at a temperature of 12<sup>o</sup> C, the samples were analyzed for organic matter and PO<sub>4</sub>-P.

## CHAPTER V

### RESULTS

#### Ham's Lake

##### Particle Size

The percent and diameter of sediment remaining in suspension at progressive time intervals after mixing are shown in Table 1. Differences in means among the five areas in Ham's Lake were highly significant ( $p < 0.005$ ). Particle size was smaller at the 8 m stations than at the 2 m stations in Ham's Lake. In the laboratory analysis, after 12 h, 56% and 60% of particles  $< 0.002$  mm remained in suspension at stations 2(8) and 5(8), respectively, while 31% and 22% remained at the 2 m stations. Particle size was intermediate at station 4(5) with 50% of the particles  $< 0.002$  mm in suspension. Variation in particle size at different depths and the grain size distribution of each station are illustrated in Fig. 3. The steeper gradients at the 2 m and 5 m stations indicated an even distribution of silt sized particles. The 8 m depths had a poor gradation in silt sized particles, depicted by the flatness of the curve over a wide range of particle diameters. Seasonal variation was also statistically significant ( $p < 0.05$ ). Particle size at the 8 m and 5 m stations generally decreased over summer with the greatest change between April and June (Appendix).

Table 1. Grain size analysis of the sediments in Ham's Lake.\*

Station (depth in m)	Variable**	Time (min)							
		0.5	1	3	5	10	20	120	720
6(2)	P	85	79	74	71	62	56	40	31
8(2)	P	76	67	55	50	42	37	27	22
5(8)	P	92	90	89	88	87	84	74	60
2(8)	P	93	91	89	88	87	84	78	56
4(5)	P	87	85	82	80	76	72	60	50
	D	.069	.050	.030	.022	.016	.011	.005	.002

\*Values are the means of four replicate cores each collected on 17 Apr, 22 Jun, 8 Aug, and 26 Oct

\*\*P-Percent of soil remaining in suspension

D-Maximum diameter (mm) of particles remaining in suspension at each station

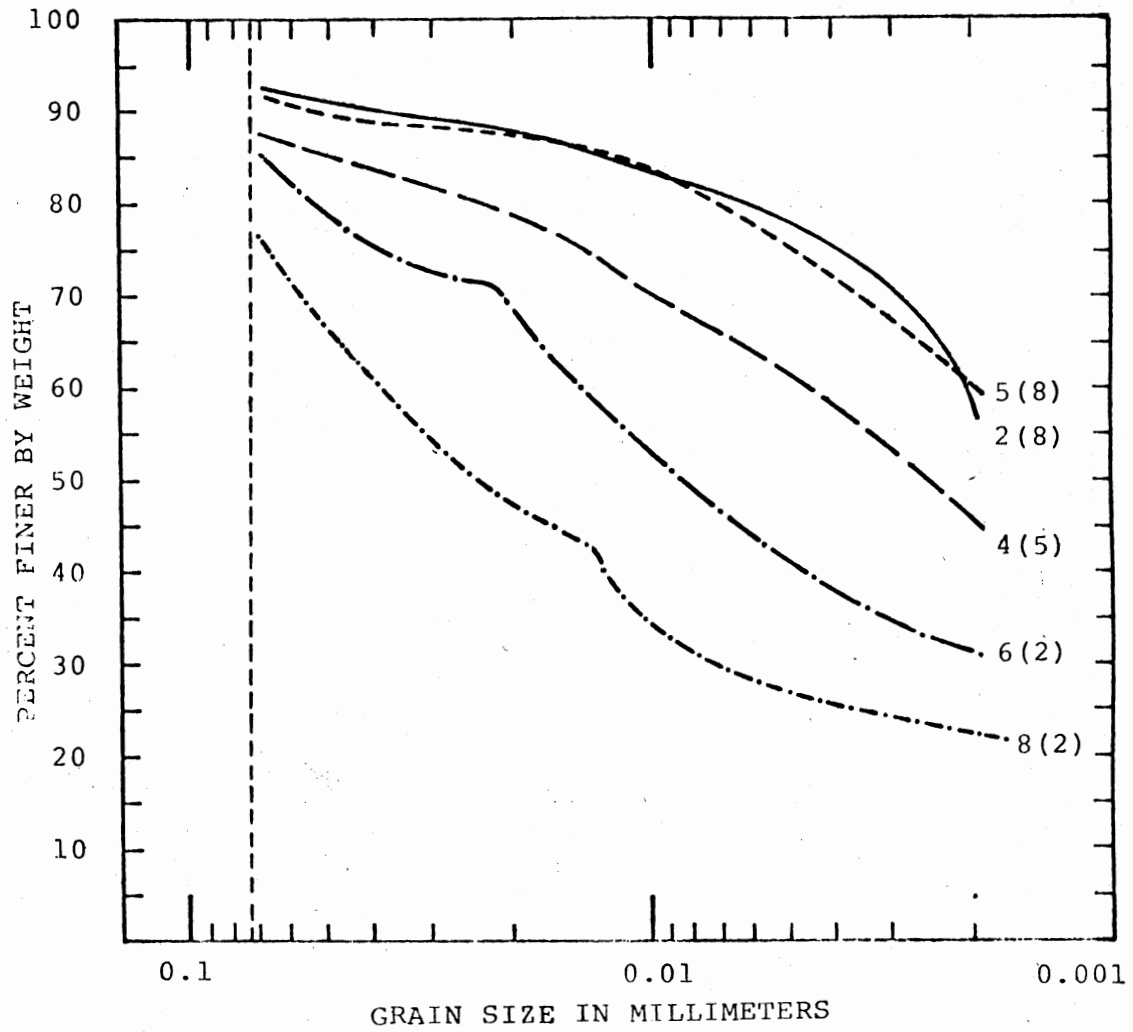


Fig. 3. Mean grain size distribution of samples taken in April, June, August, and October from the stations in Ham's Lake.

### Organic Matter

Differences in means among the five stations were not significant ( $0.75 < p < 0.90$ ). Percent organic matter of the sediments ranged from 1.0 - 7.5 at the 2 m stations and from 3.5 - 8.6 at the 8 m stations. Station 4(5) had a range of 4.3 - 6.3 (Table 2). Variation among sampling dates was significant ( $p < 0.05$ ). Organic matter increased at all stations between 15 April and 23 June and generally remained high in summer. Values at the 8 m stations decreased between 8 August and 26 October, while an increase occurred at Station 4(5).

### Sedimentation

Sediment deposited ranged from a depth of 2.5 - 4.5 mm/month, representing an oven-dry weight from 192 - 529 g/m<sup>2</sup> per month (Table 3). Although mean values were generally less at the 2 m stations than at the 8 m stations, variation among stations ( $0.05 < p < 0.10$ ) or dates ( $0.9995 < p < 0.999$ ) was not significant.

### Phosphorus

Dissolved P generally increased with water depth, while no trend with depth was observed for sediment P. Values ranged from non-detectable to 52.6 µg/l and 126 - 1323 µg/g for dissolved and sediment P, respectively (Tables 4, 5), representing significant levels of  $0.001 < p < 0.005$  and  $0.01 < p < 0.025$ . Dissolved P increased from 3 June to 27 June and decreased from 27 June to 26 October. Variation was significant ( $0.001 < p < 0.005$ ). Sediment P also changed significantly over time ( $0.001 < p < 0.005$ ). Values increased at all stations from

Table 2. Percent organic matter of the sediments in Ham's Lake.\*

Station (depth in m)	Collecting Date				
	15 Apr	27 May	23 Jun	15 Aug	26 Oct
6(2)	1.0	-	7.5	7.4	4.2
8(2)	3.7	-	6.1	2.0	3.1
5(8)	3.7	-	6.8	6.8	4.1
2(8)	3.5	-	8.6	7.6	5.6
4(5)	4.3	-	5.1	4.6	6.3

\*Values are means of four replicate cores  
 - Date not measured

Table 3. Depth and oven-dry weight of sediments deposited in Ham's Lake.\*

Date	Station (depth in m)	mm/mo	$\text{g/m}^2$ per mo
5 Jul - 4 Aug	6(5)	3.4	252
	8(5)	4.3	409
	5(8)	4.3	249
	2(8)	3.1	192
	4(5)	3.1	206
4 Aug - 26 Oct	6(5)	4.1	507
	8(5)	4.5	664
	5(8)	4.0	512
	2(8)	3.7	529
	4(5)	2.5	280

\*Values are means of four replicate samples

- Date not measured

Table 4. Dissolved P ( $\mu\text{g}/\text{l}$ ) in Ham's Lake.\*

Station (depth in m)	Collecting Date			
	3 June	27 June	26 Oct	
6(2)	Surface	-	1.3	-
	Mid-depth	-	-	5.0
	Bottom	-	-	7.5
5(8)	Surface	-	0	7.5
	Mid-depth	-	-	7.5
	Bottom	-	2.6	7.5
2(8)	Surface	0	11.2	2.5
	Mid-depth	0.1	-	2.5
	Bottom	0.3	35.5	2.5
4(5)	Surface	0.3	0	0
	Mid-depth	-	-	5.0
	Bottom	1.4	52.6	7.5

\*Values are means of three replicate samples

- Data not measured

0 Nondetectable



Table 5. Particulate P ( $\mu\text{g/g}$ ) in Ham's Lake sediment.\*

Station (depth in m)	Sediment Depth (cm)	Collecting Date			
		4 Apr	3 June	27 June	26 Oct
6(2)	1	323	-	528	155
	5	325	-	911	162
	10	303	-	712	-
	Mean	317	-	717	159
8(2)	1	-	-	826	178
	5	-	-	743	312
	10	-	-	935	306
	Mean	-	-	835	265
5(8)	1	143	-	642	627
	5	-	-	1323	672
	10	-	-	737	655
	Mean	143	-	901	651
2(8)	1	138	336	906	547
	5	126	476	775	743
	10	-	-	746	585
	Mean	132	430	809	625
4(5)	1	360	441	974	1200
	5	352	377	944	1073
	10	418	562	882	875
	Mean	377	460	933	1049

\*Values are means of four replicate cores  
 - Data not measured

4 April through 27 June, while a decrease occurred at the 8 m and 2 m stations from 27 June to 26 October, especially at the 2 m stations.

### Mineralogy

The types and relative amounts of quartz and clay minerals were identified by X-ray diffraction. The diffractograms for all of the stations were similar to that shown for station 4(5) in Fig. 4. Kaolinite and quartz were dominant at all stations; while mica, montmorillonite, and a mixed interlayering of montmorillonite-vermiculite were present in lesser amounts (Table 6). The 2 m stations had less quartz than the deeper stations.

## Arbuckle Lake

### Particle Size

Particle size of the sediments decreased with depth (Table 7). After 12 h in the laboratory analysis, over 60% of particles  $< 0.002$  mm remained in suspension at stations 1(26) and 2(24), respectively, while 51 - 57% remained at the 15 m depths. The 2 m depths had less than 25% of the particles  $< 0.002$  mm in suspension after 12 h. Variation among station means was highly significant ( $p < 0.0005$ ). Fig. 5 depicts variation in particle size at different depths and the grain size distribution of each station. The 2 m stations had a more even distribution of silt sized particles than the deeper stations. Seasonal variation was statistically significant ( $0.001 < p < 0.005$ ). Particle size generally decreased from 12 May to 13 June, changed little over the summer, and increased from 18 August to 20 October (Appendix).

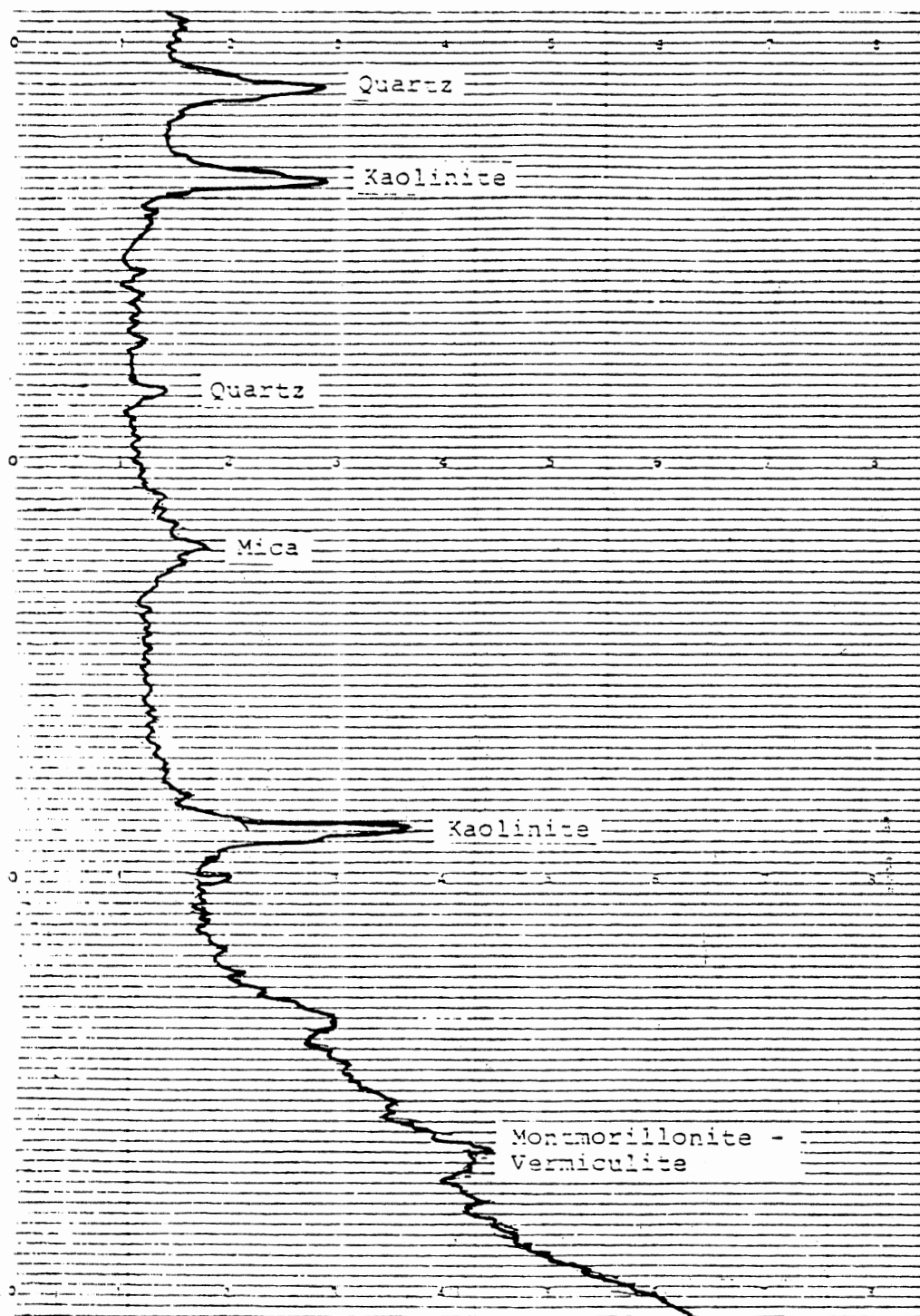


Fig. 4. Diffractogram of the sediment at station 4(5) in Ham's Lake.

Table 6. Relative amounts of quartz and clay minerals in Ham's Lake sediments.

Station (depth in m)	Quartz*	Kaolinite	Mica	Mont	V-M
6(2)	M	S	M-W	W	W
8(2)	M	S	M-W	O	W
5(8)	S	S	M-W	O	W
2(8)	S	S	M-W	O	W
4(5)	S	S	M-W	O	S

\*Quartz intensity may be partially due to quartz in the ceramic tile  
W-Weak, M-Moderate, S-Strong, O-None detected,  
Mont-Montmorillonite, V-M-Vermiculite-Montmorillonite

Table 7. Grain size analysis of the sediments in Arbuckle Lake.\*

Station (depth in m)	Variable**	Time (min)							
		0.5	1	3	5	10	20	120	720
1(26)	P	90	89	89	88	87	85	75	61
2(24)	P	92	91	91	90	89	87	77	62
3(2)	P	70	62	55	48	42	38	29	24
3(15)	P	90	88	88	86	84	82	69	56
4(2)	P	78	72	62	54	46	39	28	22
4(15)	P	89	88	88	87	85	81	69	55
5(2)	P	79	72	61	53	45	40	31	25
5(15)	P	80	78	78	77	75	73	62	51
	D	.070	.050	.029	.022	.016	.011	.005	.002

\*Values are the means of four replicate cores each collected on 12 May, 15 June, 18 July, 20 August, and 18 October

\*\*P-Percent of soil remaining in suspension

D-Maximum diameter (mm) of particles remaining in suspension at each station

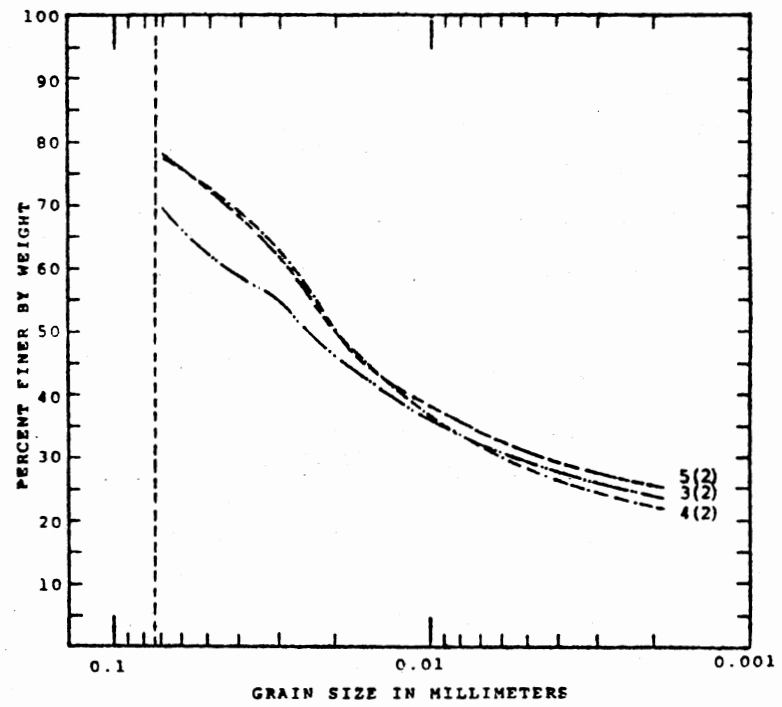
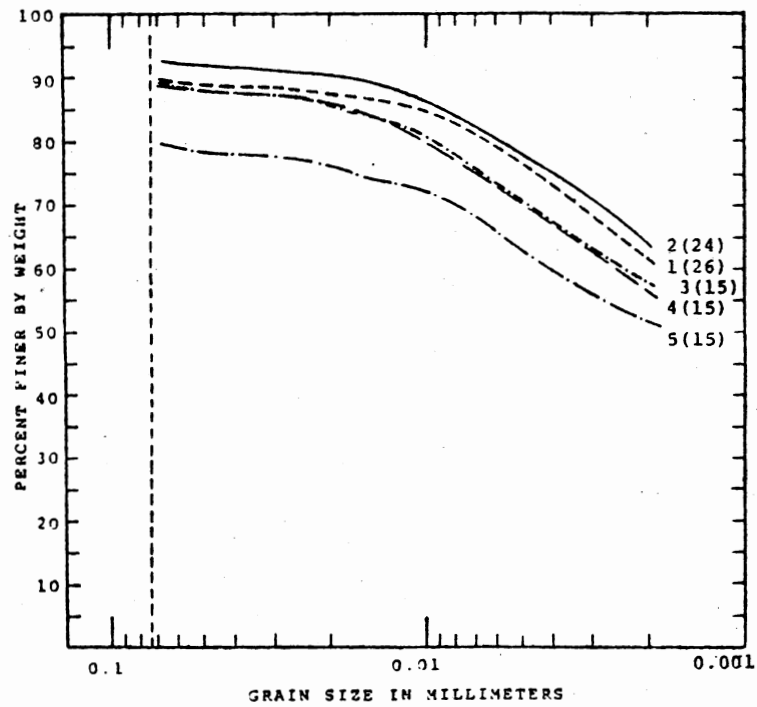


Fig. 5. Mean grain size distribution of samples taken in April, June, July, August, and October from the collecting stations in Arbuckle Lake.

### Organic Matter

Percent organic matter ranged from 2.9 - 7.5 at the 2 m stations and from 3.8 - 6.7 at the deeper stations (Table 8). Values were higher in summer at the 2 m stations than the deeper stations; however, variations among stations were not significant ( $0.75 < p < 0.90$ ). Although organic matter generally increased between July and August, seasonal variation was not significant ( $0.75 < p < 0.090$ ). Values at the 2 m stations decreased in October while values at the deeper stations remained high.

### Sedimentation

Sediment deposited varied from 4.3 mm/mo at station 3(8) to 39.4 at station 3(15) (Table 9), representing a weight of 364 - 6177 g/m<sup>2</sup> per month. Differences in means among the sampling areas ( $p < 0.05$ ) and variation among sampling periods were significant ( $p < 0.0005$ ).

### Phosphorus

Although soluble P ranged from a nondetectable level to 494.8 µg/l (Table 10), neither variation among stations ( $p < 0.25$ ) nor temporal variation was significant ( $p < 0.5$ ). Soluble PO<sub>4</sub>-P increased with depth at all stations on 14 June and 19 July. Values of the surface water increased between 19 July and 19 August. By 20 October, surface values had decreased, while bottom water increased in soluble P.

Inorganic sediment P ranged from 36 µg/g - 1196 µg/g (Table 11). Variation among stations was not significant ( $p < 0.5$ ). No trend was observed in inorganic sediment P with water depth or sediment depth.

Table 8. Percent organic matter of the sediments in Arbuckle Lake.\*

Station (depth in m)	Collecting Date				
	12 May	13 Jun	18 Jul	18 Aug	20 Oct
1(26)	-	4.8	3.9	4.5	6.6
2(25)	4.3	4.6	4.0	4.5	6.7
3(2)	-	6.7	5.8	7.5	2.9
3(15)	4.4	4.6	4.4	4.9	6.5
4(2)	-	6.2	6.0	6.5	3.2
4(15)	4.3	4.0	3.8	4.5	6.6
5(2)	-	6.2	6.0	6.3	5.4
5(15)	5.6	5.1	5.9	5.0	5.0

\*Values are means of four replicate cores  
 - Data not measured



Table 9. Depth and oven-dry weight of sediments deposited in Arbuckle Lake.\*

Date	Station (depth in m)	mm/mo	$\text{g/m}^2$ per mo
29 Jun - 27 Jul	1(26)	5.8	396
	2(24)	5.0	359
	3(8)	4.2	364
	3(15)	7.1	767
	4(8)	13.3	1826
	4(15)	7.8	818
	5(88)	18.2	2706
	5(15)	11.3	1255
	1(26)	7.9	527
	2(24)	8.8	505
	3(8)	28.0	6114
	3(15)	13.0	1625
	4(8)	13.5	1835
	4(15)	12.0	1528
	5(8)	-	-
5(15)	18.0	2651	
27 Jul	1(26)	12.4	1373
20 Oct	2(24)	15.6	1587
	3(8)	-	-
	3(15)	39.4	6177
	4(8)	17.8	3138
	4(15)	37.8	5150
	5(8)	-	-
	5(15)	18.0	2486

\*Values are means of four replicate samples  
 - Data not measured

Table 10. Dissolved P ( $\mu\text{g}/\text{l}$ ) in Arbuckle Lake.\*

Station (depth in m)	Depth	Collecting Date			
		14 Jun	19 Jul	19 Aug	20 Oct
2(24)	Surface	0	0	60.0	25.0
	Mid-depth	3.1	0.5	14.3	33.3
	Bottom	14.9	44.3	159.4	16.7
3(15)	Surface	0	0	0	8.4
	Mid-depth	-	2.4	0	16.7
	Bottom	5.7	18.1	2.4	25.0
4(15)	Surface	0	0	129.5	33.4
	Mid-depth	-	2.4	2.9	8.4
	Bottom	12.3	18.6	8.6	16.7
5(15)	Surface	0	0	494.8	8.4
	Mid-depth	-	0	19.0	25.0
	Bottom	16.7	3.3	24.8	50.0

\*Values are means of three replicate samples

- Data not measured

0 Not detectable

Table 11. Inorganic P ( $\mu\text{g/g}$ ) in Arbuckle Lake sediment.\*

Station (depth in m)	Depth (cm)	Collecting Date				
		5 May	13 Jun	19 Jul	18 Aug	26 Oct
2(26)	1	166	-	78	850	611
	5	216	-	59	1196	559
	10	250	-	79	-	644
	Mean	211	-	72	1023	605
3(2)	1	-	387	55	-	263
	5	-	350	52	-	326
	10	-	293	48	-	-
	Mean	-	340	52	-	294
3(15)	1	203	-	59	976	533
	5	196	-	62	951	554
	10	172	-	47	-	544
	Mean	190	-	56	963	544
4(2)	1	-	329	37	-	350
	5	-	287	36	-	405
	10	-	326	-	-	-
	Mean	-	314	36	-	378
4(15)	1	167	-	65	894	664
	5	163	-	60	905	564
	10	171	-	70	-	-
	Mean	167	-	65	890	614

Table 11. Continued.

Station (depth in m)	Depth (cm)	Collecting Date				
		5 May	13 Jun	19 Jul	18 Aug	26 Oct
5(2)	1	135	275	38	-	417
	5	141	271	-	-	521
	10	-	-	-	-	-
	Mean	138	273	38	-	469
5(15)	1	148	-	59	538	-
	5	165	-	74	543	-
	10	88	-	51	-	-
	Mean	134	-	61	540	-

\*Values are means of four replicate cores

- Data not measured

A significant variation existed among sampling dates ( $p < 0.0005$ ). Values were lower at all stations on 19 July than the previous 2 months. Values increased greatly from 19 July to 18 August and decreased between 18 August and 26 October.

### Mineralogy

Quartz was generally dominant, while kaolinite and mica were relatively weak (Table 12). Montmorillonite was prevalent at stations 3(15) and 5(2) only, while a significant amount of montmorillonite-vermiculite mixture was present at stations 3(2), 4(15), 4(2), and 2(24). The diffractogram for each station was similar to that shown for station 3(15) in Fig. 6.

### Aerobic-Anaerobic Study

Values representing the temporal variation of organic C and P in cores collected from stations 1(26), 3(15), 4(15), and 5(15) are shown in Table 13. Mean loss on ignition of the seven tubes collected from each station varied initially from 7.2 to 17.4%. Variation among stations was not significant ( $0.95 < p < 0.975$ ); however, values generally decreased with sediment depth. Variation in organic matter was slight. Phosphorus in the initial samples was greater at the 26 m stations than at the 15 m stations and little variation occurred with sediment depth. Values ranged from 698 to 1297  $\mu\text{g/g}$ . After incubating 2 months at  $12^{\circ}\text{C}$ , loss on ignition did not change significantly. Although values in the samples not receiving aeration were lower than corresponding values in aerated tubes, the differences were not significant ( $0.25 < p < 0.5$ ). Percent organic matter was also lowest in

Table 12. Relative amounts of quartz and clay minerals in Arbuckle Lake sediments.

Station (depth in m)	Quartz*	Kaolinite	Mica	Mont	V-M
1(26)	S	W-M	W	O	W-M
2(24)	W-M	S	W	O	M
3(2)	W-M	W-M	W	O	S
3(15)	S	M	W-M	S	O
4(2)	S	W-M	W	O	M
4(15)	M	S	W	O	M
5(2)	S	W	W	S	O
5(15)	S	W-M	O	W-M	O

\*Quartz intensity may be partially due to quartz in the ceramic tile  
W-Weak, M-Moderate, S-Strong, O-None detected, Mont-Montmorillonite, V-M-Vermiculite-Montmorillonite

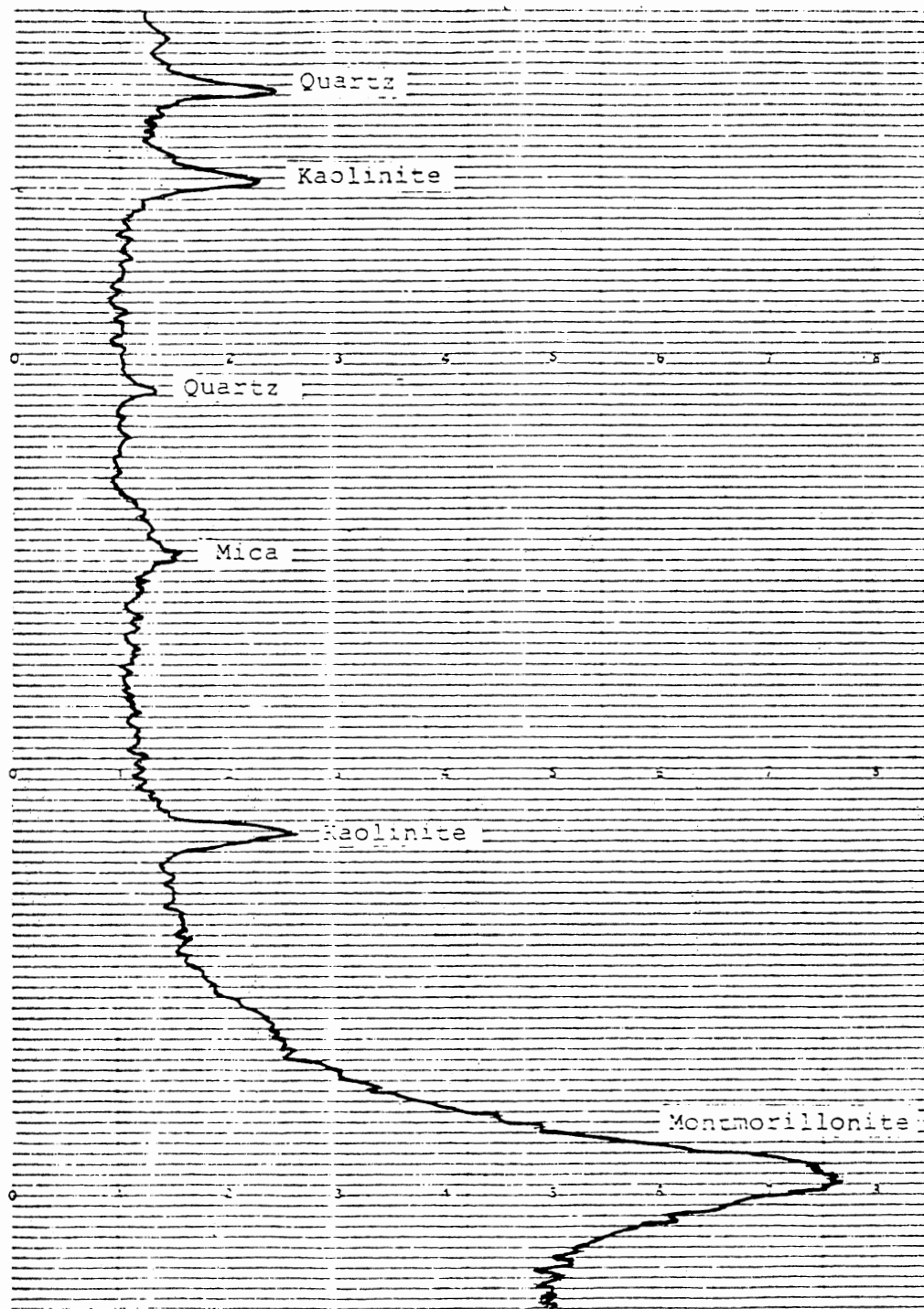


Fig. 6. Diffractogram of the sediment at station 3(15) in Arbuckle Lake.

Table 13. Percent organic matter and particulate P in Arbuckle Lake sediments analyzed after aerobic and anaerobic treatment.\*

Station (depth in m)	Variable**	Depth (cm)	Treatment		
			Initial	Aerobic	Anaerobic
1(26)	LI(%)	1	13.8	12.3	11.2
		5	12.8	12.18	9.1
		10	13.6	13.0	10.6
	POS( $\mu\text{g/g}$ )	1	1142	2047	2014
		5	1240	1981	1530
		10	1297	2275	1540
	OM(%)	1	6.7	5.7	3.9
		5			
		10			
3(15)	LI(%)	1	11.8	12.7	9.6
		5	11.0	12.6	8.1
		10	7.8	10.7	10.2
	POS( $\mu\text{g/g}$ )	1	823	1437	1109
		5	882	1538	1015
		10	807	1646	1003
	OM(%)	1	5.4	5.4	2.7
		5			
		10			
4(15)	LI(%)	1	17.4	8.1	20.4
		5	11.0	12.6	11.3
		10	10.3	15.4	11.4
	POS( $\mu\text{g/g}$ )	1	766	2093	1154
		5	698	1950	1117
		10	731	1672	1180
	OM(%)	1	5.7	6.4	4.7
		5			
		10			



Table 13. Continued.

Station (depth in m)	Variable**	Depth (cm)	Treatment		
			Initial	Aerobic	Anaerobic
5(15)	LI(%)	1	10.0	10.8	12.1
		5	8.1	9.3	11.5
		10	7.2	9.9	12.1
	POS( $\mu\text{g/g}$ )	1	815	2165	1211
		5	710	2240	1035
		10	799	2061	1165
	OM(%)	1	5.2	5.7	4.7

\*Values are means of seven replicate cores

\*\*LI-Loss on ignition, POS-Sediment phosphorus, OM-Organic matter

anaerobic samples ( $p < 0.0005$ ). Phosphorus increased significantly in the tubes receiving aeration ( $p < 0.0005$ ). Values were highest in aerated tubes reaching 2275  $\mu\text{g/g}$  in the 10 cm depth of sediment taken from station 1(26).

## CHAPTER VI

### DISCUSSION

Particle size decreased with station depth. A longitudinal gradation resulted as sediments were carried by currents from shallow to deep water. Larger particles settle first and smaller particles remain in suspension until reaching the quieter, deeper waters. Wilson (1936) found that the distribution of settled material was not uniform in Winona Lake, Wisconsin. Particulate materials migrated towards the deepest part of the lake and lodged permanently in the depressions. Wind-induced currents and wave action are the principal mechanisms for transporting sediments from littoral waters to deeper waters where currents are reduced (Scott and Mainer 1936). Frink (1969) established good correlations between particle size and water depth. Currents and wave action were sufficient to carry the fine material into deeper water without the drastic mixing occurring in more open bodies of water. In the present study, particle size tended to decrease with time at the deeper stations in both lakes. During thermal stratification, strong wind-induced currents are confined to epilimnetic waters (McKee et al. 1970) and small particles may settle in the less turbulent areas. The lack of a seasonal change in particle size at the shallow stations may be attributed to the proximity to the terrestrial environment and the greater susceptibility to natural and man made turbulence.

Organic matter did not vary significantly among stations and seasonal variation was slight. Kemp (1971) found that the quantity of organic matter in the top cm of sediments in the Great Lakes was directly proportional to the clay size fraction of sediment and independent of depth, rate of sedimentation, and degree of eutrophication. A linear relation between organic matter and sediment particle size has been observed by many workers (Trask 1932, Bordovisky 1965, Thomas 1969, and Longbottom 1970). No correlation existed between organic matter, depth, and particle size in the present study. Variation in particle size among stations may not be sufficient to influence significantly variation in the amounts of organic matter which accumulate. The actual amount of organic material reaching the sediments may be small. Kajak, Hillbricht-Ilkowska, and Pieczynska (1970) found that approximately one-half of the amount of organic C reaching the hypolimnion is oxidized before it reaches the sediments. Wojtalik (1970) observed that organic C was being decomposed in the hypolimnion of Cherokee Reservoir. Decomposing macrophytes and leaf litter, characteristic of the shallower stations, may contribute to a relatively high percent organic matter. Higher aquatic plants and benthic organisms contribute to much of the primary production of certain aquatic ecosystems (Hargrave 1969; Kajak, Hillbricht-Ilkowska, and Pieczynska 1970), and presumably excrete organic compounds.

The rate of sedimentation is larger in Arbuckle Lake than in Ham's Lake. Sedimentation rate increased from June to October in Arbuckle Lake, but little seasonal variation occurred in Ham's Lake. Factors which may influence sedimentation rate include rate of stream flow; watershed size and use; topographic and soil characteristics;

vegetational cover; and the kind, amount, and distribution of precipitation (McKee et al. 1970, Oschwald 1972). The inverse relation of depth to sedimentation rate may be explained by size sorting of particles. Smaller, less dense particles which are carried to deeper waters tend to remain in suspension, while heavier particles settle rapidly upon entering the shallower waters (Wilson 1936). Sediments trapped at the deeper stations in Arbuckle Lake contained a higher percent organic matter. The finer sediments of deep waters, consisting largely of clays, could act as organic sinks (Hendricks 1971). Organic matter has been found to increase as particle size decreases (Kemp 1971) and C may be predominantly adsorbed by clay particles (Hayes and Anthony 1958).

Inorganic P of the sediment generally decreased during summer and increased in fall. Summer stratification and the concurrent breakdown of the microzone at the sediment interface are related to P release by the sediment (Mortimer 1941). Surface water biological activity may also affect P mobility. Wildung, Schmidt, and Gahler (1974) suggested that phytoplankton use of P in Howard Bay may have provided a substantial biological sink reducing the solution concentration of  $\text{PO}_4\text{-P}$  and resulting in a decrease in sediment P. Soluble  $\text{PO}_4\text{-P}$  generally increased from June to July and decreased from July to October in both lakes. This might be explained by increased activity of the biota. Inorganic sediment P and soluble  $\text{PO}_4\text{-P}$  generally increased with increasing depth. Contents of P and several other elements, including Fe, in surface sediments generally increase with increasing depth of the overlying water column (Delfino, Bortleson, and Lee 1969; Williams et al. 1970). Phosphorus may be preferentially associated with

the fine particles characteristic of deeper waters (Seyers, Harriss, and Armstrong 1973).

Minerals comprising the sediment in both lakes were quartz, kaolinite, mica, montmorillonite, and a montmorillonite-vermiculite mixture. Amounts of kaolinite and mica were relatively greater in Ham's Lake sediment. Kaolinite was the dominant clay particle in both lakes. Kaolinite has a relatively low surface area and a low capacity to adsorb cations. The specific surface area of montmorillonite greatly exceeds the total area of kaolinite and has a high cation adsorption capacity, perhaps 10-15 times that of kaolinite (Brady 1974).

Differences in percent loss on ignition of samples analyzed initially and after aerobic and anaerobic treatment were not significant. Percent organic matter was significantly lowest in the anaerobic samples of all stations. However, rates of C mineralization are slower under anaerobic conditions within the sediments and lower hypolimnion of stratified lakes (Wetzel 1975). Lack of agreement between percent loss on ignition and percent organic matter could be attributed to error associated with method. If a large amount of clay minerals were present in the sediments, the amount of water associated with clay minerals could have caused error. If large amounts of  $Mn^{2+}$ ,  $Fe^{2+}$ , and  $Cl^-$  were present in the sediment, the oxidation procedure could have been affected (Black 1968). Inorganic sediment P was highest in the aerobic samples. The greater release of dissolved inorganic P under anoxic conditions is well documented (Mortimer 1941, Hayes 1964, and Olsen 1964). The oxidized state associated with aerobic conditions resulted in a relatively high concentration of P in the sediment. Mortimer (1941) determined that P is adsorbed strongly on ferric

hydroxide or organic complexes of ferric hydroxide in the oxidized surface mud layers of lake bottoms as long as DO is present in the overlying water. The difference in the capacity of oxidized and reduced forms of iron oxide to sorb and release  $\text{PO}_4\text{-P}$  account for the difference in sorption and release of P between oxidized and reduced soils and sediments (Patrick and Kahlid 1974).

## CHAPTER VII

### SUMMARY

1. Seasonal changes in particle size, percent organic matter, P, and sedimentation rates were studied in two lakes from May through October 1977. Types of minerals in the two lakes were determined and a laboratory study of the effects of aerobic and anaerobic conditions on inorganic P and organic matter of the sediment was conducted.

2. Particle size varied with depth. Finer sediments were found at the deeper stations, while coarser sediments were characteristic of the shallow waters. Sediments of the shallow stations generally had a more even grain size distribution from coarse to fine particles than the deeper waters where grain size was finer and more uniform. Particle size tended to decrease as the lakes stratified and to increase as mixing resumed.

3. Seasonal variation in organic matter was not significant. No apparent relation existed between organic matter, depth, and particle size.

4. Sedimentation rate was inversely related to depth in Arbuckle Lake. Rate of sedimentation generally increased from June to October. Arbuckle Lake had a greater sedimentation rate than Ham's Lake.

5. Constituent minerals in the lake sediment include quartz, kaolinite, mica, montmorillonite, and a montmorillonite-vermiculite interlayer. Kaolinite, which has a relatively low surface area and a



low capacity to adsorb cations, was the dominant clay particle in both lakes.

6. Temporal variation occurred in inorganic sediment P with a general decrease in summer and an increase in fall. Dissolved  $\text{PO}_4\text{-P}$  generally increased from June to July and decreased from July to October. Sediment P and soluble  $\text{PO}_4\text{-P}$  tended to increase with water depth.

7. A lack of agreement occurred between percent loss on ignition and the oxidation procedure used in determining organic matter. The oxidation procedure indicated that organic matter was highest in the anaerobic samples. Inorganic sediment P increased significantly in tubes which had undergone aerobic treatment.

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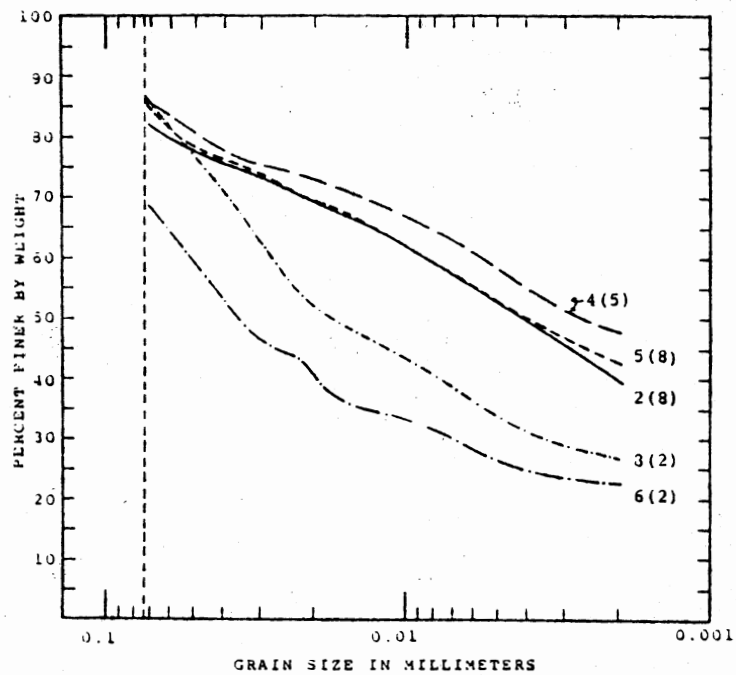
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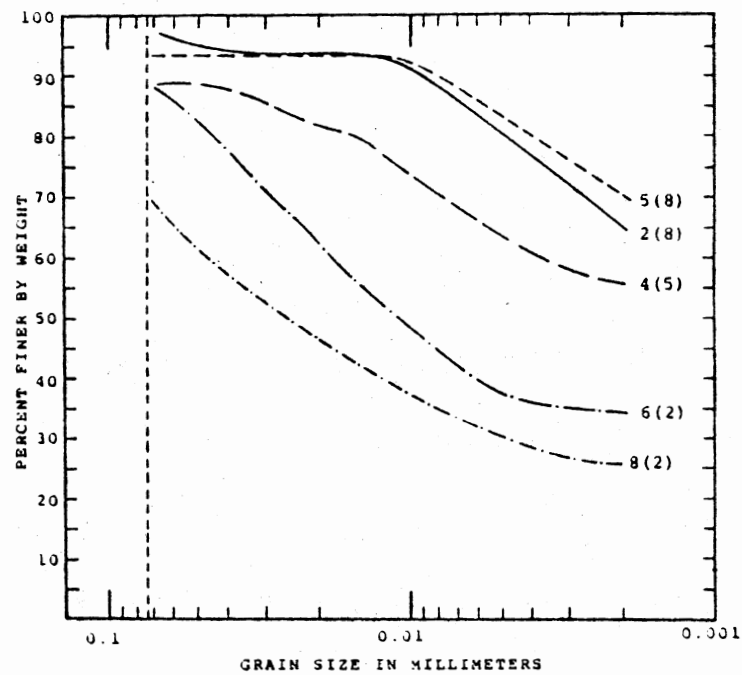


**APPENDIXES**



SAND	FINES	
FINE	SILT SIZES	CLAY

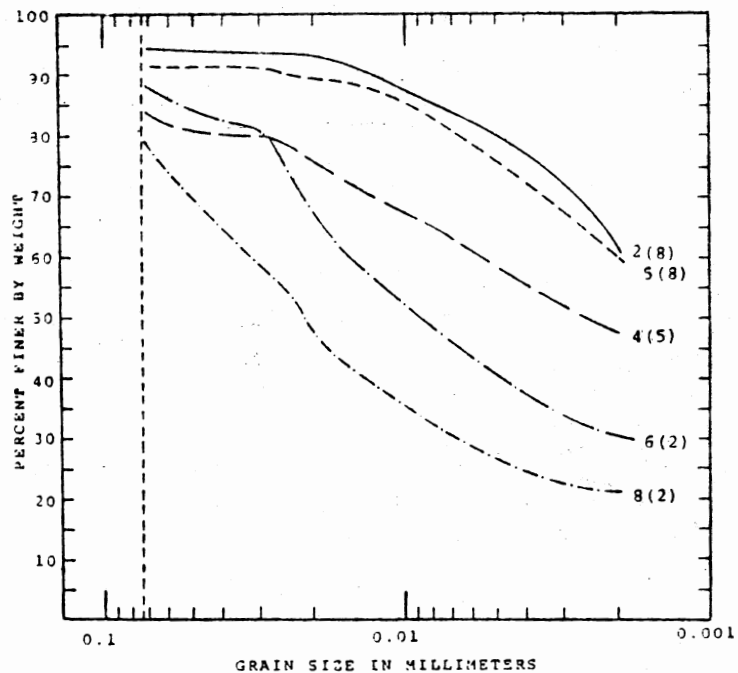
Ham's Lake April 17, 1977



SAND	FINES	
FINE	SILT SIZES	CLAY

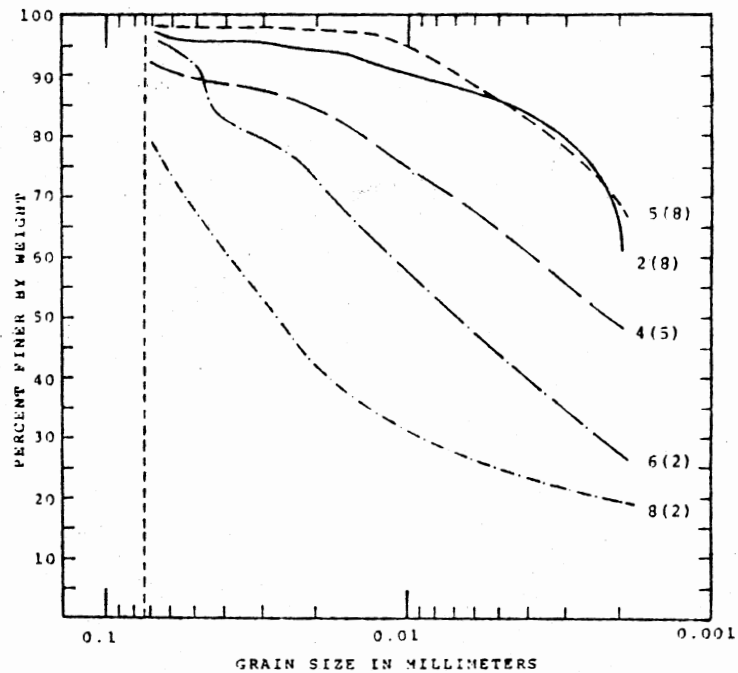
Ham's Lake 22 June, 1977

Fig. 7. Grain size distribution of samples taken in April and June at Ham's Lake.



SAND	FINES	
FINE	SILT SIZES	CLAY

Ham's Lake 26 October, 1977



SAND	FINES	
FINE	SILT SIZES	CLAY

Ham's Lake 8 August, 1977

Fig. 8. Grain size distribution of samples taken in August and October at Ham's Lake.

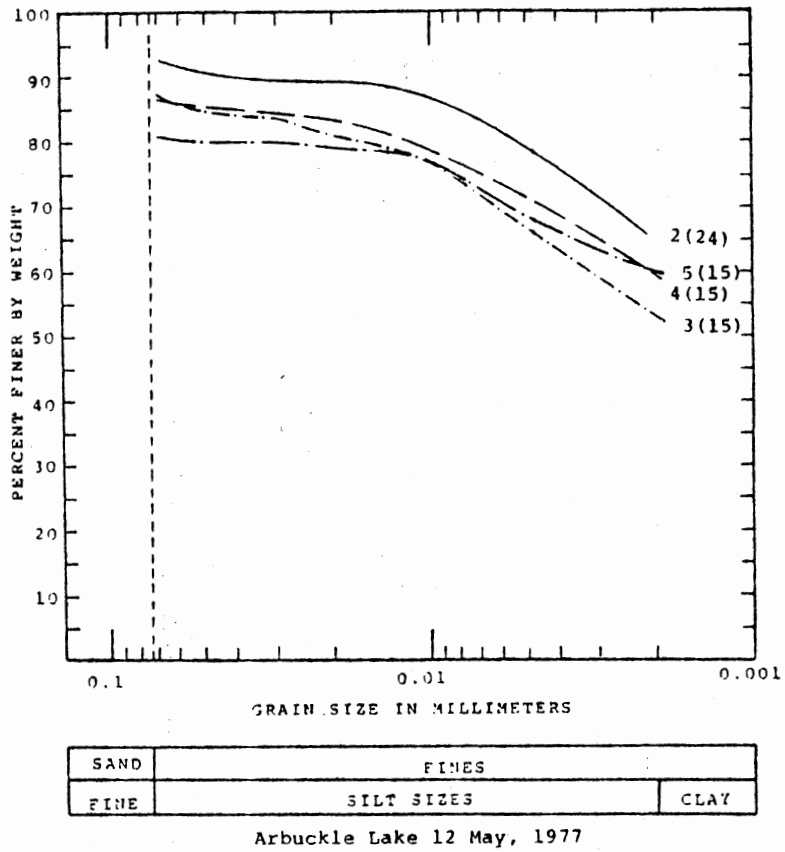
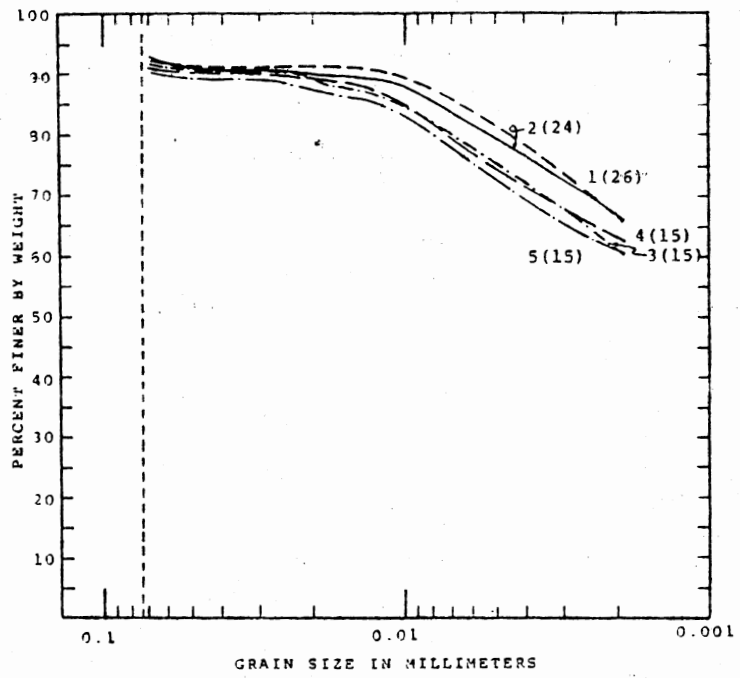
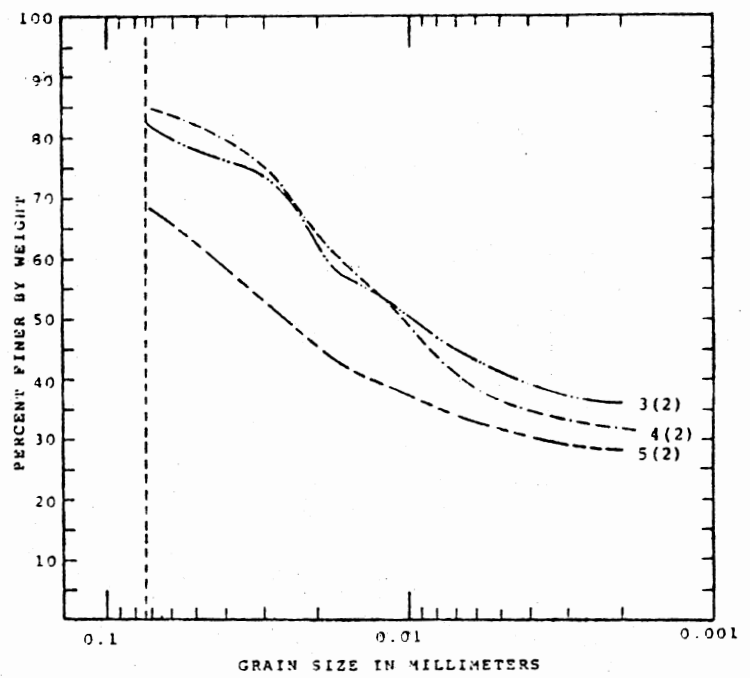


Fig. 9. Grain size distribution of samples taken in May at Arbuckle Lake.



SAND	FINES	
FINE	SILT SIZES	CLAY

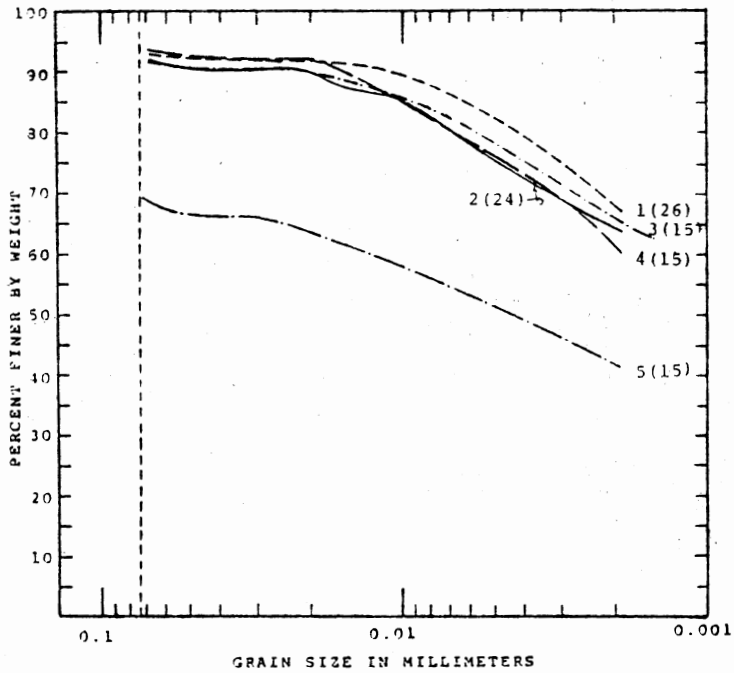
Arbuckle Lake 13 June, 1977



SAND	FINES	
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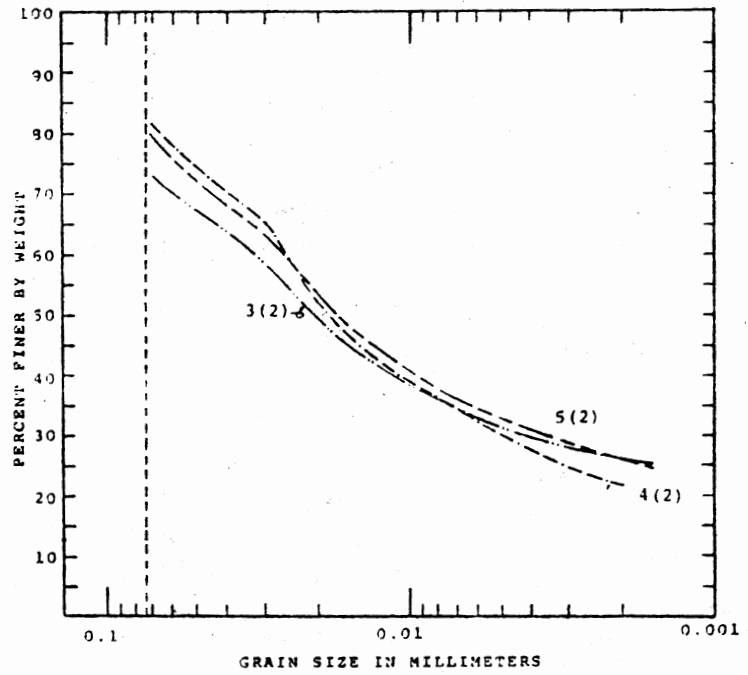
Arbuckle Lake 13 June, 1977

Fig. 10. Grain size distribution of samples taken in June at Arbuckle Lake.



SAND	FINES	
FINE	SILT SIZES	CLAY

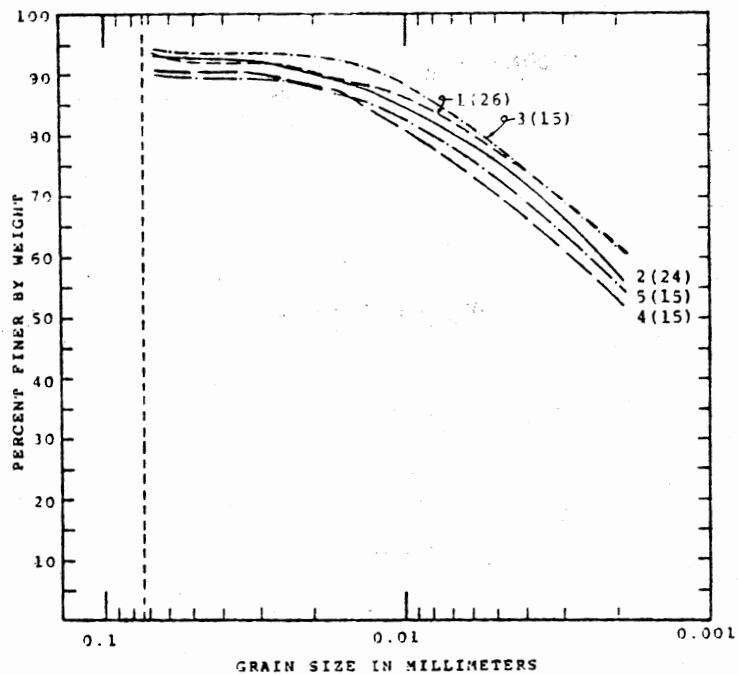
Arbuckle Lake 18 July, 1977



SAND	FINES	
FINE	SILT SIZES	CLAY

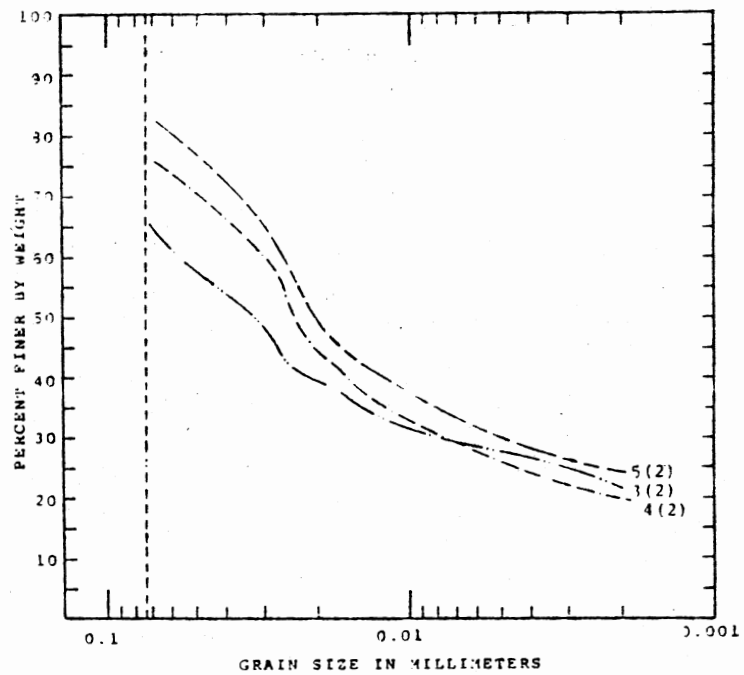
Arbuckle Lake 18 July, 1977

Fig. 11. Grain size distribution of samples taken in July at Arbuckle Lake.



SAND	FINES	
FINE	SILT SIZES	CLAY

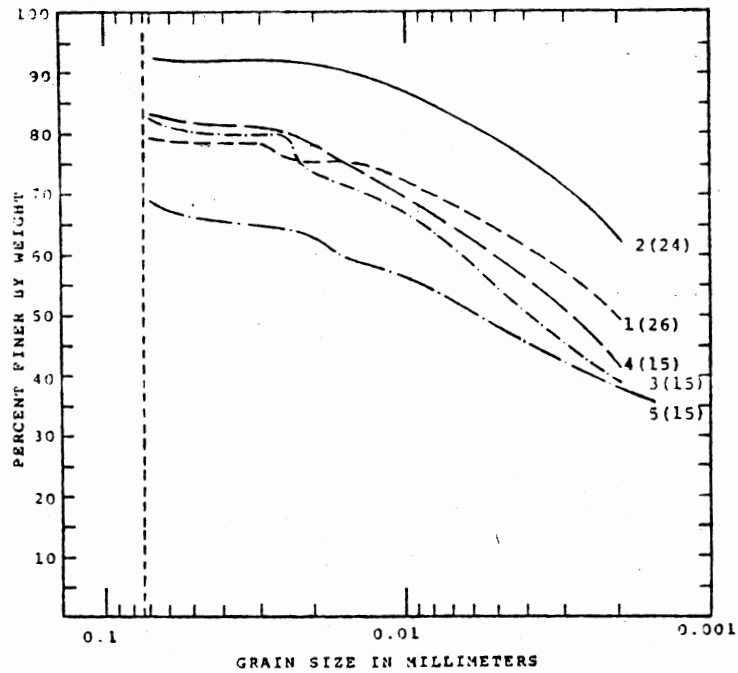
Arbuckle Lake 18 August, 1977



SAND	FINES	
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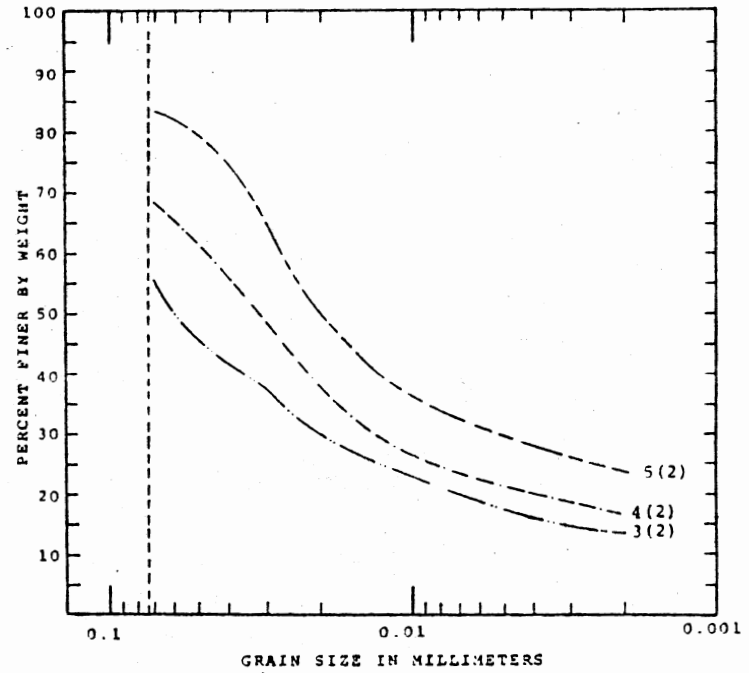
Arbuckle Lake 18 August, 1977

Fig. 12. Grain size distribution of samples taken in August at Arbuckle Lake.



SAND	FINES		
FINE	SILT SIZES		CLAY

Arbuckle Lake 20 October, 1977



SAND	FINES		
FINE	SILT SIZES		CLAY

Arbuckle Lake 20 October, 1977

Fig. 13. Grain size distribution of samples taken in October at Arbuckle Lake.



VITA 2

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