INORGANIC CHEMICAL PROFILES OF THE SEDIMENT CORES FROM SIX NORTHEASTERN OHIO RESERVOIRS

by

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ABSTRACT

INORGANIC CHEMICAL PROFILES OF THE SEDIMENTS OF SIX NORTHEASTERN OHIO RESERVOIRS

Genine M. Farran
Master of Science
Youngstown State University, 1990

The relationship between lake trophic state and lake sediments has been recognized for over fifty years. Sediment cores were collected from six Northeastern Ohio Reservoirs (the Ohio Water Service Reservoirs) Pine, Evans, Hamilton, McKelvey, Liberty and Girard. Cores were sliced into centimeter sections and each section was analyzed for water content, organic matter content, total carbon, nitrogen, sulfur, aluminum, iron, manganese, calcium and magnesium. Mean concentrations of the elements, linear regression analysis of each parameter with depth and ratio analysis were used to evaluate the trophic history of the six reservoirs. No significant increases in trophic state were found in Lake Pine, however, the high concentrations of organic matter, carbon, nitrogen and the significant positive correlation between Fe:Mn and depth, are indicative of the high trophic state of Lake Pine. Lake Evans has significant increases in carbon, nitrogen, organic matter and calcium towards recent sediments, and a significant positive correlation between Fe:Mn ratio and sediment depth indicating eutrophication. The distribution of carbon, nitrogen, sulfur, Fe:S ratios, and calcium in Lake Hamilton sediments indicates the lake has experienced a peak in productivity early in its development, and a second increase in productivity in recent times. Lake McKelvey has significant increases towards recent sediments in carbon, nitrogen, sulfur and calcium content, and significant positive correlations between Fe:S and depth and Fe:Mn and depth indicating increased productivity. Lake Liberty shows signs of eutrophication by the significant concentrations of carbon, nitrogen, organic matter and its high Fe:Mn ratio. Lake Girard has significant increases in carbon, nitrogen, organic matter, sulfur, and calcium and significant positive correlations between Fe:S and depth, and Fe:Mn and depth indicating increased productivity.

To Mom and Dad, Mark, Jack, Gramma and Grampa. All of you have been a constant source of support and encouragement, throughout the duration of this project, and always.

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INTRODUCTION

"Sediments are the product of lake life, consequently, they reflect the lake type" (Lundqvist 1938, 1942). This relationship has been recognized for over fifty years, and more recently, sediment profile analysis has been used to interpret the history of a water body (Hakanson 1983). Sediment carbon-sulfur relationships have been used to separate aerobic from anaerobic water environments (Raiswell et al. 1987). Information about the production of a water body and the degree of mineralization has been interpreted by sedimental analysis (Hargrave 1973). Bortleson and Lee (1972) have related sediment profile analysis to the trophic status of lakes. More importantly, because sediments play a critical role in determining trophic state (Golterman 1966), profile analysis of sediments contributes to the understanding of the process of lake eutrophication (Serruya 1971). In addition, Rybak and Rybak (1982) add, "the possibility of studying the history of lakes on the basis of bottom sediments is particularly important in the current period when the processes of anthropogenic eutrophication became growingly intense"; furthermore, "knowledge of these processes facilitates the evaluation of lake evolution ... and of the rate of change."

The purpose of this investigation is to interpret the trophic history of six Ohio Water Service (OWS) Reservoirs (Pine, Evans, Hamilton, McKelvey, Liberty and Girard) based on sediment core analysis. The cores were analyzed for sediment water content, carbon, nitrogen, sulfur, aluminum, calcium, magnesium, iron, manganese and weight loss on ignition. Mean concentrations of the elements and linear regression analysis of each parameter with depth and ratio analysis are used to evaluate the trophic history of the six reservoirs. Data on the water chemistry of these reservoirs includes total phosphorus, chlorophyll a and Secchi disk transparency. These data have been used to calculate trophic state indices (TSI) (Carlson 1977) for each reservoir. The relationship between present TSI and sediment surface chemical composition is correlated with the chemical composition of the deeper sediments to gain insight into past trophic conditions.

The origin of the sediments, allochthonous (derived from outside of the lake) and autochthonous (produced within the water column), each has unique characteristics. Carbon to nitrogen ratios (C:N) of allochthonous sediment is about 50:1 and the C:N ofautochthonous matter is about 12:1 (Wetzel 1983). C:N ratios will be used along with organic matter:aluminum ratio (OM:AL) to determine the source of sediment organic matter. Compounds of aluminum are among the most common components of the soil. Their origin is almost exclusively from the erosion of the watershed and transport by streams into the lake (Januszkiewicz 1983/1984). Conversely, the majority of organic matter is formed within the lake. Thus, the change in percentage of aluminum with depth of sediment will be used to estimate the relative allochthonous input. Organic matter will be related to increased production in the water column and settling of autochthonous material (Zdanowski 1983). The ratio of OM:AL with depth will also be used to estimate change in OM relative to AL with time. These analyses will allow an interpretation of the change in autochthonous organic input to sediments, and may correspond to an increase or decrease in lake trophic state.

The variation of water content of sediment core depth is dependent on the quantity and quality of the sediment, its rate of change with time and the presence of organisms effective in bioturbation (Hakanson 1983). Sediments with a greater percentage of organic matter are expected to contain higher concentrations of water. Sediments with more inorganic character are expected to exhibit lower concentrations of sediment water. Decrease in water content is expected with increasing sediment depth in all reservoirs.

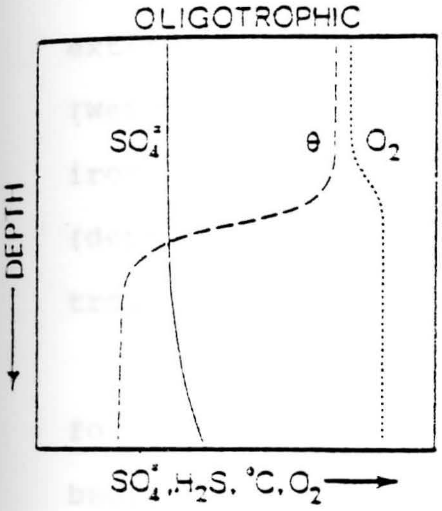
Total carbon and nitrogen contents are expected to be higher in more productive lakes, primarily because of the increase in autochthonous organic matter and its sedimentation. Nitrogen content is primarily of organic origin. Organic decomposition results in the release of soluble NH4-N, which diffuses up through the sediments into the water column to be reutilized by plants in the photic zone. Decrease in total nitrogen is expected with increasing sediment depth chiefly because of its release as soluble NH4-N during decomposition, and may be related to diminished productivity in earlier years (Fish and Andrew 1980). Total carbon is expected to remain relatively constant in non-dynamic lakes. However, where eutrophication is ongoing, total carbon content is expected to decrease with depth of sediment.

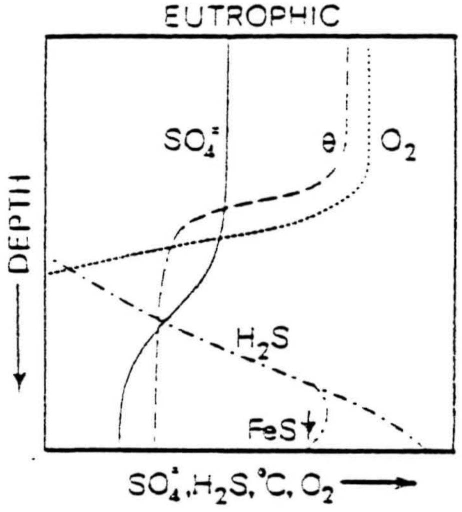
Nitrogen content has been used in conjunction with carbon for estimating the degree of "humosity" of lake sediments, as C:N (Hansen 1961), and humic sustances have been proposed to originate autochthonously, from phytoplankton (Ishiwatari et al. 1985). Hakanson (1983) suggests that an examination of the C:N ratio provides a pathway for examining lake trophic level. The C:N ratio is expected to be higher in sediment ofhumic character, in sediment of higher organic content and in lakes of greater trophic state (Ibid).

Anoxic conditions (Eh < 200 mV) in the hypolimnion permit sulfate reduction to sulfide and consequent precipitates of iron sulfide (Mitchell et al. 1983). With increasing lake trophic state, and longer periods of anoxia in the hypolimnion, greater concentrations of sulfide, thus of total sulfur, are expected to deposit onto the sediments. Other sulfur contributions are from increased organic sedimentation. Correlation analysis of percent sulfur with depth and with percent organic matter will be used to interpret past hypolimnetic oxygen conditions and will be related the change in production of each reservoir (Wetzel 1975), as a net loss of sulfur to the sediments is expected in eutrophic as opposed to oligotrophic reservoirs (Figure 1). Thus, total sediment sulfur is expected to be greatest in lakes of more eutrophic status, and is expected to exhibit a negative correlation with depth in lakes undergoing eutrophication.

Iron and manganese have been analyzed by several researchers in relationship to redox conditions, pH and in the precipitation of phosphorus and sulfur (Bortleson 1974, Januszkiewicz 1979, 1980, 1983/84, Cooke et al. 1986). The ratio of these two elements in the sediment will be used to interpret hypolimnetic oxygen conditions. At low redox (< 200 mV), a condition concurring with thermal stratification and

Figure 1. Generalized distribution of sulfate and hydrogen sulfide in lakes of very low and very high productivity, extracted from Wetzel, 1975, p. 269.


OLIGOTROPHIC
$SO_4^=$
θ
O_2
DEPTH
$SO_4^=$, H_2S, °C, O_2


EUTROPHIC
$SO_4^=$
θ
O_2
DEPTH
H_2S
FeS
$SO_4^=$, H_2S, °C, O_2

hypolimnion anoxia, manganese is reduced more readily and is released from the sediments with greater intensity than is iron (Hakanson 1983). Lakes of higher trophic state will exhibit greater periods of anoxia and are expected to have higher iron to manganese ratios, induced by the differential solubility of iron and manganese at low redox. This relationship (FE:MN) may be complicated at very low redox by the reprecipitation of iron as FeS, an extremely insoluble compound formed at Eh $\leq$ 100 mV (Wetzel 1975). Thus, correlations between sulfur and iron concentrations and their depostion over time (depth) will also be determined and related to lake trophic state.

Calcium and magnesium compounds, usually in the form of carbonates, originate from "calcareous bedrock, surface runoff, soil water and ground water enriched with Ca++" (Hakanson 1983). Complexes of both calcium and magnesium are important in the contribution to total lake hardness and act as micronutrients in freshwater ecosystems (Wetzel 1975). The endogenic precipitation of calcium carbonate has been related to lake productivity (Hakanson 1983, Wetzel 1975, Januszkiewicz 1979), and to source of carbonates (Mudrock et al. 1982). Hard water conditions are the primary cause of calcium and magnesium sedimentation. Magnesium sedimentation has been associated with larger grain size, such as near the shoreline (Clay and Wilhm 1979). Thus, an analysis of calcium, magnesium and the ratio of CA:MG with depth in the sediment may correlate with change in production, and more importantly, with their relationship to water hardness and watershed conditions. Because magnesium is more soluble than calcium at low redox (Wetzel 1975), the ratio of calcium to magnesium (Ca:Mg) is expected to decrease with depth and be greater in more eutrophic reservoirs.

The expected effects of lake productivity on sediment chemical parameters and their change with depth are summarized in Table 1.

Table 1. A summary of sediment chemical parameters in a reservoir undergoing eutrophication and the expected change in concentration with depth (DP) of sediment.

H2O:DP	-	FE:DP	-
C:DP	-	MN:DP	-
N:DP	-	C:N	+
S:DP	-	OM:AL	+
AL:DP	0	FE:MN	+
CA:DP	-	FE:S	+
MG:DP	-	CA:MG	-

0 = no change, - = decrease w/ depth, + = increase w/ depth

DESCRIPTION OF SIX OHIO WATER SERVICE RESERVOIRS

The six reservoirs presented in this study (Pine, Evans, Hamilton, McKelvey, Liberty and Girard) were built by the Ohio Water Service Company, Struthers, Ohio, a subsidiary of Consumer Water Corporation, Portland, Maine. The oldest of the reservoirs, Lake Hamilton, was constructed in 1905, primarily to meet the growing demands of the Youngstown steel industry. Construction of the five other reservoirs soon followed with the last lake, Evans, dammed in 1948. Each reservoir is unique in morphometry (Table 2), watershed use and development, and water chemistry. Due to the lack of appropriate topographic map data from Lake McKelvey, limited quantitative data is available on its morphometry.

Sediment-water relationships reflect the size and nature of the lake and its drainage basin (Januszkiewicz 1979). Lakes with greater watershed to lake surface area ratio (WSA:LSA) are influenced far more by the watershed than those with low ratios. Hamilton Lake has the greatest WSA:LSA ratio (85). McKelvey has the second greatest ratio (44), followed by Girard (31), Liberty (24), Evans (10) and Pine (6) (Table 3).

Table 2. Morphometry of Six Ohio Water Service Reservoirs.

LAKE	MAX LENGTH (km)	MAX WIDTH (km)	MAX DEPTH (m)	SHORE LENGTH (km)	SURFACE AREA $(m^2 x10^{-4})$	BASIN VOLUME $(m^3 x10^{-4})$	MEAN DEPTH (m)	RELATIVE DEPTH (m)	%MEAN SLOPE %	SHORELINE DEVELOPMENT %
PIN	3.05	1.10	3.0	9.21	191.0	174	0.91	0.91	0.38	1.88
EVA	3.60	1.39	12.5	14.59	264.0	1330	5.03	0.68	1.36	2.53
HAM	1.14	0.67	17.0	4.13	39.7	274	7.08	4.79	9.57	3.70
MCK*					49.7		7.73			
LIB	1.34	0.62	14.0	6.40	41.9	194	4.62	1.92	3.83	2.79
GIR	1.93	1.28	15.0	10.90	101.0	482	4.77	1.32	2.64	3.06

*McKelvey data supplied by Janis Markusic, Ohio Water Service Co. Files, 1988.

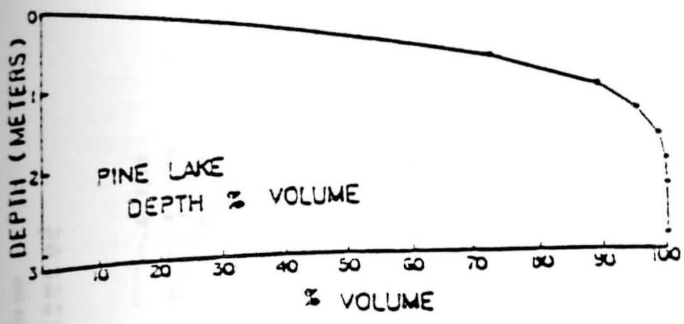
Table 3. Watershed surface area (WSA) and the watershed:lake surface area ratio (WSA:LSA) of six Ohio Water Service Reservoirs.

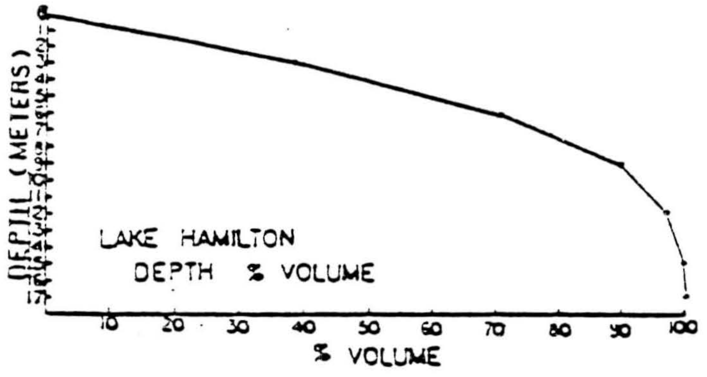
	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
WATERSHED SA (SQUARE KM)	12.3	27.0	33.7	22.1	10.0	31.6
WSA:LSA %	6	10	85	44	24	31

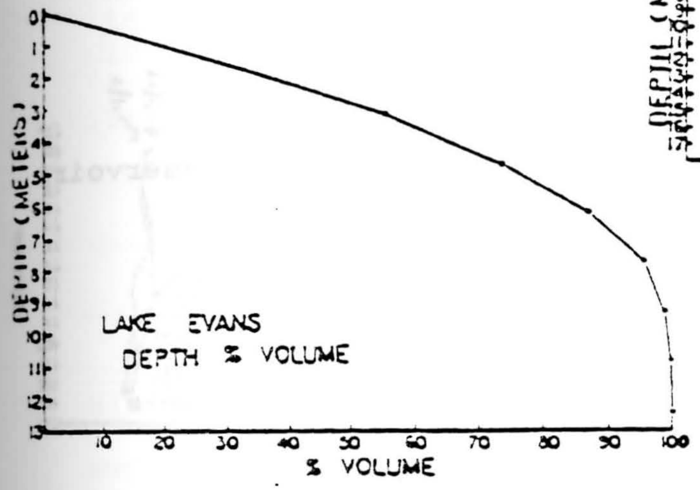
PINE

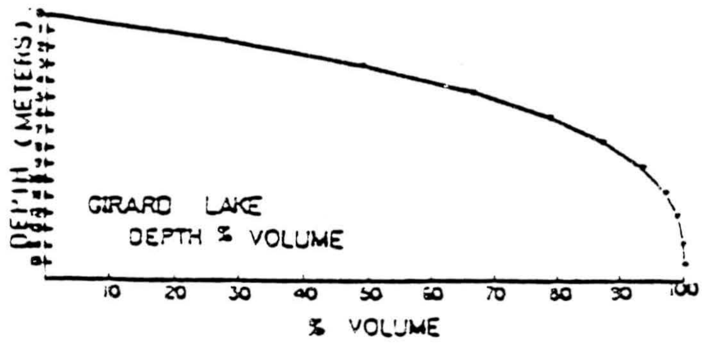
The lake situated furthest to the south is Pine. It is the second oldest reservoir, constructed in 1911. Pine is also the shallowest reservoir with a mean depth of 0.91 meters. Pine has considerably greater area for macrophyte development, as the majority of the water is less than one meter in depth (Figure 2). During unusually calm, hot summers, Pine will weakly stratify, but rarely is anoxic (Figure 3, Table 4). Slight changes in temperature cause thermal mixing and periodic high wind action readily mixes the entire water column. Dobolyi and Bidlo (1980) determined that sediment/water column interaction is much more pronounced in shallow lakes than in deeper ones. Pine's sediments are rich in organic matter and support a healthy population of benthos, an average of 318 mg m^{-2} (Schroeder and Farran 1987, unpub. pap.). Next to Evans Lake, Pine has the longest fetch (Table 2). This, combined with its shallow depth and low mean slope (0.38%), allow increased contact between nutrient-rich sediments and the water column. As a result, Pine is highly productive, as evident from the low Secchi disk readings of 0.72 meters ± 0.64 meters (Ibid). In addition, its shallow depth allows macrophyte development along the littoral zone and well into the central portions of the lake. Weed beds in Pine make excellent habitat for the varied

Figure 2. Depth to %Volume Hypsographs of Five OWS Reservoirs.


PINE LAKE
DEPTH % VOLUME
DEPTH (METERS)
0
1
2
3
10
20
30
40
50
60
70
80
90
100
% VOLUME


LAKE HAMILTON
DEPTH % VOLUME
DEPTH (METERS)
0
17
10
20
30
40
50
60
70
80
90
100
% VOLUME


LAKE EVANS
DEPTH % VOLUME
DEPTH (METERS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
10
20
30
40
50
60
70
80
90
100
% VOLUME


GIRARD LAKE
DEPTH % VOLUME
DEPTH (METERS)
10
20
30
40
50
60
70
80
90
100
% VOLUME

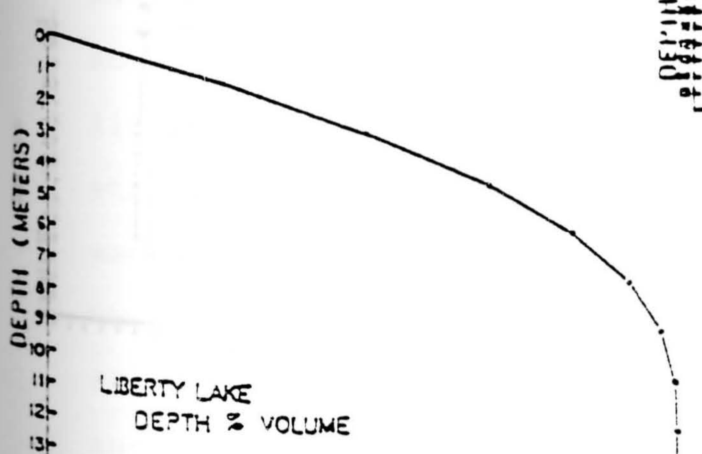
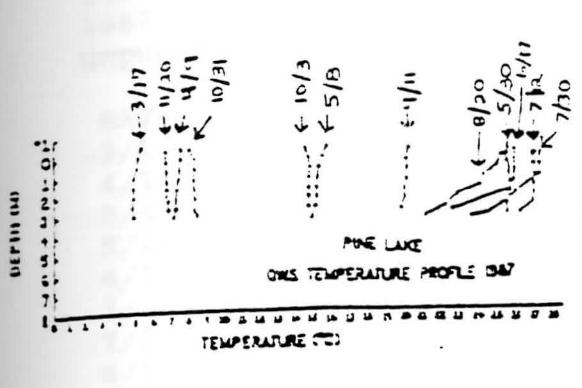
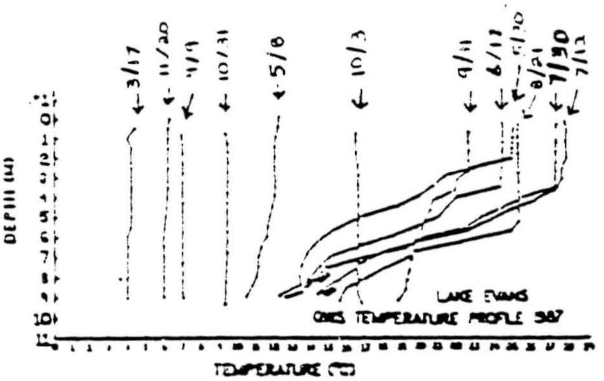
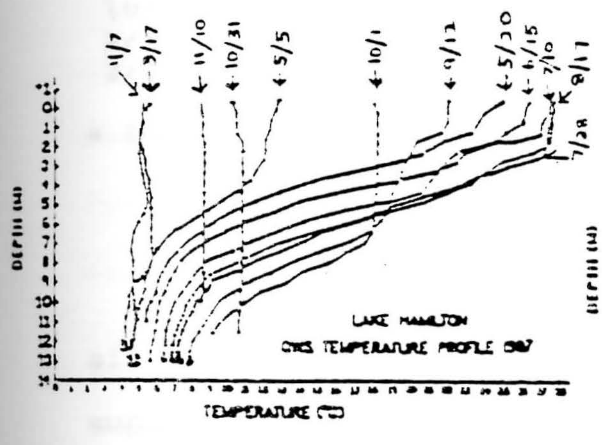
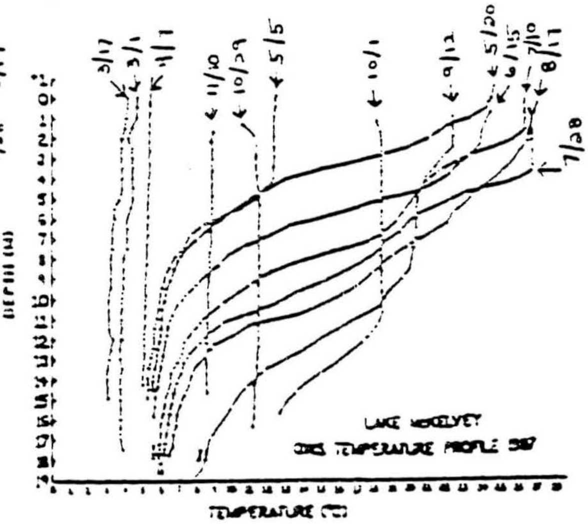

LIBERTY LAKE
DEPTH % VOLUME
DEPTH (METERS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
10
20
30
40
50
60
70
80
90
100
% VOLUME

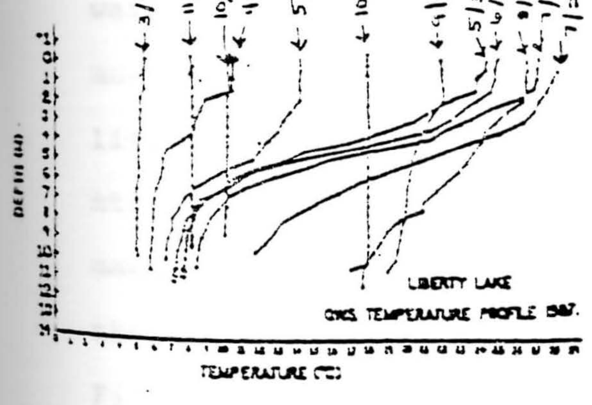
Figure 3. Temperature Profiles of Six OWS Reservoirs in 1987.

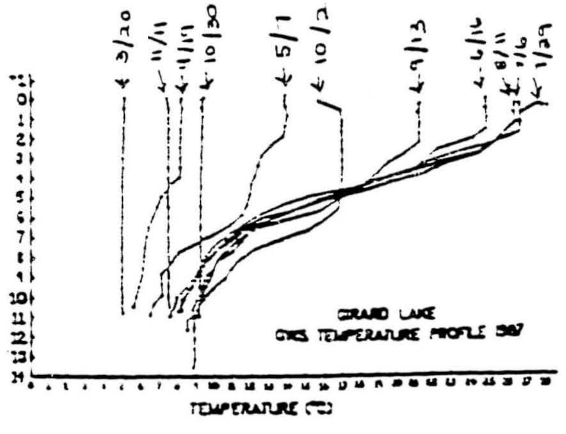

PINE LAKE
OWS TEMPERATURE PROFILE 1987
DEPTH (M)
TEMPERATURE (°C)
3/17
11/20
4/19
10/31
10/3
5/8
9/11
8/20
5/30
6/11
7/12
7/30


LAKE EVANS
OWS TEMPERATURE PROFILE 1987
DEPTH (M)
TEMPERATURE (°C)
3/17
11/20
4/19
10/31
5/8
10/3
9/11
6/11
5/30
8/21
7/30
7/12


LAKE HAMILTON
OWS TEMPERATURE PROFILE 1987
DEPTH (M)
TEMPERATURE (°C)
4/7
3/17
11/10
10/31
5/5
10/1
9/12
5/20
6/15
7/10
8/11
7/28


LAKE MCKELVEY
OWS TEMPERATURE PROFILE 1987
DEPTH (M)
TEMPERATURE (°C)
3/17
3/1
4/7
11/10
10/29
5/5
10/1
9/12
5/20
6/15
7/10
8/11
7/28


LIBERTY LAKE
OWS TEMPERATURE PROFILE 1987.
DEPTH (M)
TEMPERATURE (°C)
3/20
11/11
10/30
4/19
5/1
10/2
9/13
5/30
6/16
8/11
7/6
7/29


GRAND LAKE
OWS TEMPERATURE PROFILE 1987
DEPTH (M)
TEMPERATURE (°C)
3/20
11/11
4/19
10/30
5/1
10/2
9/13
6/16
8/11
7/6
7/29

fish community it supports.

Table 4. Hypolimnion Oxygen Concentrations, mg/l, from March 1987 to March 1988 (extracted from Schroeder and Farran, 1987 unpublished paper).

DATE	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
3/17	12.1	12.1	6.5	7.4	11.9	13.1
4/17	11.4	10.0	6.3	10.2	8.8	9.4
5/5	9.1	7.3	3.1	8.5	4.8	4.5
5/28	6.9	0.0*	1.8	6.2	1.0	0.4
6/15	11.3	0.0*	0.1*	4.9	0.0*	0.0*
7/10	5.7	0.2*	0.0*	4.2	0.0*	0.0*
7/28	6.2	1.1	0.0*	2.6	0.0*	0.0*
8/17	7.2	0.0*	0.0*	0.2*	0.0*	0.0*
9/11	5.5	2.3	0.0*	0.0*	0.1*	0.0*
10/1	7.2	0.0*	0.0*	0.0*	6.2	5.1
10/29	9.6	9.0	7.6	6.9	9.1	6.7
2/11	10.1	15.9	11.5	9.4	11.4	8.4
3/21	13.1	12.9	12.1	5.5	12.6	11.0

* Indicates Anoxia

EVANS

Constructed in 1948, Lake Evans is the youngest of all of the OWS Reservoirs. Evans is the main water supply for the Village of Poland, sections of Struthers, Lowellville and Boardman. It is also the lake with the largest surface area (Table 2). Its watershed comprises 27.0 square kilometers of land, much of which has been strip mined for at least the life of the lake. Several creeks originating from the strip mines enter the lake. High concentrations of manganese, iron, calcium and magnesium are evident in these watershed creeks (Ohio Water Service Company Files 1987). This is due to the acid mine drainage and its dissolution of compounds in the soil. In addition, a section of the western bank of Evans Lake is developed into a golf course. Immediately to the North of the course is Fonderlac Country Club, where a secondary sewage treatment station is situated whose effluents flow directly into the Lake. A second sewage treatment plant on the Fonderlac Golf Course also drains into Evans. Though the flow of effluent is relatively low (<0.1 ft.^{3}/sec.), its high total phosphorus content (10.75 ppm) makes a significant contribution to Lake Evans' total lake phosphorus (Ohio Water Service Company Files, 1987). The remainder of the watershed is in the form of farmland and real estate. There is virtually no forested area immediately around Lake Evans; consequently, the supply of allochthonous particulate matter (leaf litter) is low compared to that of a lake surrounded by woodlands. However, it is likely that fertilizer application is active on the surrounding farmland and golf course, providing another source of lake nutrients for algal (autochthonous) growth. Lake Evans is the largest reservoir, with a storage capacity of 2751 million gallons. Its maximum depth is 12.5 meters and its mean depth is 5.03 meters (Table 2). Lake Evans stratifies, but less effectively than Hamilton, Liberty or Girard (Figure 3), usually at depths of four to five meters. With the high influxes of calcium and magnesium from the watershed creeks originating from the strip mines, Lake Evans is among the hardest of the six reservoirs (Ohio Water Service Files, 1988). The high concentration of calcium and magnesium in Lake Evans may result in a significant deposition of calcium and magnesium in its sediments.

HAMILTON

The oldest of the reservoirs is Hamilton, constructed in 1905. It has a small surface area (39.7 square km) compared to the five other reservoirs, but the largest watershed area, comprising 33.7 square kilometers, and the greatest WSA:LSA ratio (85). Thus, the watershed is expected to have a marked effect on the water chemistry of Lake Hamilton, and be reflected in the chemistry of its sediments. Most of the land surrounding the lake is moderately forested. Hamilton's watershed is low density urban development (Shroeder and Farran 1987 unpub. pap.), but also includes surface mines and agriculture. Hamilton is fed primarily by Yellow Creek, which originates south of Pine Lake, flows through Lakes Evans and Hamilton and terminates into the Mahoning River. Periodically, lime and alum effluents used in the treatment and preparation of Lake Evans water at the Ohio Water Service Filtration Plant, are discharged into Burgess Run Creek, a Yellow Creek Tributary (Markusic 1988, pers. comm.). Calcium, sulfur and aluminum in the plant effluent may contribute to their sedimentation in Lake Hamilton. The reservoir has a large mean depth of 7.08 meters and relative depth of 4.79 meters (Table 2). Its steep slopes (mean slope of 9.6%, Table 2) provide little area for shoreline vegetation development. The steep slope, deep, protected lake result in a thermocline often as shallow as 2 meters (Schroeder and Farran, 1988 unpub. pap.). This permits prolonged anoxia that affect the dissolution and precipitation of elements at the sediment/water interface.

MCKELVEY

McKelvey has a relatively small surface area (49.7 square km), however, its watershed comprises 22.1 square kilometers. This allows for a relatively high watershed to lake surface area ratio, making for significant contributions from the watershed. McKelvey water is among the softest of the six reservoirs (OWS Files, 1988), and is probably the best potable water supply (Schroeder and Farran 1987, unpub. pap.). Unfortunately, lack of topographic map data necessitates a qualitative description of McKelvey's morphometry. The slopes of the lake are particularly steep, perhaps exceeding that of Hamilton Lake. Its mean depth is 7.73 meters (Table 2). McKelvey is surrounded mostly by forest and residential development. The steep slope and woodlands protect surface waters from wind action. Nutrients in the water column are relatively low, and McKelvey has the lowest Trophic State Index of all the OWS Reservoirs, TSI(McK) = 45.7 (Table 5).

LIBERTY AND GIRARD

Both of these reservoirs share the same watershed, Girard Lake draining directly into Liberty Lake. Both have minimal watershed development that includes farm activity and moderate forestation. Volume hypsographs of the lakes (Figure 2) indicate Liberty and Girard have approximately the same capacities for littoral development. Both have near equavilent mean depths, Gir = 4.77, and Lib = 4.62 meters, and similar maximum length (1.93 and 1.34, respectively). Girard Lake is substantially larger than Liberty, having a basin volume nearly three times that of Liberty. Temperature profiles indicate Girard stratifies more effectively than Liberty; however, they have equally long periods of anoxia in their hypolimnions (Figure 3, Table 4). Liberty and Girard have similar water chemistry.

Table 5. Trophic State Indices of Six OWS Lakes in Increasing Order.

LAKE	TSI(SD)	TSI(CHLA)	TSI(TP)	TSI(AVG)
MCK	45.8 ± 6.6	49.4 ± 10.2	42.0 ± 13.2	45.7 ± 3.7
EVA	50.6 ± 9.2	52.9 ± 15.2	50.2 ± 8.7	51.2 ± 1.5
HAM	53.5 ± 10.0	57.9 ± 13.2	54.3 ± 8.3	55.2 ± 2.3
LIB	53.1 ± 10.7	59.3 ± 15.2	56.5 ± 6.0	56.3 ± 3.1
GIR	56.0 ± 10.8	61.8 ± 18.7	61.6 ± 7.9	59.8 ± 3.3
PIN	63.2 ± 9.1	61.2 ± 12.8	59.6 ± 12.7	61.3 ± 1.8

when $p < 0.05$,

McKelvey < Evans ≤ Hamilton < Liberty < Girard < Pine

MATERIALS AND METHODS

Selection of sediment sample site for lake representation is chiefly dependent upon morphometry. Incoming sediments to reservoirs have a tendency to migrate towards the deepest area of the lake. These depressions are "zones of accumulation" which are just before the dam (Hakanson 1983). Accumulation areas "prevail where fine materials, medium silt with grain sizes less than 0.006 millimeters, can be deposited continuously" (Ibid). Sediments along the shoreline are subject to wave action and are constantly being eroded and redistributed throughout the water column. A zone of transition connects these areas of erosion at the shore to the deeper zones of accumulation. In this zone of transition, only periodic settling of sediment occurs, as wave action, turbidity currents and gravity disrupt sediments. The zone of accumulation (the deepest area of each lake) was selected for sediment core collection.

Sediments were collected with a Wildco Gravity Core Sampler, Model 2404 A14. One tube (50 cm long and 5.08 cm diameter) fits inside of the sampler and is the main device for containing the sediments. An inverted "eggshell" structure is placed at the open end of the tube, allowing sediments to enter the tube, but inhibiting escape upon core retrieval. Table 6 lists the water depth at each reservoir collection site. Figure 4 depicts sampling sites in each reservoir.

Table 6. Water depth on 2-12-88 at each reservoir sample site.

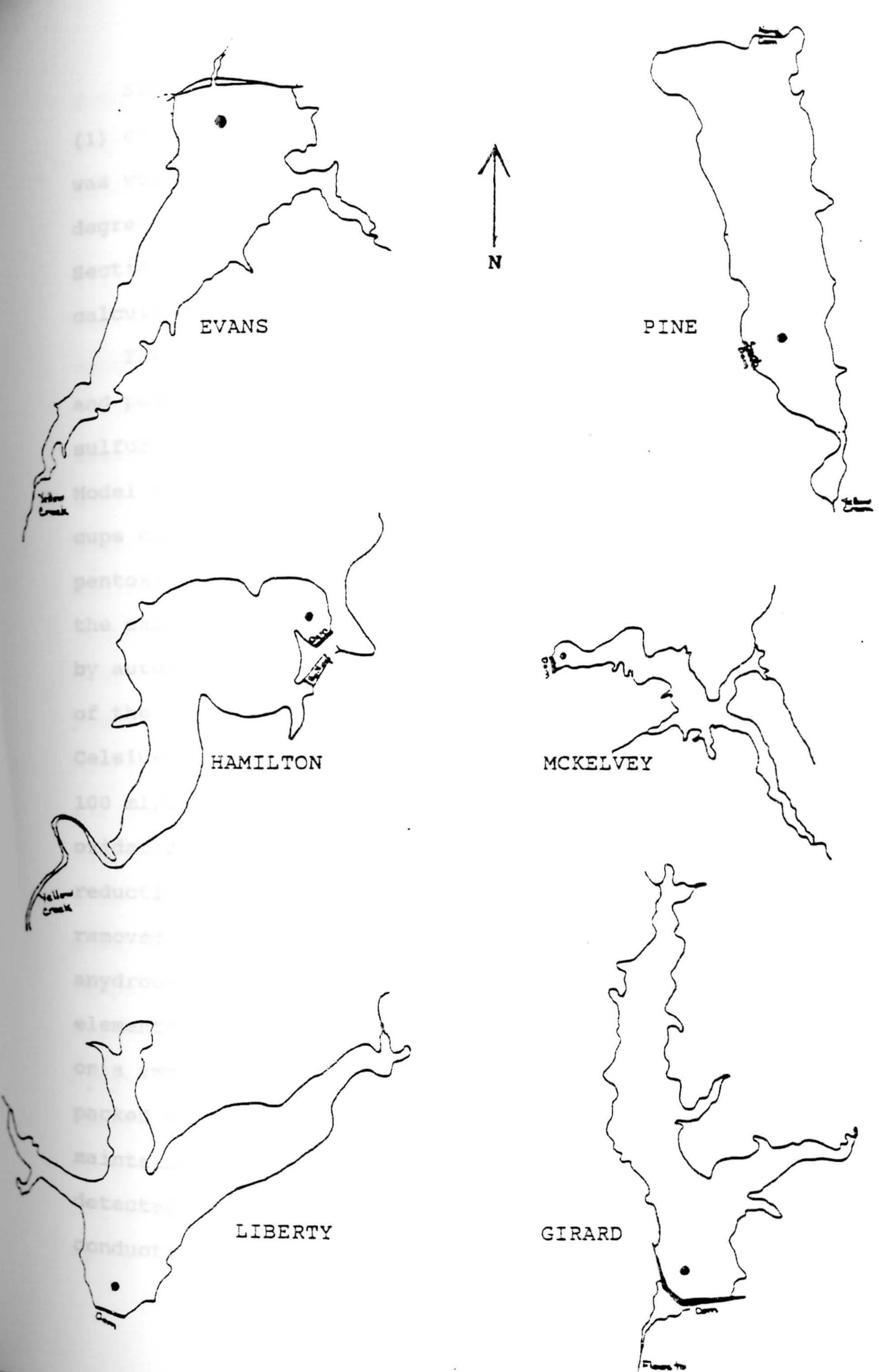
LAKE	WATER DEPTH (M)
PINE	3.0
EVANS	9.0
HAMILTON	11.5
MCKELVEY	18.0
LIBERTY	10.0
GIRARD	10.8

Two sediment cores were collected on 2-12-88 from each lake, were frozen on dry ice, transported back to the university laboratory and placed in cold storage (-70 Celcius) until analyzed. In addition to the sediment samples, a hypolimnetic water sample, one meter above the sediments, was retrieved and analyzed for dissolved oxygen by Winkler Method (Wetzel and Likens 1979). All hypolimnions were oxygenated on 2-12-88 (Table 7).

Table 7. List of oxygen concentrations in the hypolimnion waters of all reservoirs on 2-12-88.

LAKE	DEPTH (M)	PPM OXYGEN
PINE	2.3	10.11 ± 0.05
EVANS	8.0	9.83 ± 0.01
HAMILTON	10.5	11.18 ± 0.02
MCKELVEY	17.0	7.53 ± 0.00
LIBERTY	9.0	10.06 ± 0.06
GIRARD	9.5	12.10 ± 0.04

Figure 4. Sample Location in Each OWS Reservoir.


EVANS
Yellow Creek
N
PINE
Dam
Yellow Creek
HAMILTON
Dam
Yellow Creek
MCKELVEY
Dam
LIBERTY
Dam
GIRARD
Dam
Flows to

Sediment cores were sliced into approximately one (1) centimeter sections with a band saw. Each section was weighed to 0.01 grams and oven dried at 105 degrees Celsius until constant weight (24 hr). Sections were then reweighed and percent water content calculated.

Each dry sediment section was ground with a mortar and pestle and analyzed for total carbon, nitrogen and sulfur by gas chromatography using a Carlo Erba CNS Model NA 1500 Analyzer. Samples were weighed into tin cups contaning approximately 12 mg of vanadium pentoxide. Cups were crushed, completely enclosing the sample and excluding air. Samples were introduced by autosampler along with a burst of oxygen to the top of the combustion tube maintained at 1000 degrees Celsius. The combustion products were carried by a 100 ml/min flow of high purity helium through an oxidation catalyst of tungstic anhydride and a reduction packing of metallic copper. Water was removed from the gas stream by a tube packed with anydrous magnesium perchlorate. The remaining elemental nitrogen, carbon and sulfur were separated on a 2mm x 5.8 mm teflon gas chromatography column packed with poropak QS, 80/100 mesh (Supelco, Inc.), maintained at 88 degrees Celsius. Elements were detected by a change in current through a thermal conductivity detector at 190 degrees Celsius (Carlo

Erba 1986). Chromatograms were recorded, peak areas determined, and percentages calculated using a Shimadzu C-R3A integrator.

Every section from the Lake Evans core and every fifth section of the cores from the other five reservoirs was analyzed for total aluminum, iron, manganese, calcium and magnesium using an Instrumentations Laboratory Plasma 200 Emission Spectrometer. Sediments were prepared for ICP analysis using CEM Microwave Application Note for Acid Digestion (Dr. Scott Martin, Dept. of Civil Engineering, and Dr. Daryl Mincey, Dept. of Chemistry, Youngstown State Universtity, pers. comm.), where a 0.5000 g dry sediment sample was placed into a teflon pressure vessel with 10 milliliters of concentrated nitric acid. Vessels were closed and tightened to 12 ft. lbs. using a CEM capping station. Samples were digested in a CEM 850S digestion microwave oven for 2.50 minutes at 100 % power, and 30 minutes at 70 % power. Samples were allowed to cool to room temperature, hand vented and 5 milliters of 30 % hydrogen peroxide was added. When the H_2O_2-induced effervescence ceased, samples were centrifuged for 30 minutes at 2000 RPM in a Damon/IEC Centrifuge, Model CU-500. The supernatant was poured off into 100 milliliter volumetric flasks and brought up to volume with deionized water.

Loss on ignition, used to estimate sediment organic matter, was determined for every fifth centimeter section from all six OWS Reservoirs. Samples were weighed to 0.0001 grams and ashed at 550 degrees Celsius in a Hoskins Electric Furnace, Type FH202C for 1 hour (Hakanson 1983). Upon cooling to room temperature in a dessicator, samples were reweighed and percent weight loss calculated.

RESULTS

Sediment Water Content:

All lakes decrease in percent sediment water content from more than 90% to less than 70% (Table 8, Figure 5). Evans Lake has the lowest percent water from 0 - 9 centimeters (92.1 - 73.2 %), and Liberty Lake the highest from 0 - 3 centimeters (97.2 - 92.8 %). All reservoirs have similar concentrations of water in their sediments from 10 - 24 centimeters, after which changes in water content are markedly different.

Hamilton has the highest water content in sediments deeper than 24 centimeters (Figure 5); in fact, an increase of 2 - 3 percent water content is observed there. Girard's sediments decrease rather drastically in water content at 34 centimeters (from 62.3 to 41.5 %), continuing so until the end of the core. Evans Lake decreases moderately towards the end of the core. McKelvey's sediments decrease in water uniformly to 31 centimeters, then increase 7-8 percent in water content until the end of the core.

Organic Matter (OM), (Loss on Ignition):

Organic matter as percentage of dry weight was relatively constatn with depth but varied among lakes (Table 9, Figure 6). Pine Lake has the highest percentage OM throughout its sediments with an

Table 8. Percent sediment water content in six OWS Reservoirs.

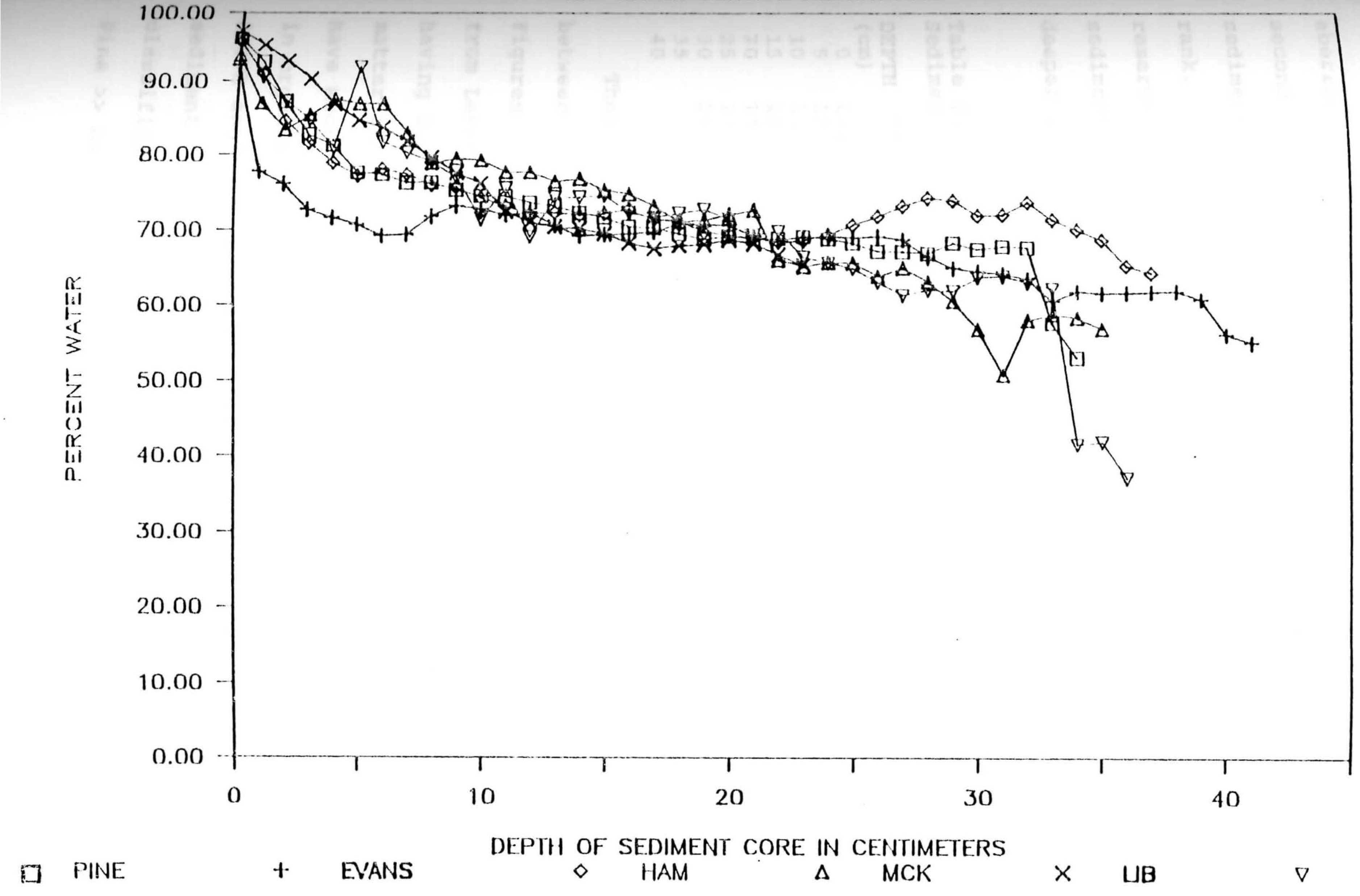
DEPTH CM	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	96.14	92.11	95.52	93.52	97.20	95.52
1	92.70	77.72	90.94	86.95	95.13	90.58
2	87.14	76.00	84.50	83.34	92.80	87.32
3	82.70	72.64	81.49	85.34	90.30	84.59
4	81.22	71.56	78.84	87.46	86.87	80.91
5	77.53	70.70	77.04	86.84	84.60	81.92
6	77.33	69.19	77.98	86.86	83.66	81.70
7	76.20	69.36	77.24	82.84	81.82	80.24
8	76.25	71.81	75.83	78.83	79.69	78.91
9	75.21	73.17	75.48	79.44	77.48	76.81
10	74.46	72.72	74.14	79.21	76.14	71.45
11	74.44	71.98	73.06	77.60	72.42	75.45
12	73.57	72.31	72.13	77.56	71.00	69.10
13	73.13	70.56	72.27	76.36	70.45	74.27
14	72.24	69.20	71.92	76.75	70.24	74.29
15	71.68	69.43	72.16	75.19	69.53	74.53
16	70.49	69.51	72.72	74.72	68.30	72.22
17	70.26	69.80	71.33	73.15	67.60	71.63
18	69.55	70.90	71.20	71.14	67.96	72.19
19	68.82	70.68	69.70	71.37	68.15	72.72
20	69.22	70.70	69.38	72.03	68.74	71.45
21	68.96	69.19	68.93	72.64	68.26	69.45
22	68.91	68.68	68.39	66.08	66.80	69.83
23	69.21	69.13	68.58	65.25	65.47	66.48
24	68.88	69.24	69.42	65.78		65.69
25	68.34	69.06	70.65	65.73		64.93
26	67.25	69.22	71.79	63.93		63.09
27	67.21	68.76	73.15	65.03		61.37
28	66.99	66.49	74.20	63.22		62.10
29	68.37	64.98	73.87	60.51		61.92
30	67.55	64.54	71.92	56.75		63.75
31	67.91	64.25	72.00	50.79		63.95
32	67.78	63.61	73.67	57.95		63.02
33	57.61	60.54	71.43	58.78		62.26
34	53.01	61.83	70.08	58.30		41.49
35		61.62	68.70	56.79		41.87
36		61.71	65.29			37.07
37		61.82	64.32			
38		61.93				
39		60.79				
40		56.06				
41		54.98				

Five replicate analyses give a coefficient of variance of 0.002.

Figure 5. Percent Sediment Water Content of Six OWS Reservoirs.

SEDIMENT WATER CONTENT

OHIO WATER SERVICE RESERVOIRS



aberrant peak of 25.13% at 30 cm. Girard Lake has the second highest percent OM for the first 15 cm of sediment; thereafter, Lake Hamilton assumes this rank. Lake Evans is markedly lower than all other reservoirs in organic matter (8 - 9%) in its surface sediments (0-8 cm) and appears to decrease steadily in deeper sediments.

Table 9. Percent Organic Matter in Six OWS Reservoir Sediments.

DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	14.37	9.13	13.49	11.09	12.72	13.67
5	13.86	8.74	12.41	12.62	12.05	12.86
10	13.32	8.62	11.40	11.43	9.54	12.62
15	13.55	8.30	10.69	9.22	8.39	10.85
20	13.43	8.37	10.29	9.03	9.39	9.79
25	13.10	8.27	10.11	8.76		7.44
30	25.13	7.54	9.88	6.35		7.59
35		7.42				8.92
40		7.10				

There were significant negative correlations between OM with depth in all reservoirs (Table 10, Figures 7a - 7c). The slopes of linear regressions from Lakes Evans and Pine are similar but with Pine having significantly higher concentrations of organic matter throughout the core. The four other reservoirs have much steeper slopes, indicating a greater change in organic content towards surface sediments. One-way ANOVA analysis of total weighted mean OM content in sediment cores where $p < 0.05$ allows the following classification:

Pine >> Hamilton > Girard = Liberty ≥ McKelvey ≥ Evans

Figure 6. Percent Sediment Organic Matter in Six OWS Reservoirs.

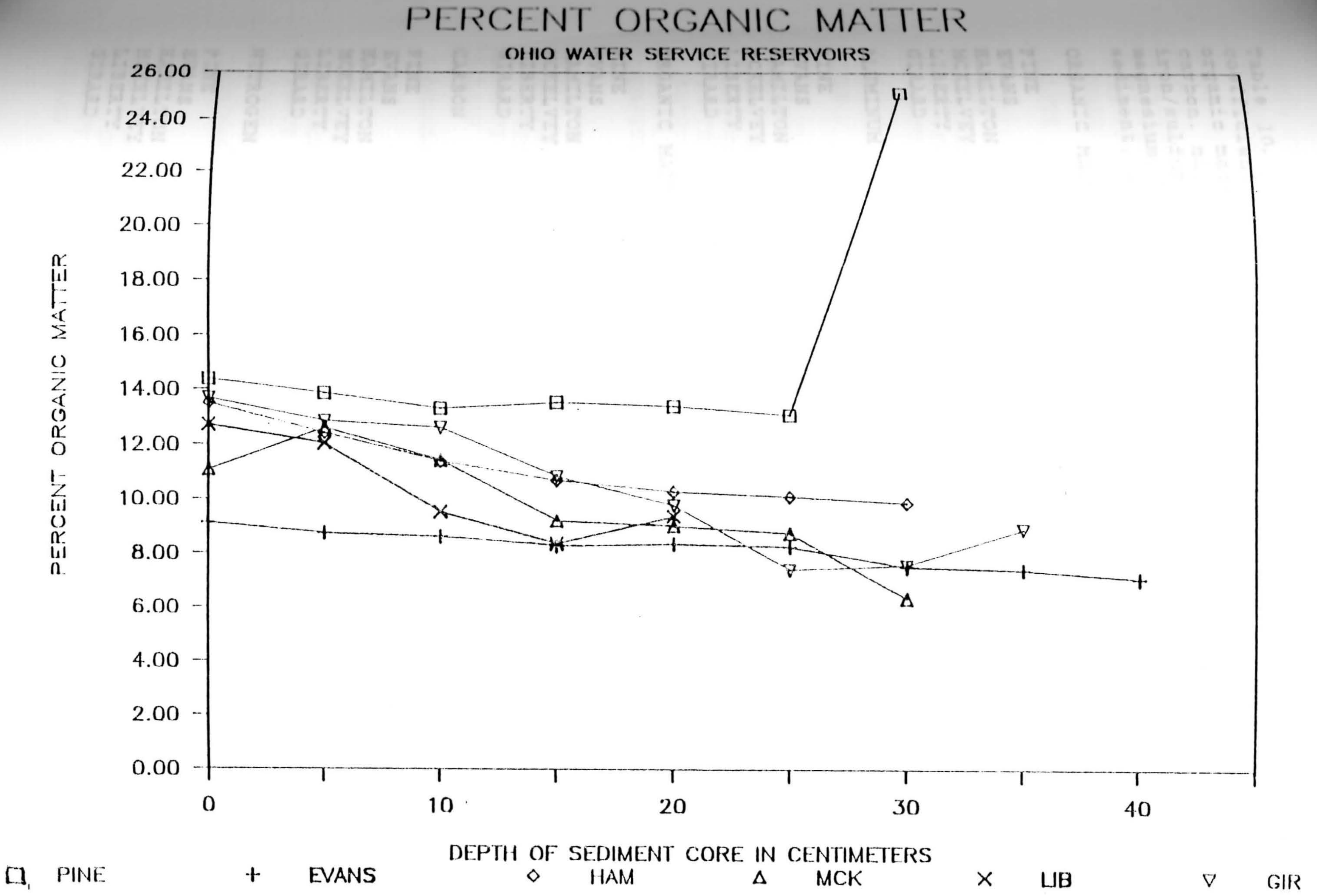

PERCENT ORGANIC MATTER
OHIO WATER SERVICE RESERVOIRS
PERCENT ORGANIC MATTER
26.00
24.00
22.00
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
10
20
30
40
DEPTH OF SEDIMENT CORE IN CENTIMETERS
□ PINE
+ EVANS
◇ HAM
Δ MCK
× LIB
▽ GIR

Table 10. List of intercept (a), slope (b), and correlation coefficient (r) values of linear regression analysis of organic matter, aluminum, organic matter/aluminum ratio, carbon, nitrogen, carbon/nitrogen ratio, sulfur, iron, iron/sulfur ratio, manganese, iron/manganese ratio, calcium, magnesium, and calcium/magesium ratio all with depth of sediment, where substance (y) = a + b(depth).

ORGANIC MATTER

	a	b	r^2
PINE	14.18	-.042	-.877*
EVANS	9.16	-.047	-.968*
HAMILTON	13.24	-.133	-.963*
MCKELVEY	15.58	-.172	-.894*
LIBERTY	12.70	-.208	-.880*
GIRARD	13.82	-.181	-.917*

ALUMINUM

	a	b	r^2
PINE	2.27	.015	.526
EVANS	2.81	.002	.081
HAMILTON	3.36	-.011	-.198
MCKELVEY	3.02	-.017	-.441
LIBERTY	3.10	.022	.604
GIRARD	3.07	.010	.216

ORGANIC MATTER/ALUMINUM

	a	b	r
PINE	6.47	-.069	-.696
EVANS	3.33	-.020	-.678*
HAMILTON	4.19	-.038	-.480
MCKELVEY	4.24	-.040	-.746*
LIBERTY	4.06	-.082	-.862*
GIRARD	4.63	-.070	-.773

CARBON

	a	b	r^2
PINE	6.32	-.004	-.111
EVANS	3.16	-.026	-.937*
HAMILTON	4.63	-.054	-.672*
MCKELVEY	4.61	-.067	-.859*
LIBERTY	4.78	-.097	-.875*
GIRARD	4.47	-.069	-.939*

NITROGEN

	a	b	r^2
PINE	0.66	-.008	-.965*
EVANS	0.35	-.003	-.937*
HAMILTON	0.44	-.006	-.774*
MCKELVEY	0.43	-.006	-.821*
LIBERTY	0.55	-.012	-.926*
GIRARD	0.57	-.009	-.954*

Table 10 continued.

CARBON/NITROGEN	a	b	r^2
PINE	9.15	.175	.917 *
EVANS	9.09	.007	.206
HAMILTON	10.37	.029	.553 *
MCKELVEY	10.79	.006	.078
LIBERTY	8.60	.040	.564 *
GIRARD	7.71	.018	.602 *

SULFUR	a	b	r^2
PINE	0.68	-.001	-.111
EVANS	1.15	-.001	-.087
HAMILTON	1.58	-.006	-.204
MCKELVEY	1.55	-.029	-.778*
LIBERTY	0.85	-.004	-.340
GIRARD	1.47	-.029	-.893*

IRON	a	b	r^2
PINE	2.88	.003	.233
EVANS	3.48	.007	.440
HAMILTON	6.10	-.075	-.723*
MCKELVEY	5.07	-.029	-.710
LIBERTY	4.06	.018	.617
GIRARD	4.30	.002	.108

IRON/SULFUR	a	b	r^2
PINE	4.54	-.024	-.406
EVANS	2.16	.054	.767
HAMILTON	3.90	-.033	-.418
MCKELVEY	2.99	.116	.797*
LIBERTY	4.97	.018	.250
GIRARD	2.39	.157	.935*

MANGANESE	a	b	r^2
PINE	0.07	-.001	-.949 *
EVANS	0.26	-.004	-.947 *
HAMILTON	0.26	-.002	-.560
MCKELVEY	0.07	-.001	-.788 *
LIBERTY	0.07	-.002	-.970 *
GIRARD	0.07	-.001	-.921 *

IRON/MANGANESE	a	b	r^2
PINE	40.17	.953	.917*
EVANS	11.06	.546	.950*
HAMILTON	25.85	-.891	-.293
MCKELVEY	71.78	.816	.755*
LIBERTY	54.26	2.945	.960*
GIRARD	61.04	.867	.847*

Table 10 continued.

CALCIUM	a	b	r^2
PINE	0.65	-.039	-.791 *
EVANS	1.29	-.024	-.891 *
HAMILTON	3.08	-.052	-.701 *
MCKELVEY	0.45	-.007	-.939 *
LIBERTY	0.50	-.010	-.849 *
GIRARD	0.48	-.006	-.968 *

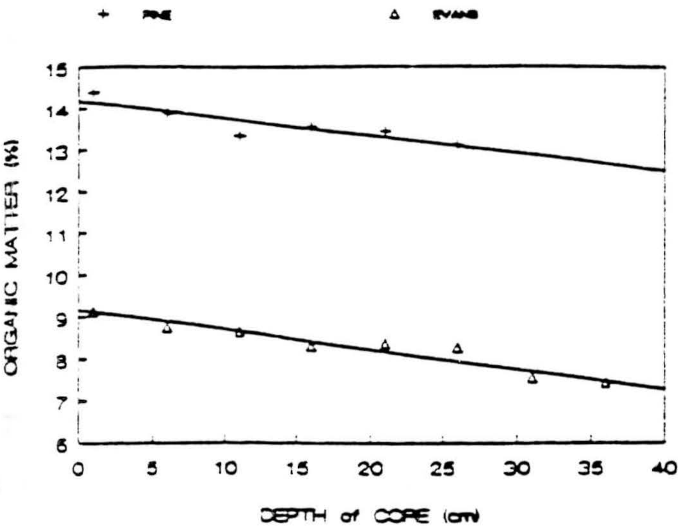
MAGNESIUM	a	b	r^2
PINE	0.41	-.004	-.727
EVANS	0.52	-.001	-.548
HAMILTON	0.61	-.003	-.540
MCKELVEY	0.42	-.002	-.612
LIBERTY	0.46	.002	.354
GIRARD	0.48	0	0

CALCIUM/MAGNESIUM	a	b	r^2
PINE	1.85	-.108	-.763 *
EVANS	2.54	-.044	-.864 *
HAMILTON	5.12	-.068	-.554
MCKELVEY	1.09	-.013	-.879 *
LIBERTY	1.01	-.024	-.906 *
GIRARD	1.01	-.014	-.935 *

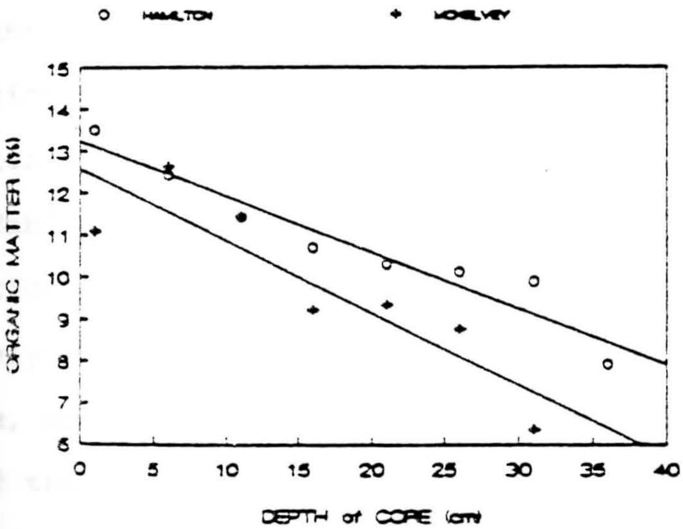
$p < 0.05$

Figure 7a - 7c. Percent Sediment Organic Matter of Six OWS Reservoirs.

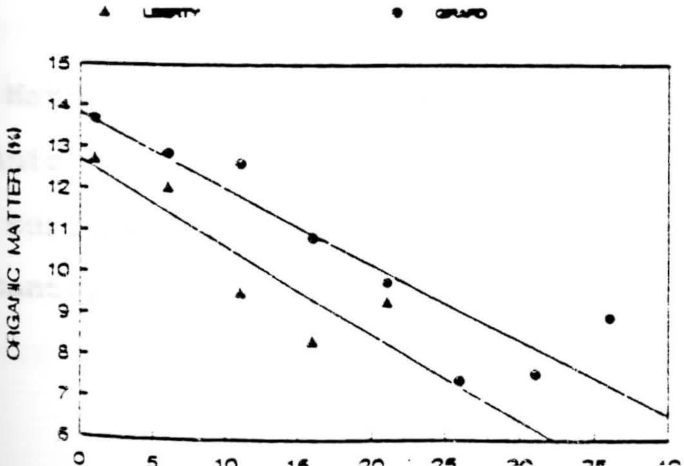
7a. ORGANIC MATTER



7b. ORGANIC MATTER



7c. ORGANIC MATTER



Pine Lake is significantly higher in percent organic matter than all other reservoirs, and Hamilton has significantly more sediment OM than Lakes Girard, Liberty, McKelvey and Evans, whose concentrations of percent OM are not significantly different from each other (Appendix A).

Percent Aluminum:

The percent aluminum with increasing sediment depth is given in Table 11 and Figure 8. Lake Hamilton has an unusual pattern. Its aluminum content steadily increases to 20 cm, then decreases until the end of the core. All other lakes show some fluctuation of percent aluminum with depth. Linear regression analyses of percent aluminum to sediment depth (Table 10, Figures 9a - 9f) show no significant correlations between the two variables. Aluminum is relatively stable with depth in all reservoirs except Hamilton, where a peak is evident at midcore. Oneway ANOVA of the weighted mean percent aluminum between lakes (Appendix A) at $p < 0.05$ yields the following: Liberty = Girard = Hamilton > Evans = McKelvey = Pine

Organic Matter : Aluminum Ratio (OM:Al) with DEPTH:

Organic matter increases with respect to aluminum towards surface sediments in all reservoirs, significantly in Lakes Evans, McKelvey and Girard where $p < 0.05$ (Table 10, Figures 10a - 10f). The relationship of OM:Al with depth in Lake Hamilton is largely a reflection of the pattern of aluminum deposition, where OM:Al decreases toward the middle of the core, then increases until the end of the core.

Table 11. Percent Aluminum in Six OWS Reservoir Sediments

DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	2.0	2.4	2.5	2.8	3.4	3.8
5	2.4	3.0	3.0	2.7	2.9	2.4
10	2.7	2.7	3.7	3.2	3.3	2.8
15	2.5	3.3	3.9	2.8	3.4	3.3
20	3.0	2.8	3.8	2.7	3.7	3.8
25	2.4	3.0	3.5	3.1		3.3
30	2.6	2.9	2.8	1.9		2.8
35		3.0				3.8
40		2.5				

Five replicate sample analyses give a coefficient of variance of 0.132.

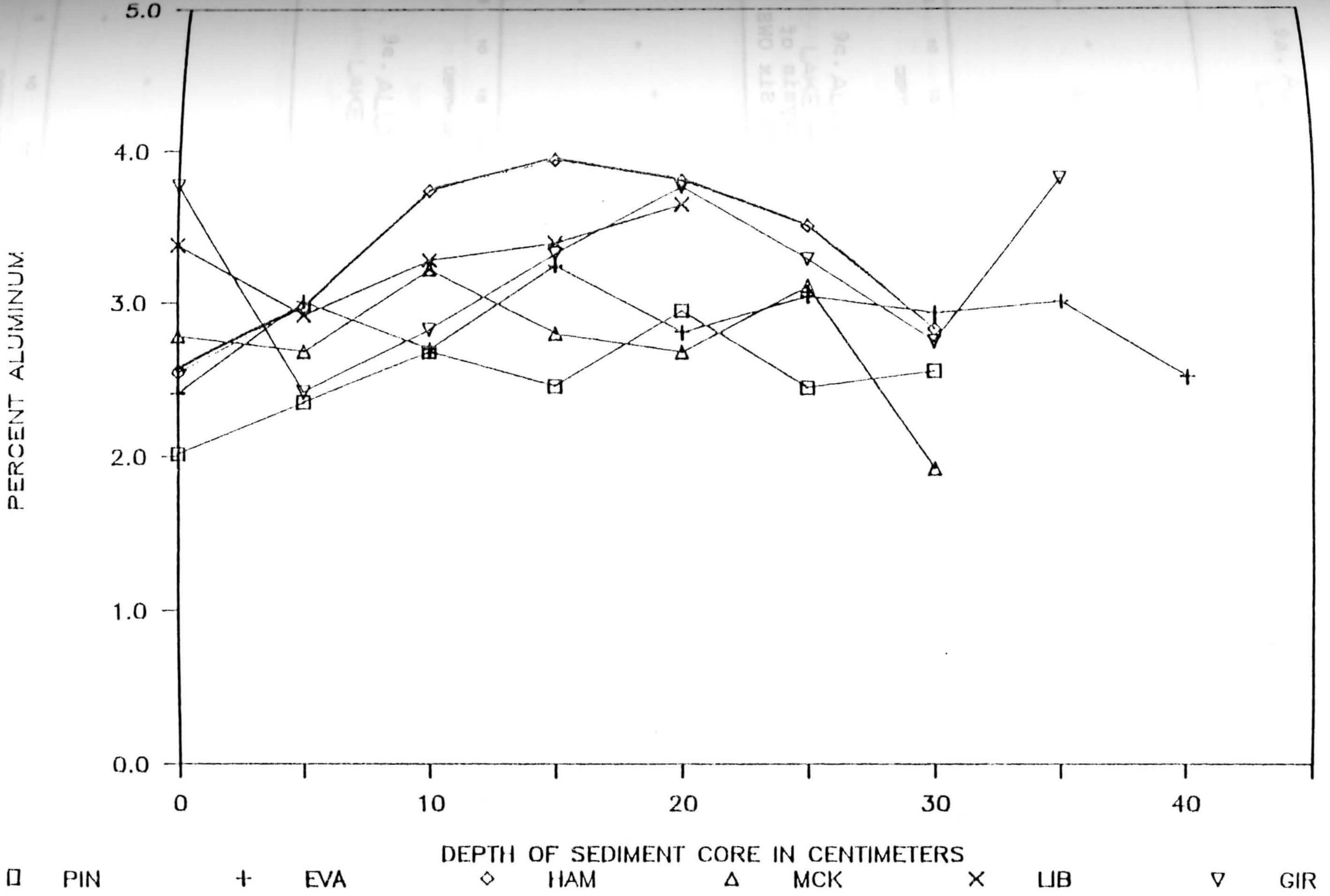
Total Carbon Content:

Pine Lake has the highest concentration of total percent sediment carbon throughout its core, and Evans Lake has the lowest percent sediment carbon from 0 - 15 cm (about 2 - 3 %). Thereafter, Evans percent carbon values are very close to those of Lakes Girard and McKelvey (Table 12, Figure 11). The aberrant peak in percent carbon in Pine Lake at 32 cm is probably due to a piece of wood included in the core. Carbon of Lake Hamilton decreases rapidly from 0 - 11 cm, then has two peaks at 15 and 29 cm. Liberty Lake also has a peak in carbon at the terminal end of the core, corresponding to the increase in organic matter there

Figure 8. Percent Sediment Aluminum in Six OWS Reservoirs.

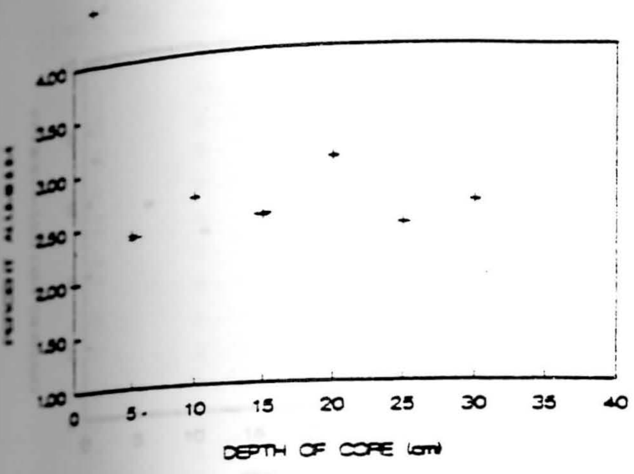
PERCENT ALUMINUM

OHIO WATER SERVICE RESERVOIR SEDIMENTS

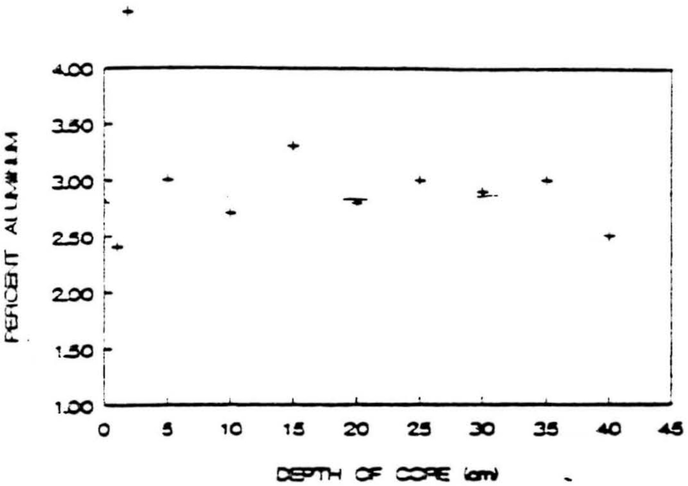


Figures 9a - 9f. Linear Regression Analysis of Percent Aluminum with Depth of Sediment in Six OWS Reservoirs.

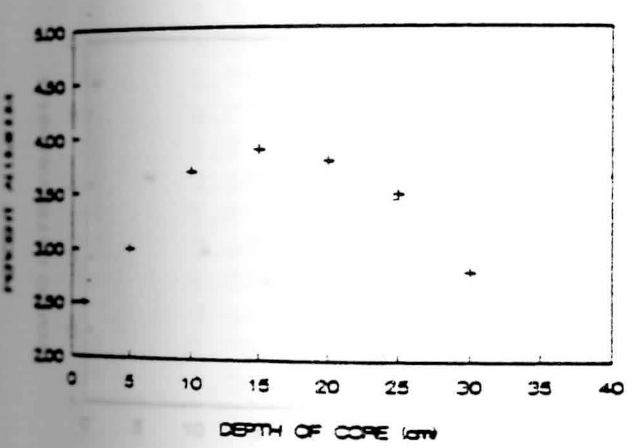
9a. ALUMINUM
LAKE PINE



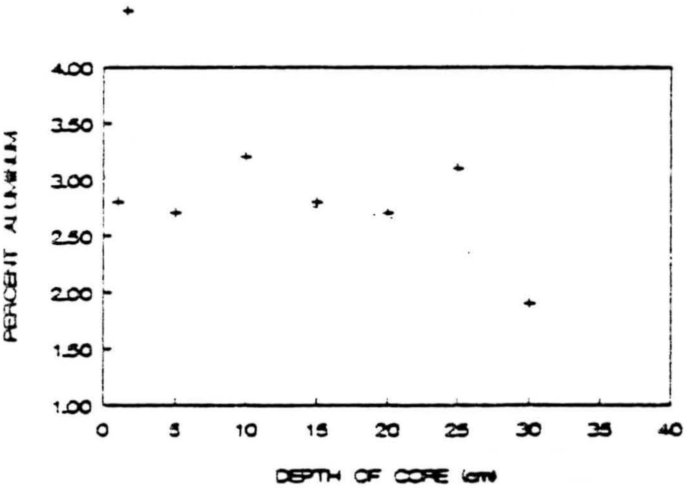
9b. ALUMINUM
LAKE EVANS



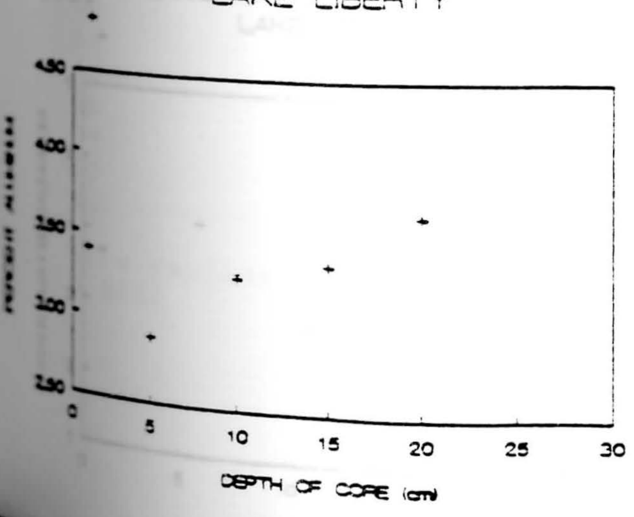
9c. ALUMINUM
LAKE HAMILTON



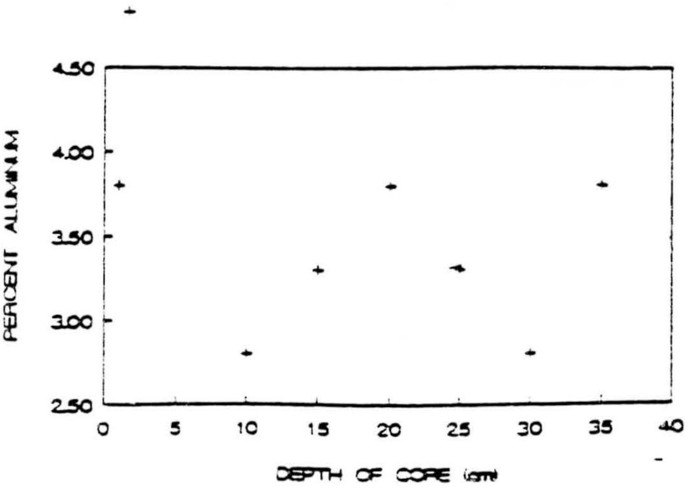
9d. ALUMINUM
LAKE MCKELVEY



9e. ALUMINUM
LAKE LIBERTY

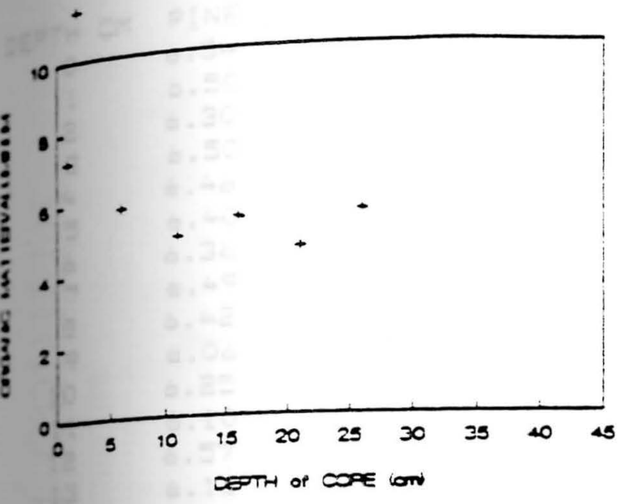


9f. ALUMINUM
LAKE GIRARD

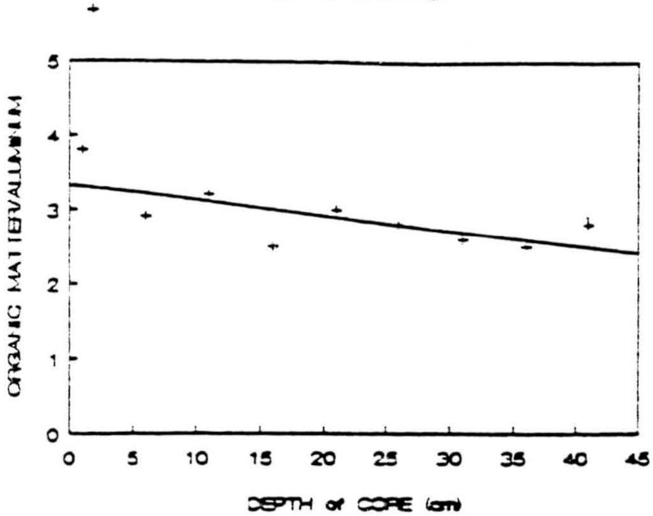


Figures 10a - 10f. Linear Regression Analysis of Organic Matter:Aluminum Ratio with Sediment Depth in Six OWS Reservoirs.

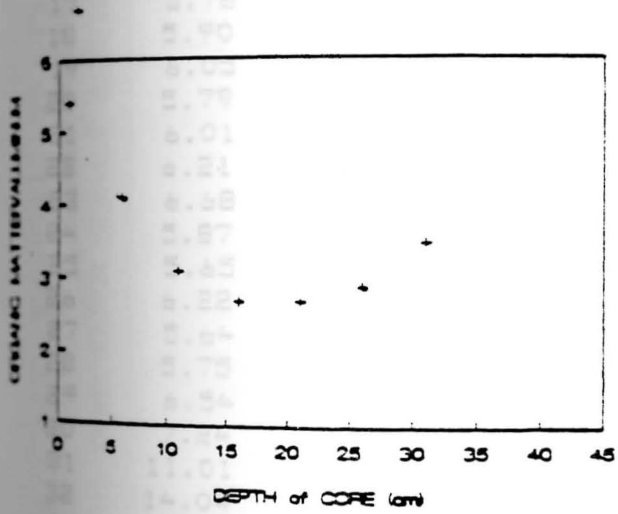
10a. ORGANIC MATTER: ALUMINUM RATIO LAKE PINE



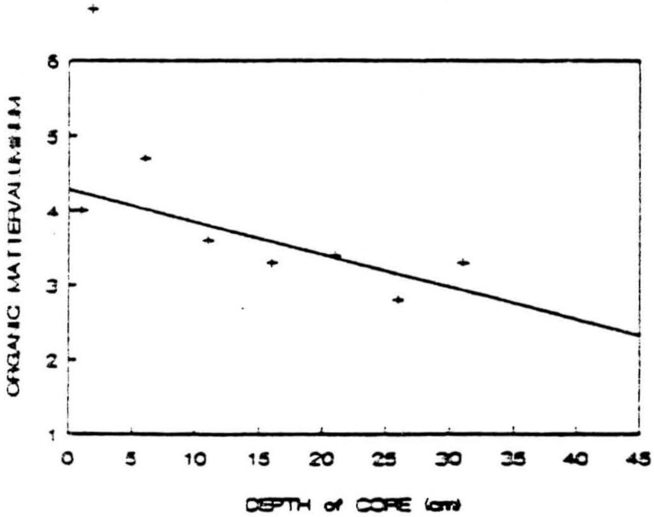
10b. ORGANIC MATTER: ALUMINUM RATIO LAKE EVANS



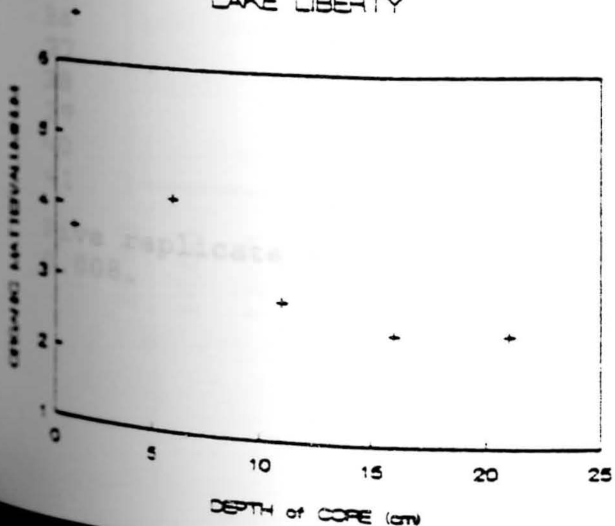
10c. ORGANIC MATTER: ALUMINUM RATIO LAKE HAMILTON



10d. ORGANIC MATTER: ALUMINUM RATIO LAKE MCKELVEY



10e. ORGANIC MATTER: ALUMINUM RATIO LAKE LIBERTY



10f. ORGANIC MATTER: ALUMINUM RATIO LAKE GIRARD

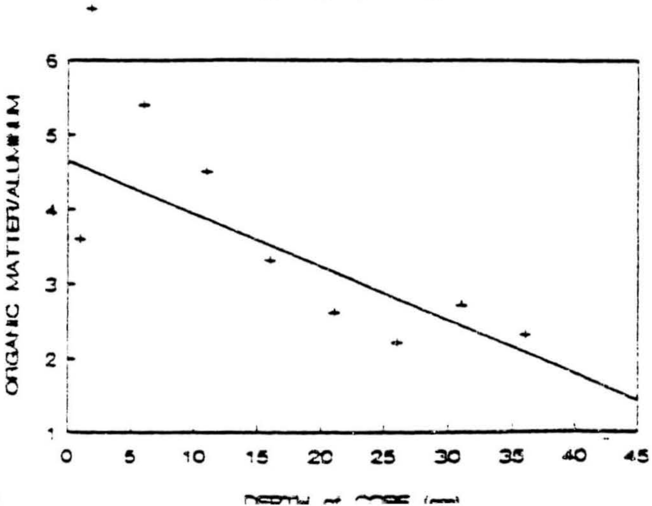


Table 12. Percent sediment carbon in six OWS Reservoirs.

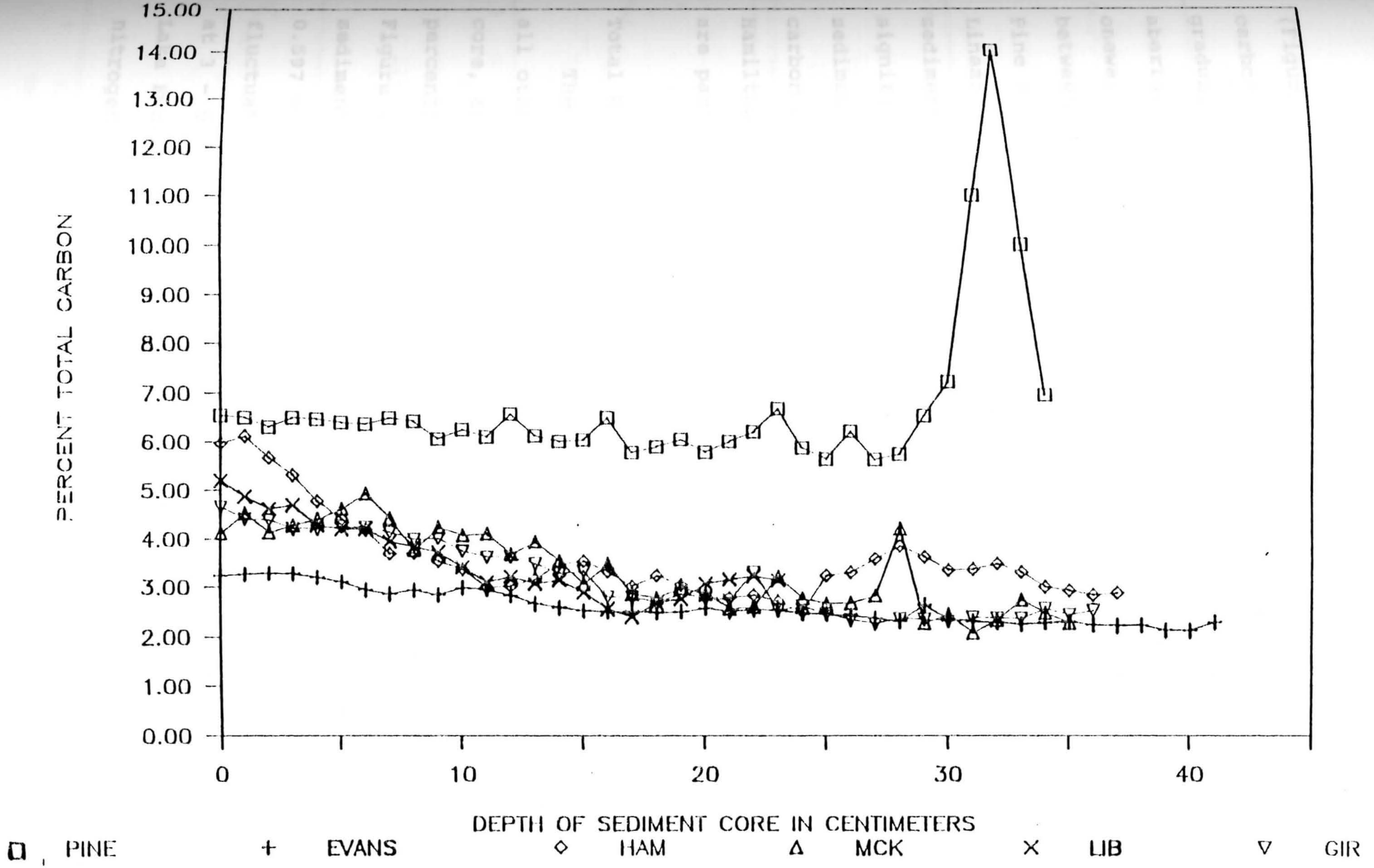
DEPTH CM	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	6.54	3.24	5.97	4.12	5.20	4.66
1	6.50	3.27	6.11	4.53	4.88	4.42
2	6.30	3.29	5.66	4.14	4.63	4.39
3	6.50	3.28	5.31	4.29	4.70	4.23
4	6.46	3.20	4.78	4.41	4.29	4.22
5	6.40	3.11	4.41	4.63	4.21	4.26
6	6.36	2.94	4.19	4.94	4.22	4.25
7	6.49	2.86	3.69	4.43	3.95	4.15
8	6.42	2.94	3.71	3.77	3.84	4.00
9	6.06	2.84	3.54	4.25	3.73	4.02
10	6.25	2.98	3.36	4.09	3.41	3.75
11	6.10	2.95	2.98	4.12	3.11	3.63
12	6.57	2.82	3.01	3.69	3.22	3.63
13	6.13	2.66	3.16	3.95	3.08	3.49
14	6.01	2.59	3.48	3.55	3.14	3.29
15	6.04	2.53	3.54	3.06	2.89	3.33
16	6.50	2.50	3.32	3.49	2.55	2.80
17	5.78	2.52	3.01	2.86	2.41	2.79
18	5.90	2.49	3.24	2.78	2.68	2.69
19	6.05	2.50	3.04	2.98	2.76	2.86
20	5.79	2.58	2.80	2.86	3.08	2.77
21	6.01	2.51	2.77	2.57	3.16	2.73
22	6.21	2.55	2.83	2.61	3.24	3.31
23	6.68	2.54	2.70	3.22	3.14	2.54
24	5.87	2.47	2.50	2.77		2.61
25	5.65	2.46	3.24	2.66		2.46
26	6.22	2.43	3.30	2.68		2.34
27	5.64	2.38	3.59	2.83		2.27
28	5.75	2.32	3.86	4.23		2.37
29	6.54	2.65	3.63	2.28		2.35
30	7.24	2.36	3.35	2.45		2.33
31	11.01	2.31	3.37	2.09		2.39
32	14.04	2.29	3.49	2.34		2.38
33	10.03	2.26	3.31	2.75		2.37
34	6.97	2.28	3.00	2.49		2.56
35		2.31	2.92	2.28		2.44
36		2.24	2.83			2.53
37		2.23	2.87			
38		2.24				
39		2.14				
40		2.13				
41		2.30				

Five replicate samples give a coefficient of variance of 0.008.

Figure 11. Percent Sediment Carbon in Six OWS Reservoirs.

PERCENT TOTAL CARBON CONTENT

OHIO WATER SERVICE RESERVOIR SEDIMENTS



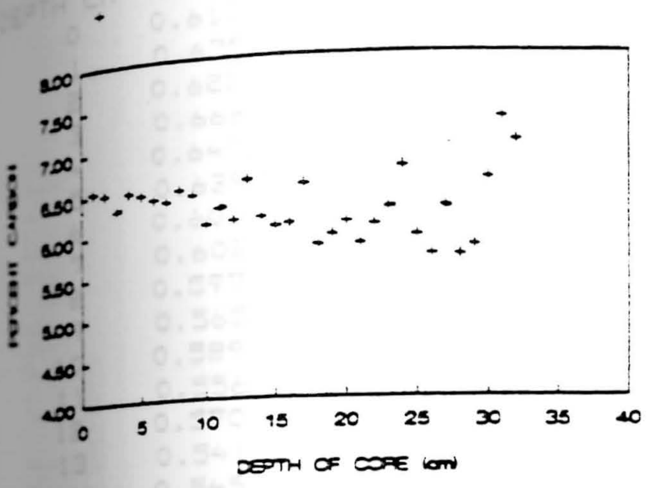
(Figure 6). McKelvey Lake actually increases in carbon from 0 - 6 cm (from 4.12% to 4.94%), then gradually decreases to the end of the core, with one aberrant peak of 4.23% carbon at 28 cm. Results of oneway ANOVA of the weighted mean percent carbon between the six reservoirs (Appendix A) show:

Pine > Hamilton = Liberty > Mckelvey = Girard > Evans

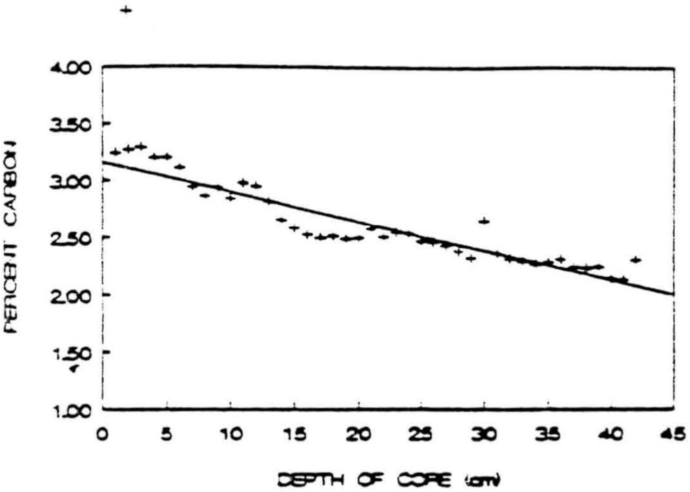
Linear regression analysis of percent carbon to sediment depth indicates all lakes but Pine have significant decreases in percent carbon with increased sediment depth (Table 10, Figures 12a - 12f). The two carbon peaks in the lower core section of Lake Hamilton and one at the terminal end of Liberty's core are particularly evident in Figures 12c and 12e.

Total Nitrogen Content:

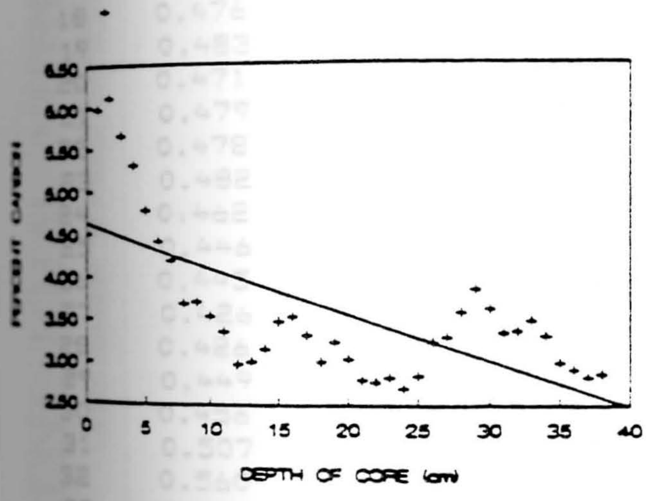
The nitrogen content in Pine Lake exceeds that of all other reservoirs throughout the length of its core, and similar to carbon and organic matter, the percentage nitrogen increases at 32 cm (Table 13, Figure 13). Girard Lake has the second highest sediment nitrogen content from 0 - 22 cm (where % N = 0.597 - 0.356). McKelvey Lake has the greatest fluctuation in percent nitrogen, as peaks are apparent at 3 - 5 cm, 7 - 10 cm, and 26 - 28 cm (Figure 13). Lake Evans has the lowest concentration of sediment nitrogen from 0 - 14 cm (where % N = 0.377 - 0.290), Figures 12a - 12f. Linear Regression Analysis of Percent Carbon with Sediment Depth in Six OWS Reservoirs.



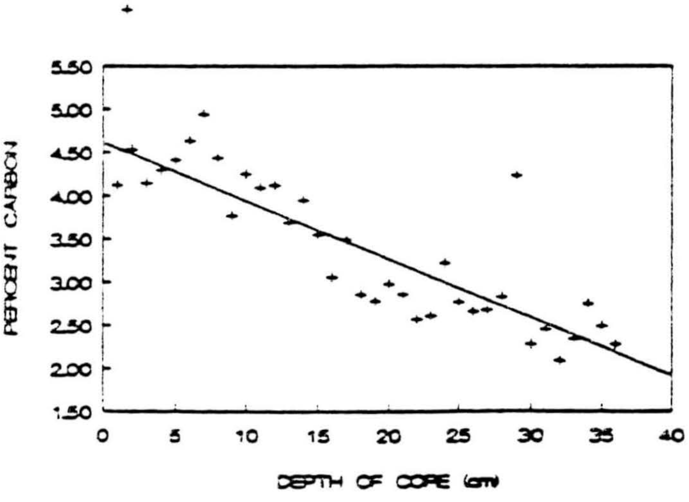
12a CARBON
LAKE PINE



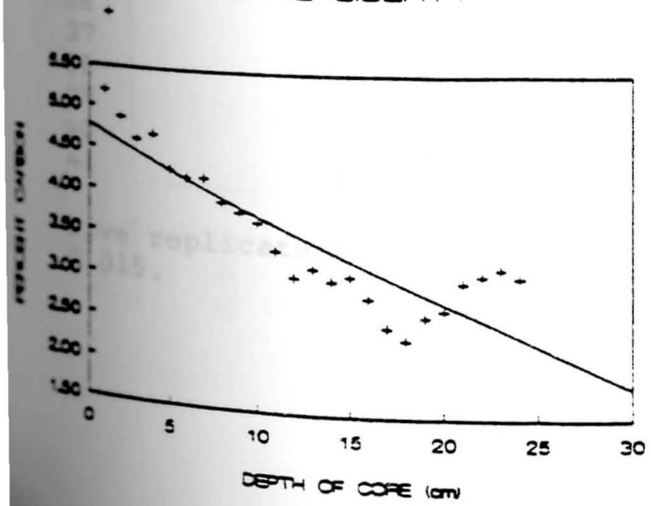
12b CARBON
LAKE EVANS



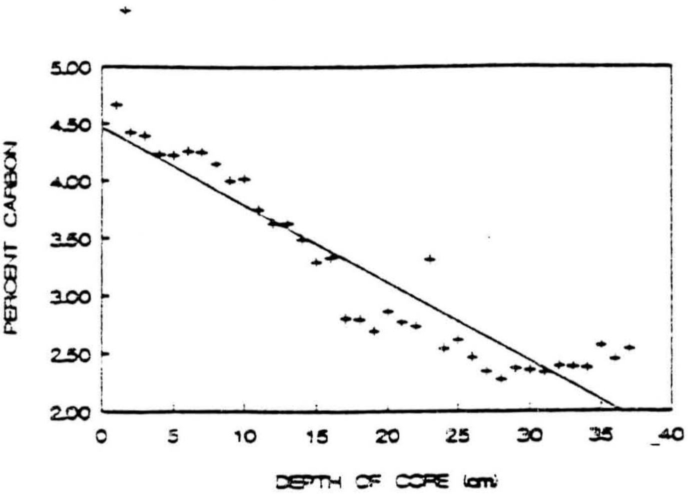
12c. CARBON
LAKE HAMILTON



12d. CARBON
LAKE MCKELVEY



12e. CARBON
LAKE LIBERTY



12f. CARBON
LAKE GIRARD

Table 13. Percent sediment nitrogen in six OWS Reservoirs.

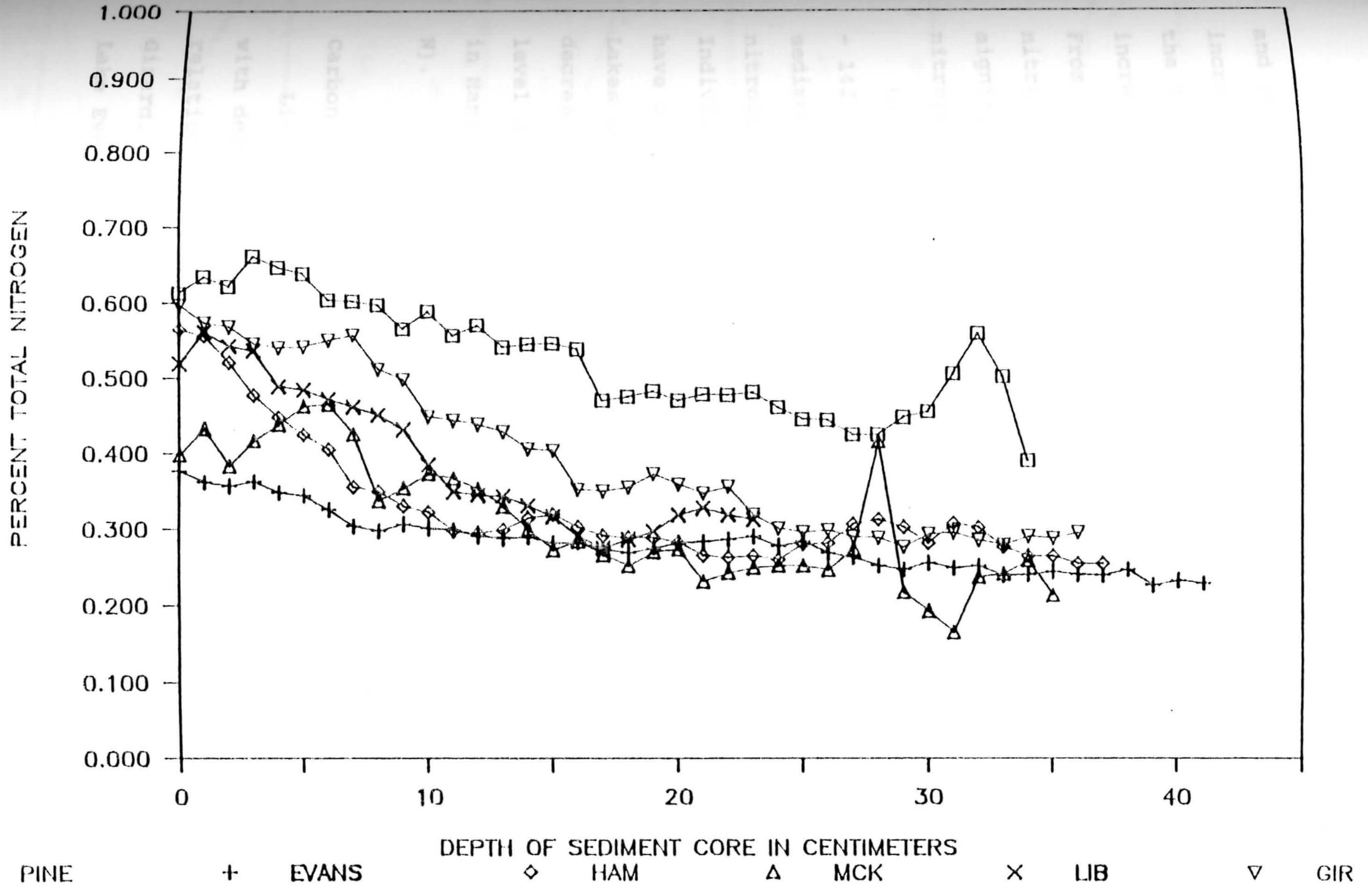
DEPTH CM	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	0.613	0.377	0.564	0.398	0.519	0.597
1	0.635	0.362	0.555	0.433	0.561	0.573
2	0.622	0.357	0.520	0.383	0.542	0.568
3	0.662	0.363	0.477	0.417	0.536	0.545
4	0.647	0.348	0.447	0.439	0.489	0.540
5	0.639	0.344	0.425	0.463	0.484	0.541
6	0.604	0.325	0.405	0.465	0.472	0.550
7	0.602	0.304	0.355	0.426	0.462	0.557
8	0.597	0.298	0.349	0.337	0.451	0.512
9	0.565	0.307	0.330	0.354	0.432	0.498
10	0.589	0.301	0.322	0.373	0.385	0.449
11	0.556	0.299	0.298	0.367	0.349	0.444
12	0.570	0.291	0.295	0.353	0.345	0.439
13	0.541	0.288	0.299	0.330	0.343	0.429
14	0.545	0.290	0.314	0.300	0.331	0.406
15	0.546	0.282	0.319	0.273	0.317	0.404
16	0.538	0.283	0.303	0.284	0.291	0.352
17	0.471	0.274	0.291	0.267	0.275	0.350
18	0.476	0.269	0.289	0.252	0.287	0.355
19	0.483	0.276	0.288	0.271	0.297	0.373
20	0.471	0.282	0.283	0.274	0.319	0.359
21	0.479	0.284	0.266	0.232	0.328	0.347
22	0.478	0.287	0.263	0.243	0.319	0.356
23	0.482	0.291	0.265	0.250	0.313	0.319
24	0.462	0.278	0.260	0.253		0.301
25	0.446	0.285	0.281	0.253		0.296
26	0.445	0.269	0.282	0.247		0.299
27	0.426	0.264	0.307	0.275		0.290
28	0.426	0.253	0.313	0.417		0.289
29	0.449	0.248	0.303	0.218		0.277
30	0.456	0.257	0.282	0.193		0.294
31	0.507	0.250	0.308	0.166		0.296
32	0.560	0.253	0.302	0.238		0.286
33	0.503	0.240	0.277	0.242		0.280
34	0.391	0.241	0.265	0.260		0.291
35		0.245	0.265	0.214		0.298
36		0.241	0.255			0.296
37		0.240	0.255			
38		0.248				
39		0.227				
40		0.233				
41		0.229				

Five replicate samples give a coefficient of variance of 0.015.

Figure 13. Percent Sediment Nitrogen in Six OWS Reservoirs.

PERCENT TOTAL NITROGEN CONTENT

OHIO WATER SERVICE RESERVOIR SEDIMENTS



and its nitrogen distribution steadily decreases with increased sediment depth. An increase in nitrogen in the lower 5 cm of Liberty sediments concurs with the increase in organic matter and carbon at this depth. From one-way ANOVA (Appendix A) of the weighted mean nitrogen values, no reservoir sediments differ significantly from each other in percent sediment nitrogen.

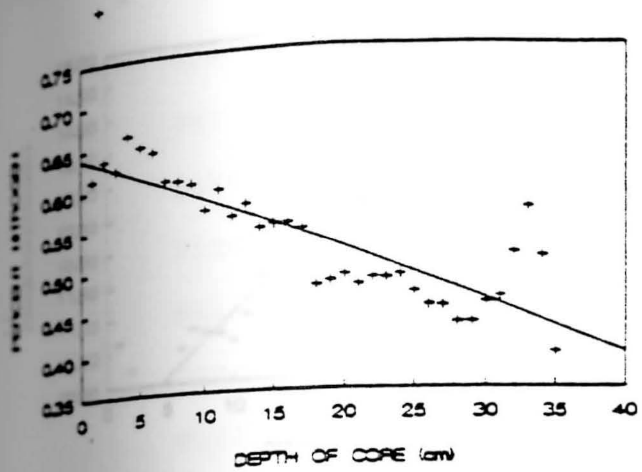
Linear regression analyses (Table 10, Figures 14a - 14f) of percent nitrogen with increasing depth of sediment show all lakes have significant decreases in nitrogen content with increasing depth of sediment. Individual data points show Pine, Evans and Mckelvey have steady decreases in nitrogen with depth, while Lakes Hamilton, Girard and Liberty exhibit rapid decreases in nitrogen from surface to midcore, then level off, and even increase in concentration at 29 cm in Hamilton (0.313% N) and 23 cm in Liberty (0.328% N).

Carbon : Nitrogen Ratio (C:N) with Depth

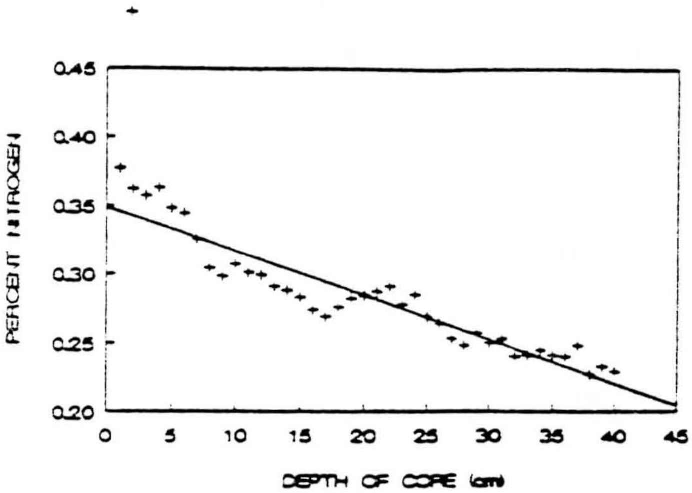
Linear regression analysis of carbon : nitrogen with depth (Figures 15a - 15f) show direct relationships in Lakes Pine, Hamilton, Liberty and Girard. No such distributions are apparent in either Lake Evans or McKelvey.

Figures 14a-14f. Linear Regression Analysis of Percent Nitrogen with Depth in Six OWS Reservoirs.

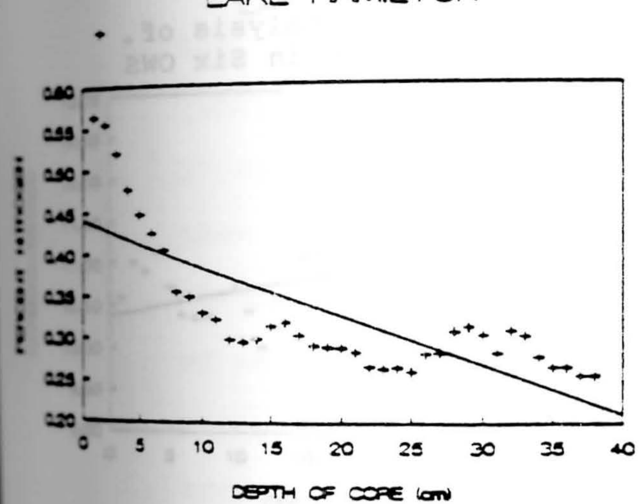
14a. NITROGEN
LAKE PINE



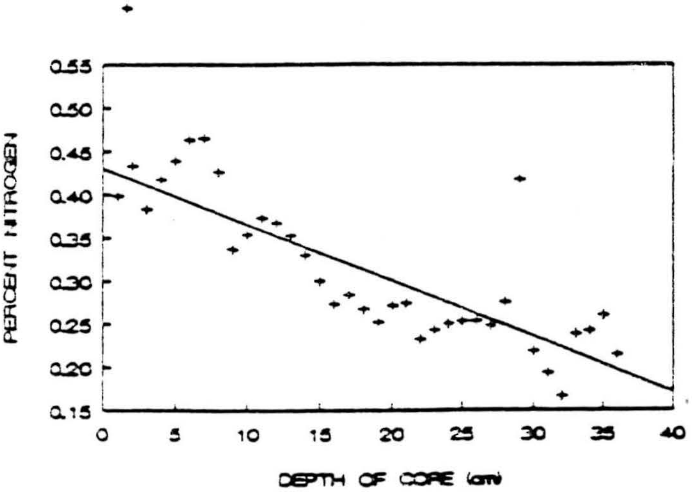
14b. NITROGEN
LAKE EVANS



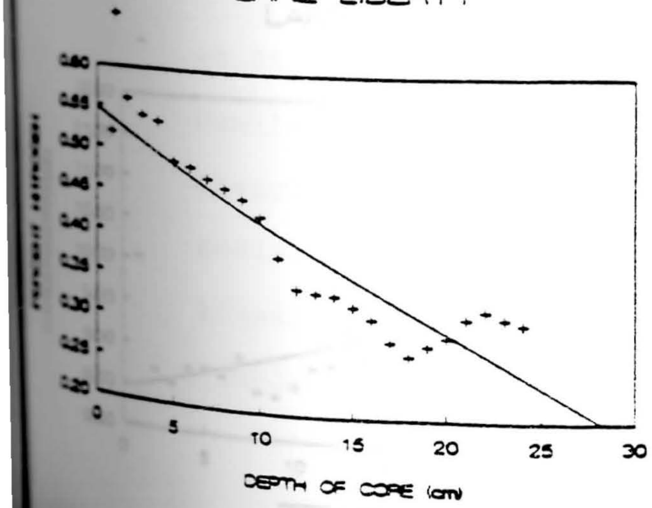
14c. NITROGEN
LAKE HAMILTON



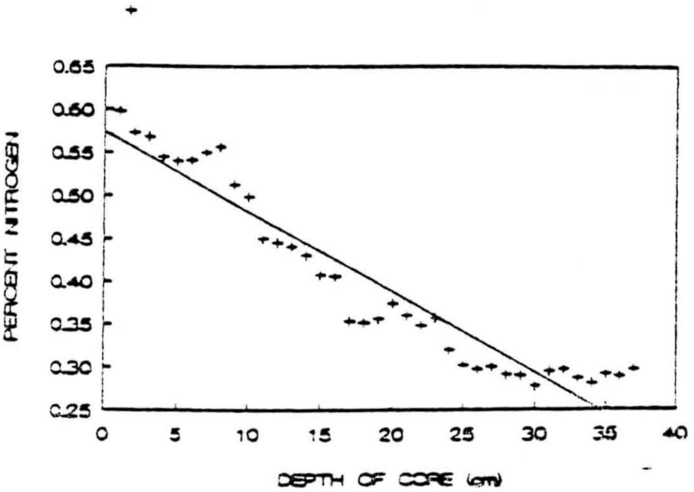
14d. NITROGEN
LAKE MCKELVEY



14e. NITROGEN
LAKE LIBERTY



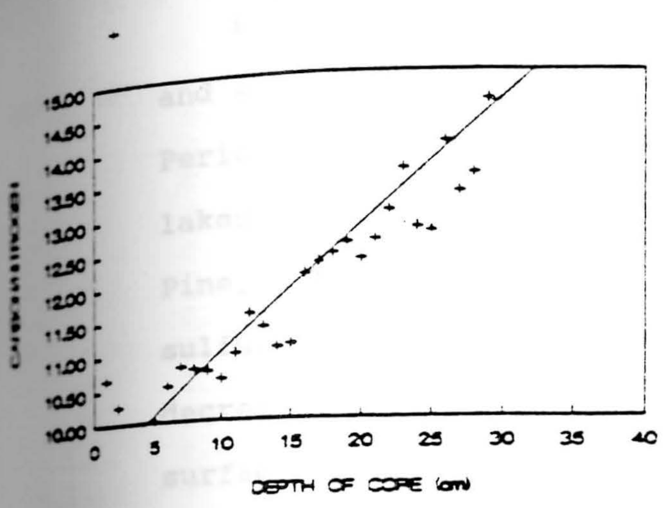
14f. NITROGEN
LAKE GIRARD



Figures 15a - 15f. Linear Regression Analysis of Carbon:Nitrogen Ratio with Sediment Depth in Six OWS Reservoirs.

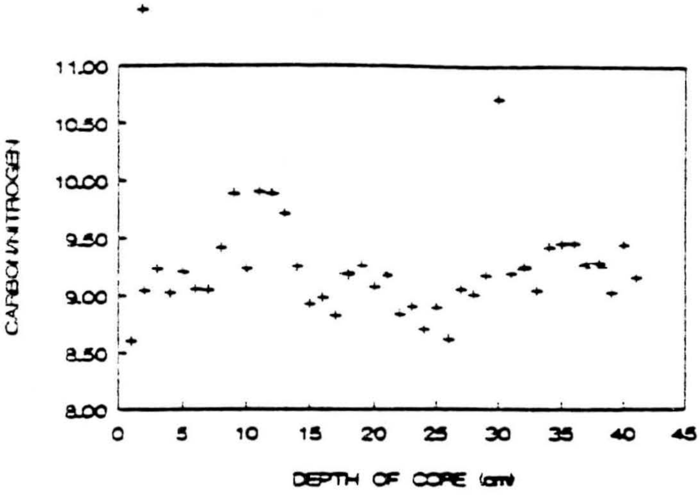
15a.

CARBON:NITROGEN RATIO
LAKE PINE



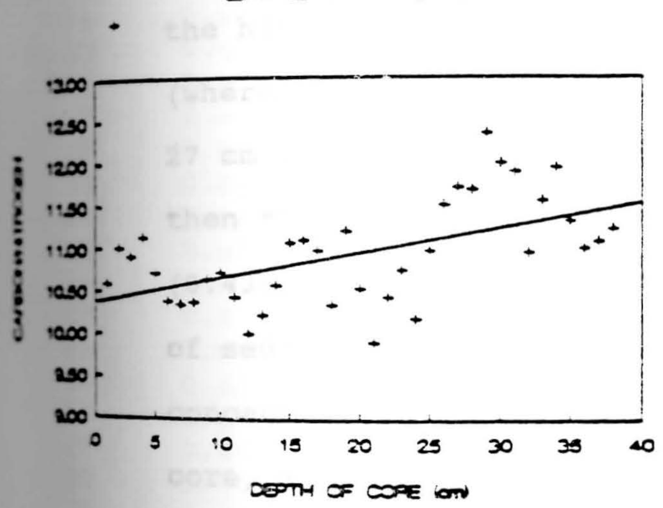
15b.

CARBON:NITROGEN RATIO
LAKE EVANS



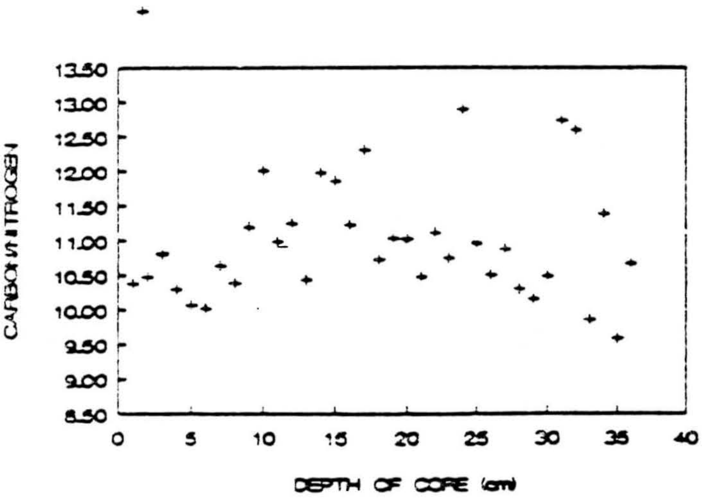
15c.

CARBON:NITROGEN RATIO
LAKE HAMILTON



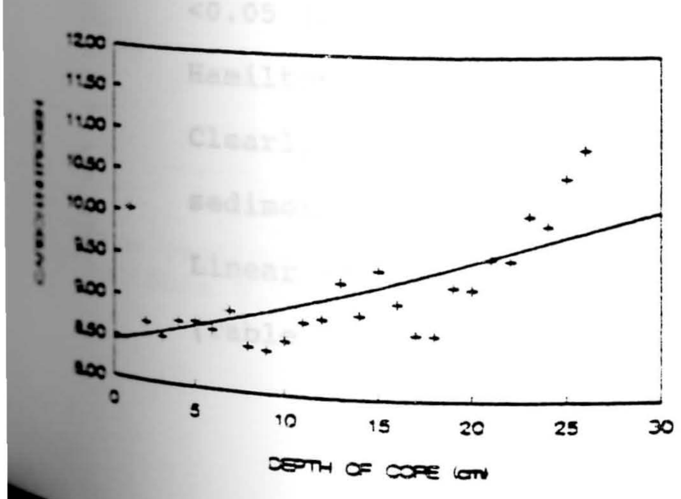
15d.

CARBON:NITROGEN RATIO
LAKE MCKELVEY



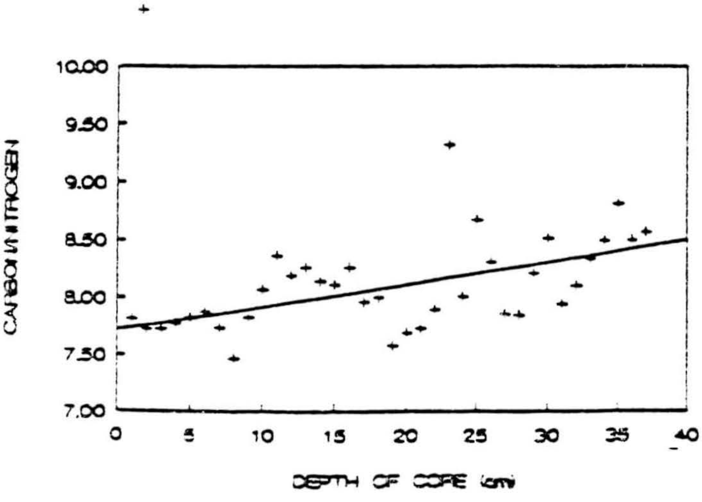
15e.

CARBON:NITROGEN RATIO
LAKE LIBERTY



15f.

CARBON:NITROGEN RATIO
LAKE GIRARD



Total Sulfur Content:

Sulfur concentration varies greatly between lakes and with sediment depth (Table 14, Figure 16). Periodic increases and decreases are apparent in all lakes. Just beneath the surface sediments, Lakes Pine, Evans, Girard, McKelvey and Hamilton increase in sulfur concentrations. Lake Liberty, however, decreases in sulfur concentration just below the surface sediments. The least apparent difference between reservoir sediment sulfur concentration exists between 10 and 20 cm (Figure 16). Hamilton exhibits the highest concentration of sulfur from 0 - 10 cm (where % S = 1.67 - 1.31). McKelvey peaks briefly at 27 cm for third highest sulfur concentration (0.78%), then rapidly drops to its lowest percent sulfur (0.43%). Pine Lake has the least apparent flucuation of sediment sulfur with depth of core, and its highest concentration of sulfur is at the terminal end of its core, at 32 cm (1.10%), the depth at which organic content, carbon and nitrogen content also increased.

Total weighted mean sulfur concentrations where $p < 0.05$ (Appendix A) show:

Hamilton > Evans > McKelvey = Girard > Liberty > Pine

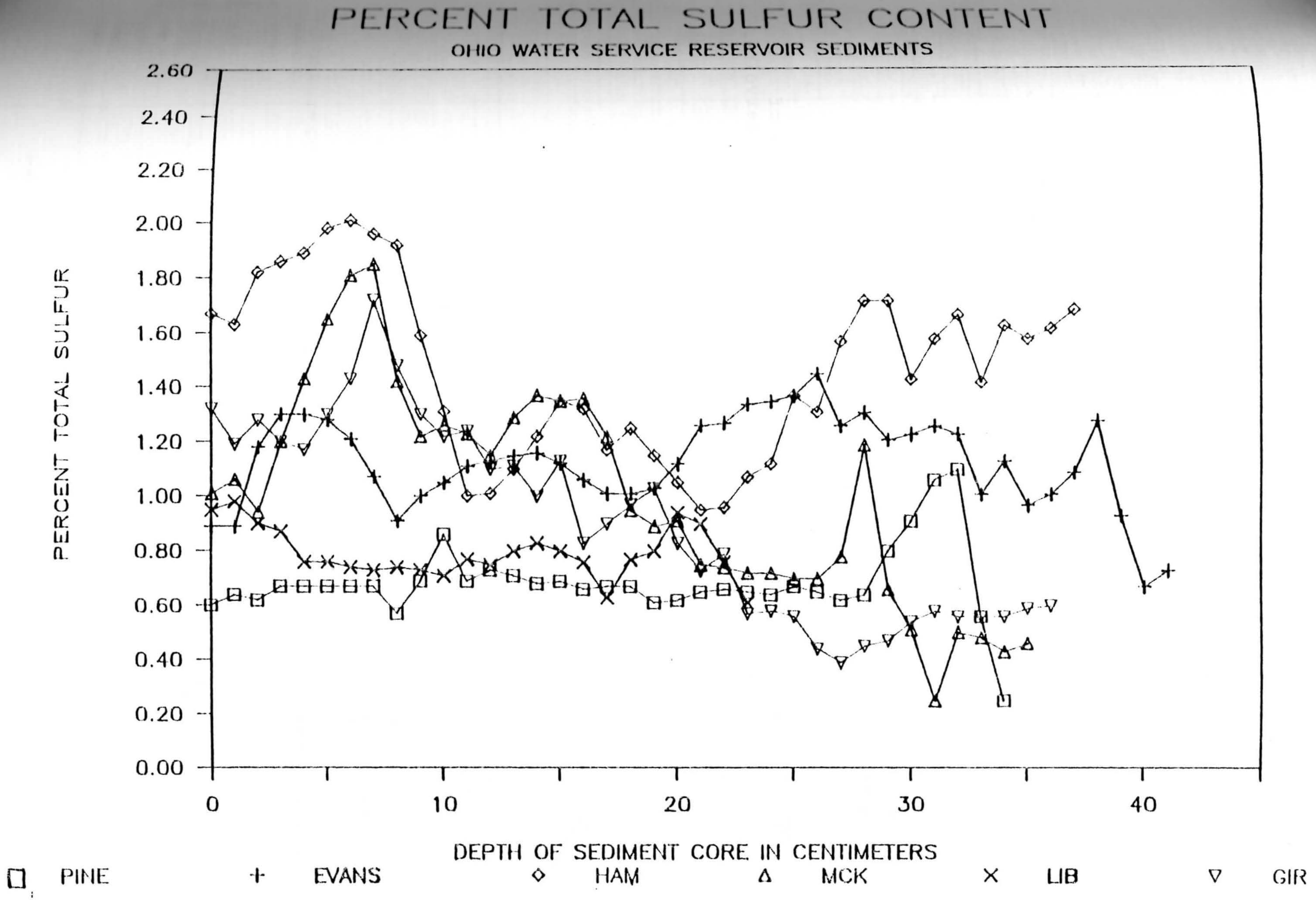
Clearly, Hamilton and Evans are much higher in sediment sulfur than the four other reservoirs. Linear regression analyses between sulfur and depth (Table 10, Figures 17a - 17f) depict significant

Table 14. Percent sediment sulfur in six OWS Reservoirs.

DEPTH CM	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	0.60	0.89	1.67	1.01	0.95	1.32
1	0.64	0.89	1.63	1.06	0.98	1.19
2	0.62	1.18	1.82	0.94	0.90	1.28
3	0.67	1.30	1.86	1.20	0.87	1.20
4	0.67	1.30	1.89	1.43	0.76	1.17
5	0.67	1.28	1.98	1.65	0.76	1.30
6	0.67	1.21	2.01	1.81	0.74	1.43
7	0.67	1.07	1.96	1.85	0.73	1.72
8	0.57	0.91	1.92	1.42	0.74	1.48
9	0.69	1.00	1.59	1.22	0.73	1.30
10	0.86	1.05	1.31	1.26	0.71	1.22
11	0.69	1.11	1.00	1.23	0.77	1.24
12	0.73	1.13	1.01	1.15	0.75	1.10
13	0.71	1.15	1.10	1.29	0.80	1.11
14	0.68	1.16	1.22	1.37	0.83	1.00
15	0.69	1.12	1.35	1.35	0.80	1.13
16	0.66	1.06	1.32	1.36	0.76	0.83
17	0.67	1.01	1.17	1.22	0.63	0.90
18	0.67	1.01	1.25	0.95	0.77	0.97
19	0.61	1.03	1.15	0.89	0.80	1.03
20	0.62	1.12	1.05	0.91	0.94	0.83
21	0.65	1.26	0.95	0.75	0.90	0.73
22	0.66	1.27	0.96	0.74	0.76	0.79
23	0.65	1.34	1.07	0.72	0.61	0.57
24	0.64	1.35	1.12	0.72		0.58
25	0.67	1.37	1.37	0.70		0.56
26	0.65	1.45	1.31	0.70		0.44
27	0.62	1.26	1.57	0.78		0.39
28	0.64	1.31	1.72	1.19		0.45
29	0.80	1.21	1.72	0.66		0.47
30	0.91	1.23	1.43	0.51		0.54
31	1.06	1.26	1.58	0.25		0.58
32	1.10	1.23	1.67	0.50		0.56
33	0.56	1.01	1.42	0.48		0.56
34	0.25	1.13	1.63	0.43		0.56
35		0.97	1.58	0.46		0.59
36		1.01	1.62			0.60
37		1.09	1.69			
38		1.28				
39		0.93				
40		0.67				
41		0.73				

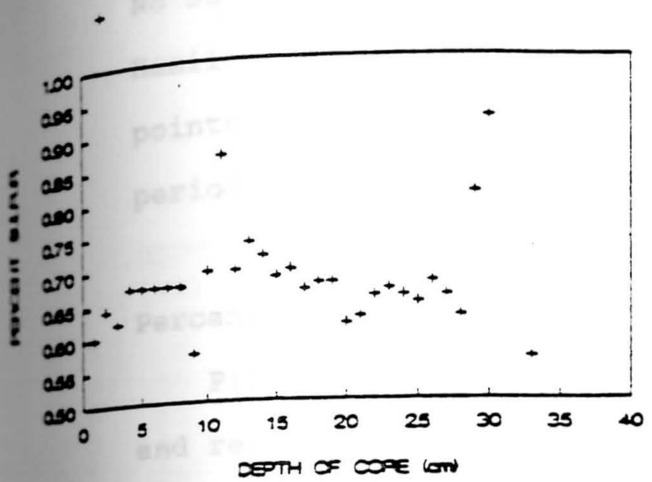
Five replicate sample analysis give a coefficient of variance 0.019.

Figure 16. Percent Sediment Sulfur in Six OWS Reservoirs.

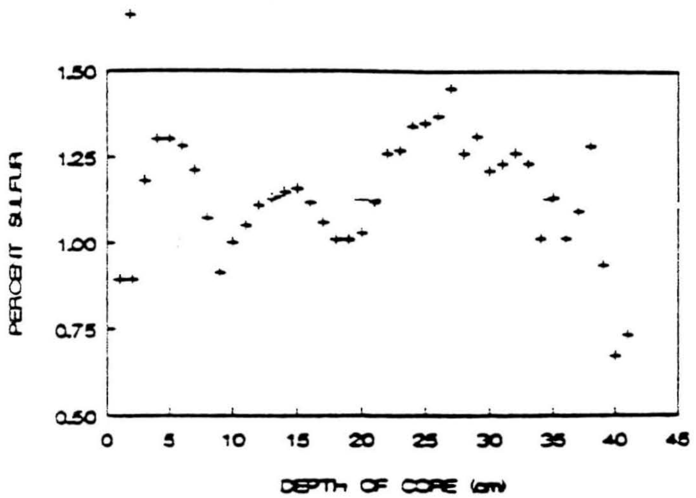

PERCENT TOTAL SULFUR CONTENT
OHIO WATER SERVICE RESERVOIR SEDIMENTS
PERCENT TOTAL SULFUR
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
DEPTH OF SEDIMENT CORE IN CENTIMETERS
□ PINE
+ EVANS
◇ HAM
△ MCK
× LIB
▽ GIR

Figures 17a - 17f. Linear Regression Analysis of
Percent Sulfur with Sediment Depth in Six OWS Reservoirs.

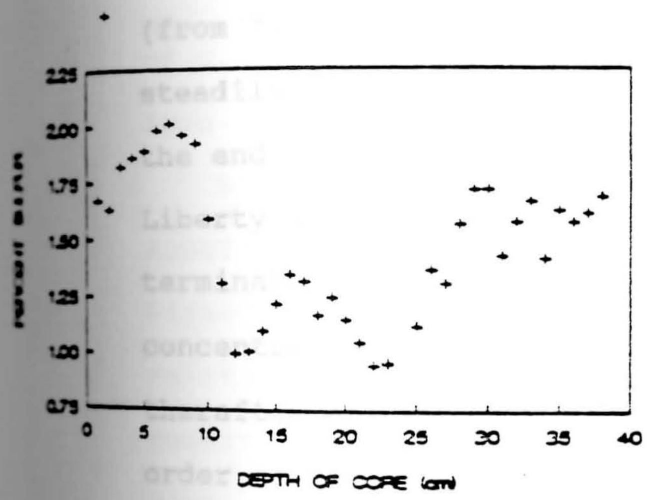
17a. SULFUR
LAKE PINE



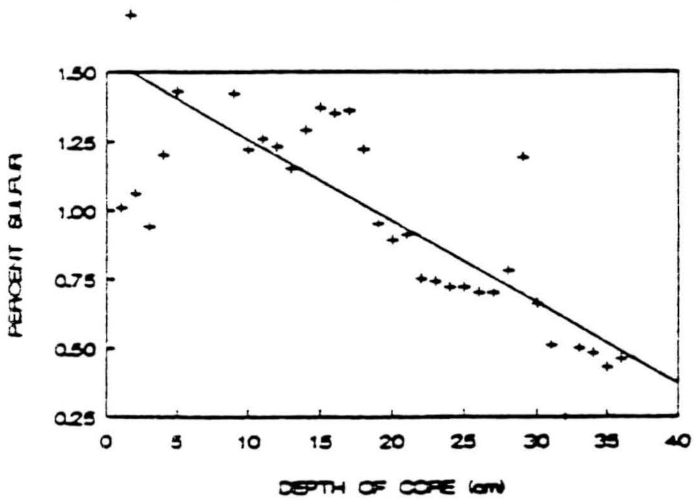
17b. SULFUR
LAKE EVANS



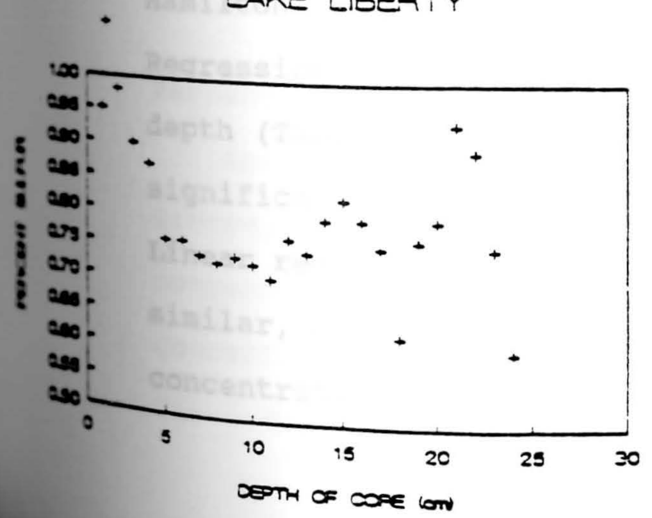
17c. SULFUR
LAKE HAMILTON



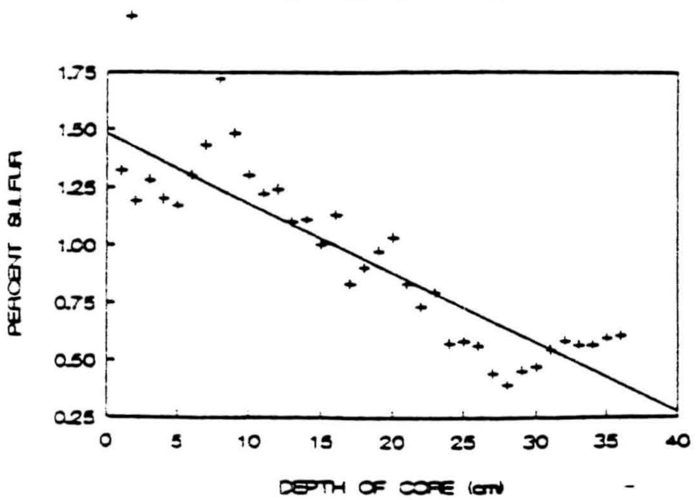
17d. SULFUR
LAKE MCKELVEY



17e. SULFUR
LAKE LIBERTY



17f. SULFUR
LAKE GIRARD



negative correlations in Lakes McKelvey and Girard. No such relationships occur in Lakes Pine, Evans, Hamilton or Liberty; however, the distribution of data points in Lakes Evans, Hamilton and Liberty shows periodic deposition of of sulfur.

Percent Iron:

Pine has the lowest percent iron of all reservoirs and retains this position throughout the length of the core (Table 15, Figure 18). A dramatic drop in iron content is obvious, from 0 to 5 cm in Hamilton Lake (from 7.58% to 4.15 %); thereafter its concentration steadily increases to 25 cm, then drops about 1 % to the end of the core. Iron concentrations in Lakes Liberty and Girard mimic each other until Liberty terminates at 20 cm. Evans Lake increases in iron concentration from 0 - 25 cm by nearly 1 %, and therafter decreases. From a one-way ANOVA, the rank order of mean percent iron for the reservoirs (Appendix A) is:

Hamilton = McKelvey = Girard = Liberty > Evans >Pine

Regression analyses of percent iron with sediment depth (Table 10, Figures 19a - 19f) indicate a significant negative correlation in Lake Hamilton. Linear regression slopes in Evans and Pine are similar, although they differ significantly in concentration. Liberty Lake and Girard Lake display similar iron depositional patterns with Liberty retaining a lower concentration throughout the sediment core (Figure 19).

Table 15. Percent Iron in Six Ows Reservoir Sediments.

DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	3.05	3.16	7.58	4.63	4.29	4.42
5	2.75	3.60	4.15	5.09	3.88	4.00
10	2.91	3.56	4.68	4.85	4.23	4.26
15	2.83	3.71	4.69	4.84	4.44	4.56
20	2.96	3.84	4.74	4.50	4.47	4.64
25	2.87	4.01	4.74	4.62		4.26
30	3.07	3.71	3.70	3.72		4.18
35		3.60				4.39
40		3.57				

Five replicate sample analyses give a coefficient of variance of 0.019.

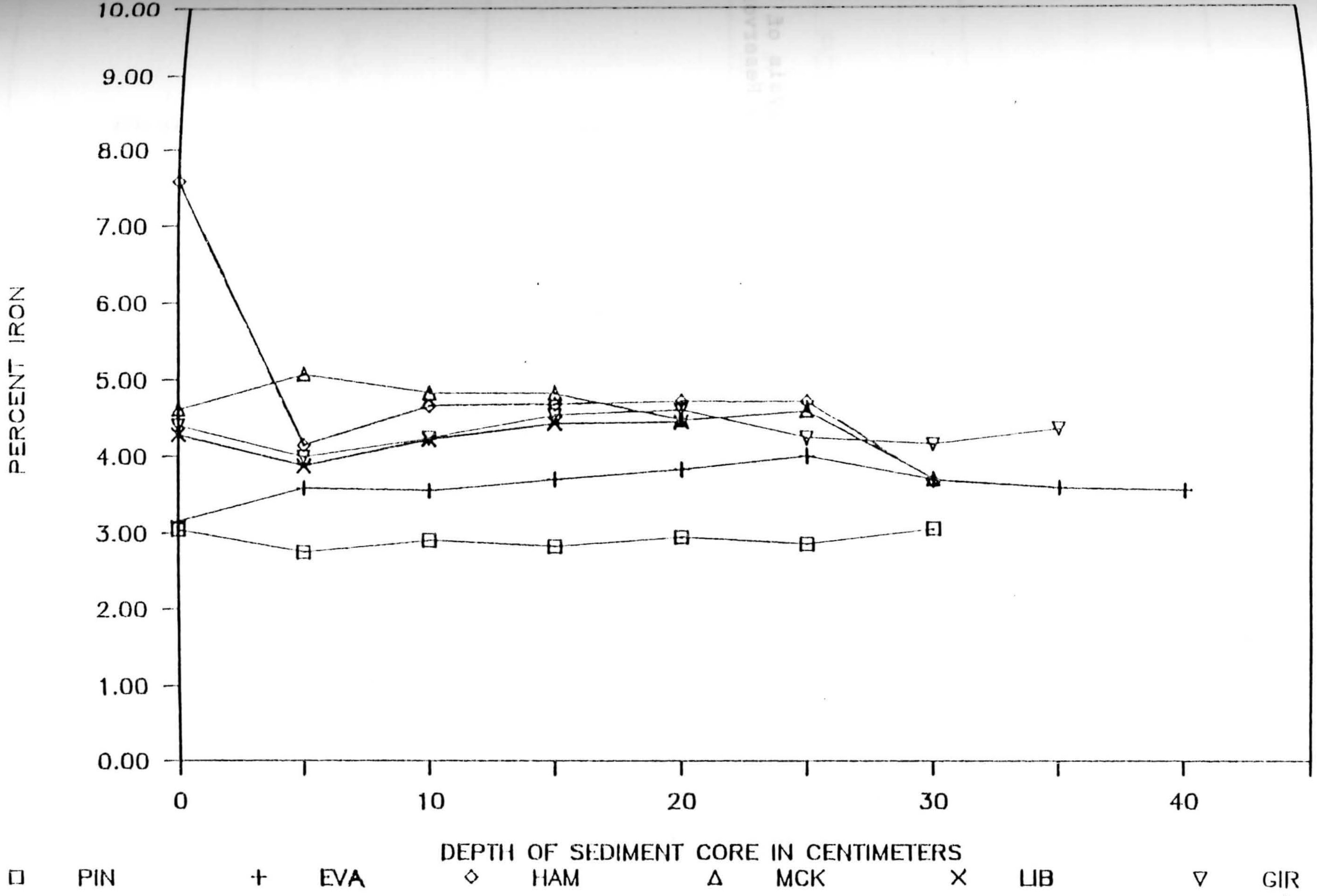
Iron : Sulfur

Significant direct linear relationships are apparent between iron and sulfur in Lakes McKelvey and Girard (Table 10, Figures 20a - 20f), while nonlinear relationships are apparent in the four other reservoirs. The distribution of the data points in Pine, Evans, Liberty and Girard suggests period deposits of FeS.

Percent Manganese:

Apart from Evans and Hamilton, Lakes Liberty, Girard, McKelvey and Pine exhibit similar manganese concentrations, and show decreases in manganese concentration with sediment depth (Table 16, Figure 21). Hamilton and Evans have significantly higher

Figure 18. Percent Sediment Iron in Six OWS Reservoirs.

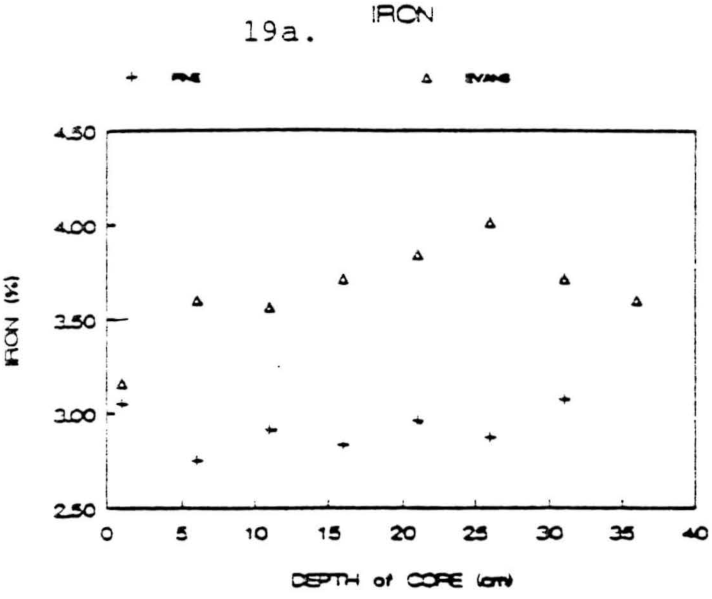


PERCENT IRON

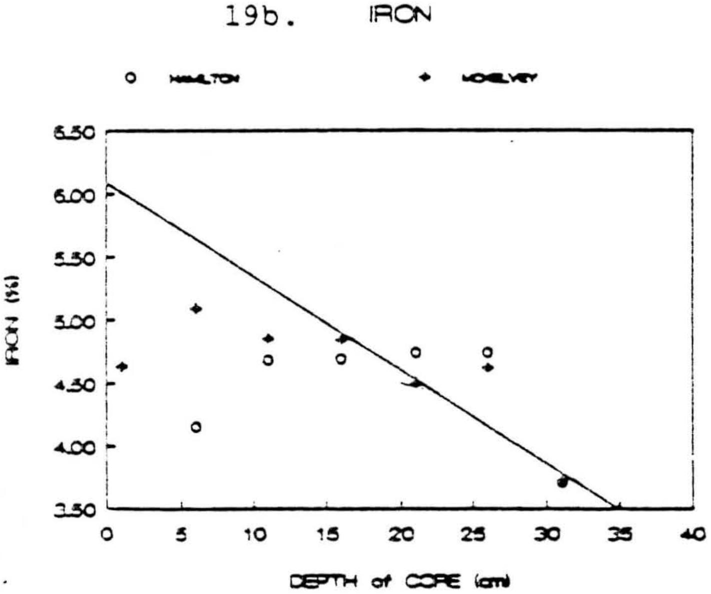
OHIO WATER SERVICE RESERVOIR SEDIMENTS

Figure 19a - 19f. Linear Regression Analysis of Percent Iron with Sediment Depth in Six OWS Reservoirs.

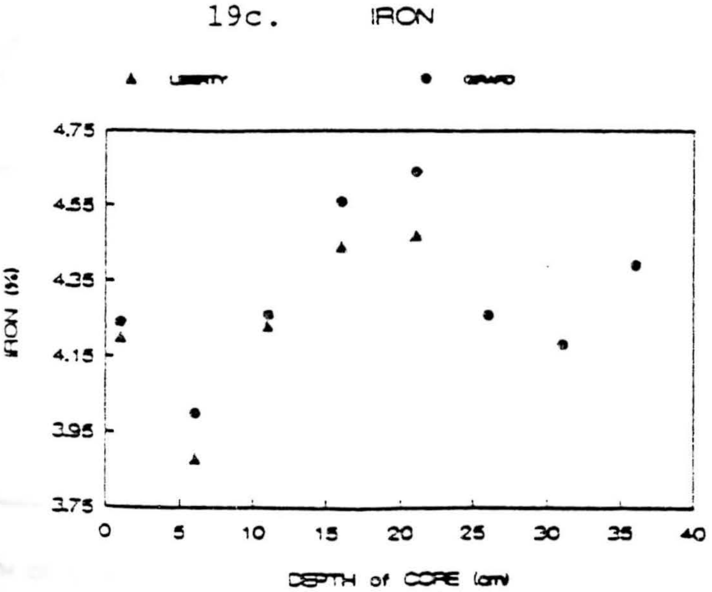
19a.


IRON
+ PINE
△ EVANS
4.50
4.00
3.50
3.00
2.50
IRON (%)
0
5
10
15
20
25
30
35
40
DEPTH of CORE (cm)

19b.

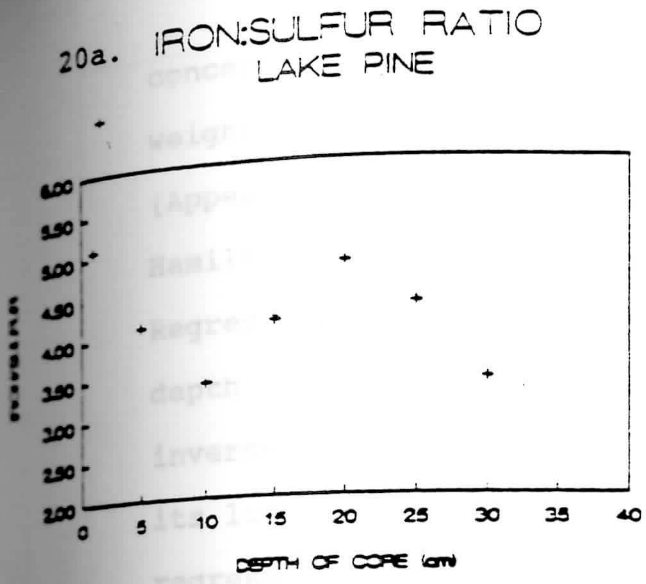

IRON
○ HAMILTON
◆ MCKELVEY
6.50
6.00
5.50
5.00
4.50
4.00
3.50
IRON (%)
0
5
10
15
20
25
30
35
40
DEPTH of CORE (cm)

19c.

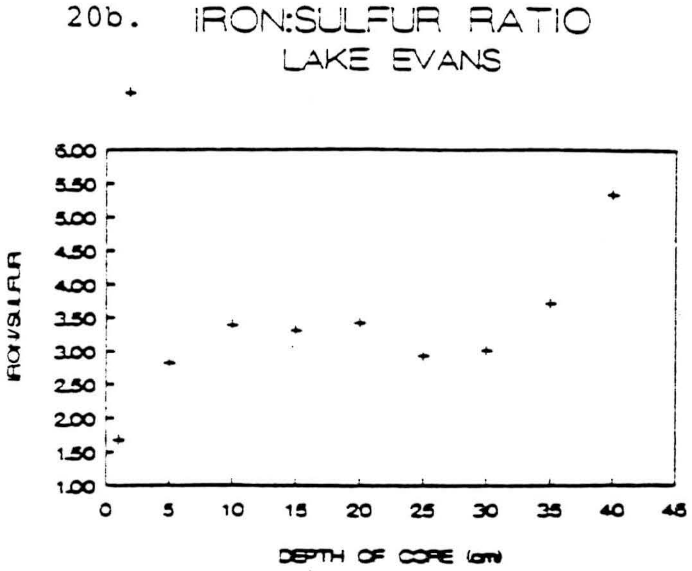

IRON
▲ LIBERTY
● GIRARD
4.75
4.55
4.35
4.15
3.95
3.75
IRON (%)
0
5
10
15
20
25
30
35
40
DEPTH of CORE (cm)

Figures 20a - 20c. Linear Regression Analysis of Iron:Sulfur Ratio with Sediment Depth in Six OWS Reservoirs.

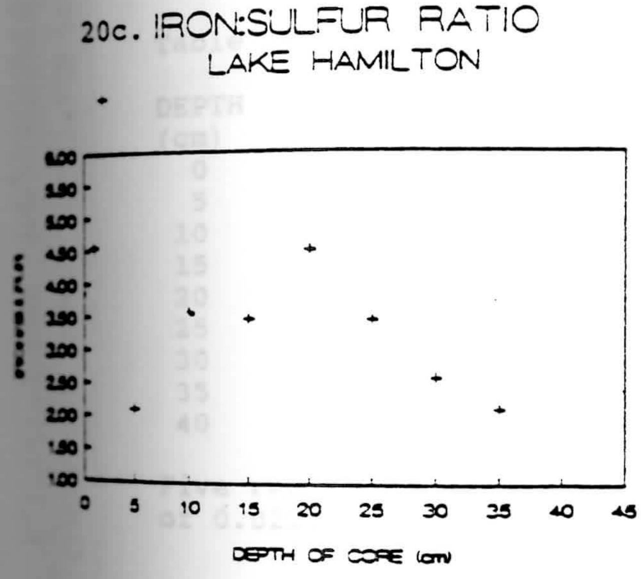
20a.



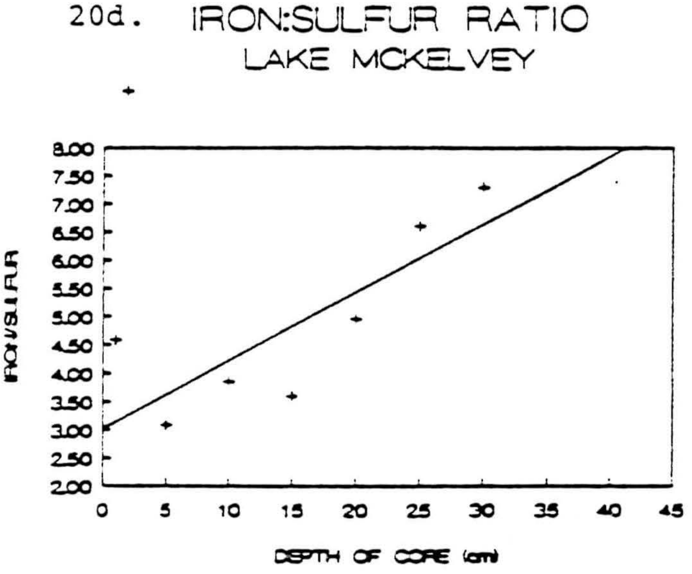
20b.



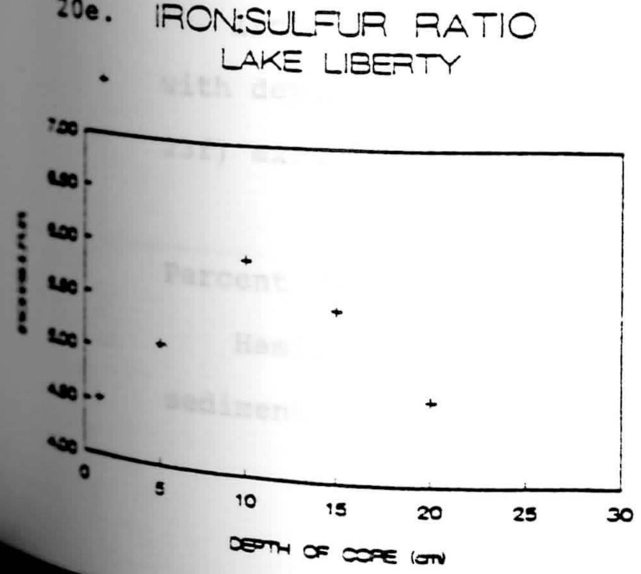
20c.



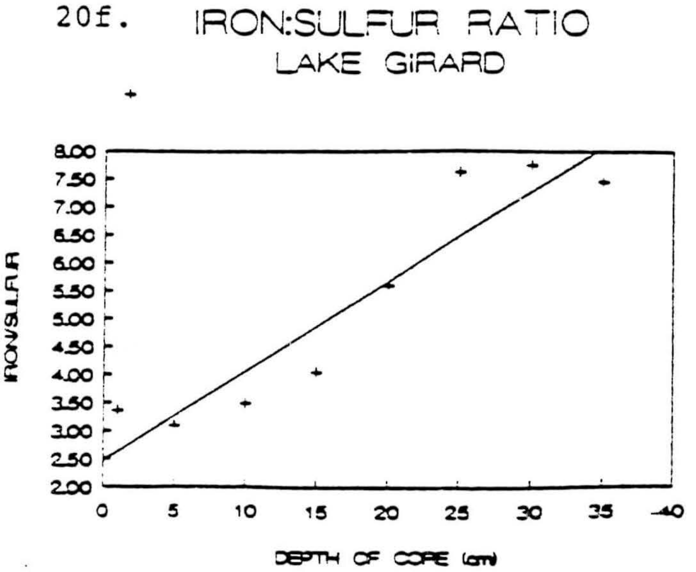
20d.



20e.



20f.



concentrations of manganese. Rank order of the total weighted mean percent manganese of each sediment core (Appendix A) (One-way ANOVA, $p < 0.05$) is:

Hamilton > Evans > Girard = McKelvey = Pine = Liberty

Regression analyses of percent manganese with sediment depth (Table 10, Figures 22a - 22c) reveal significant inverse relationships in all Lakes but Hamilton, where its low surface manganese value may skew the linear regression curve.

Table 16. Percent Manganese in Six OWS Reservoir Sediments

DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	0.07	0.26	0.22	0.06	0.07	0.07
5	0.07	0.26	0.34	0.08	0.06	0.07
10	0.06	0.21	0.21	0.06	0.05	0.06
15	0.05	0.17	0.20	0.05	0.04	0.06
20	0.05	0.16	0.22	0.05	0.04	0.05
25	0.05	0.18	0.21	0.05		0.05
30	0.04	0.16	0.19	0.04		0.05
35		0.11				0.05
40		0.10				

Five replicate sample analyses give a coefficient of variance of 0.023.

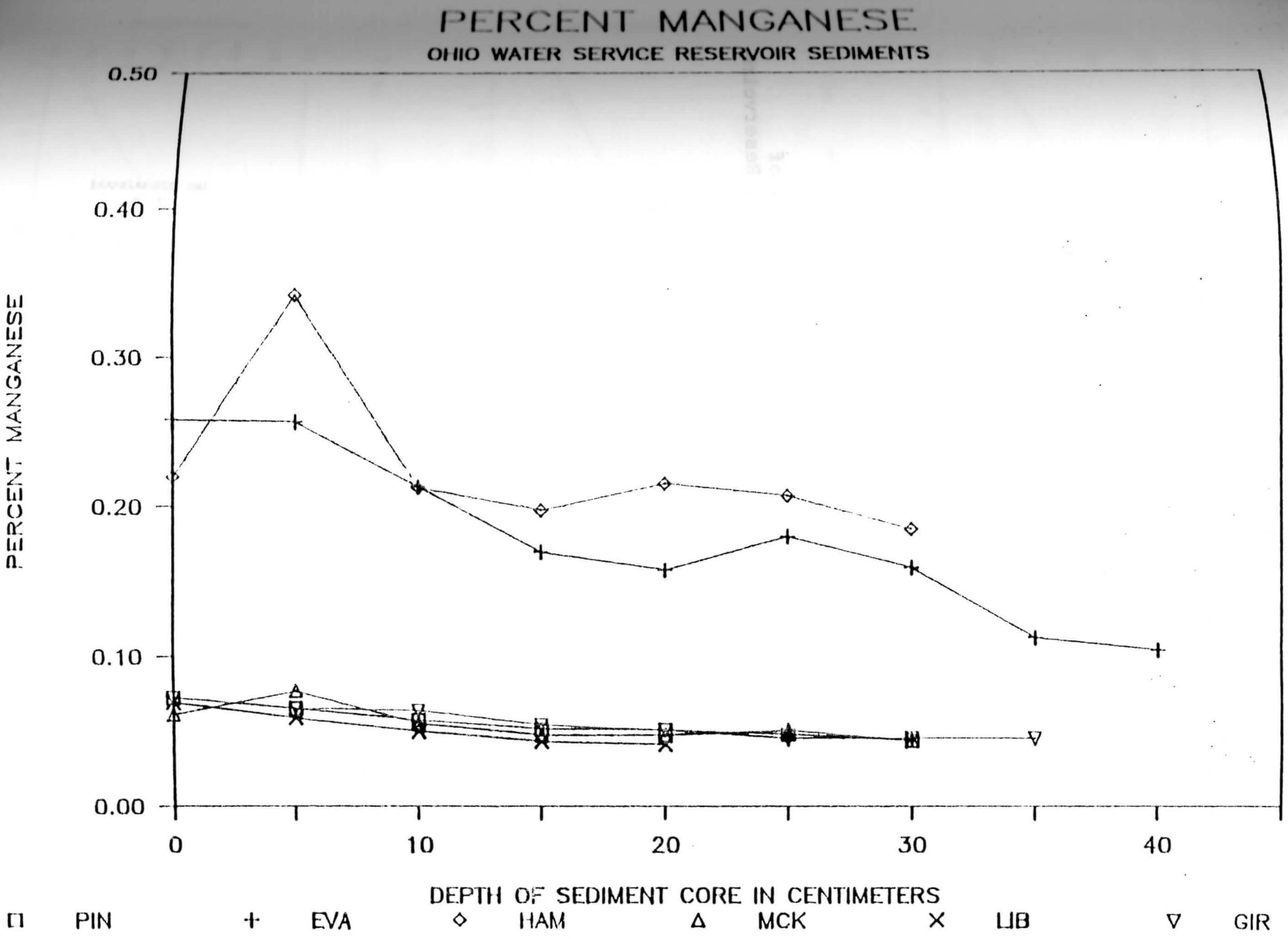
Iron : Manganese

Iron : Manganese ratio increased significantly with depth in all reservoirs (Table 10, Figures 23a - 23f) except Lake Hamilton.

Percent Calcium:

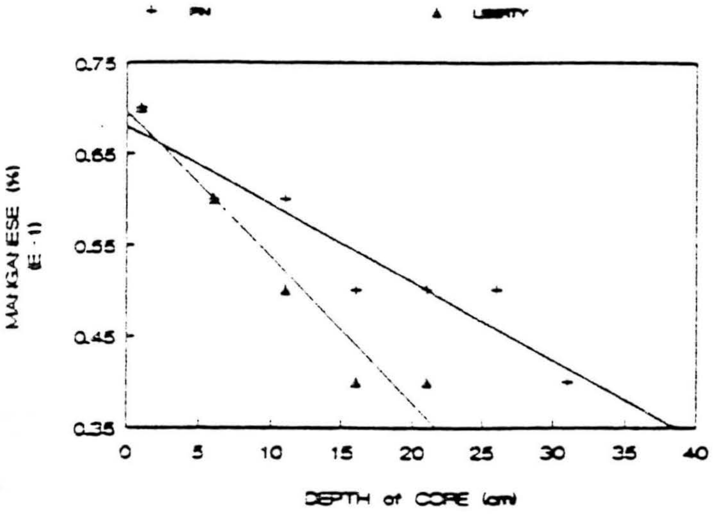
Hamilton Lake exhibits the highest percentage of sediment calcium, its surface values approaching 4

Figure 21. Percent Sediment Manganese in Six OWS Reservoirs.

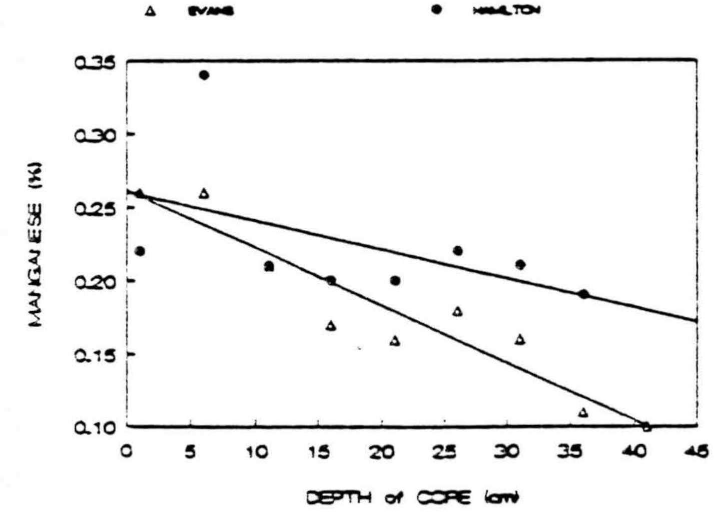

PERCENT MANGANESE
OHIO WATER SERVICE RESERVOIR SEDIMENTS
PERCENT MANGANESE
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
DEPTH OF SEDIMENT CORE IN CENTIMETERS
□ PIN
+ EVA
◇ HAM
△ MCK
× LIB
▽ GIR

Figures 22a - 22f. Linear Regression Analysis of Percent Manganese with Sediment Depth in Six OWS Reservoirs.

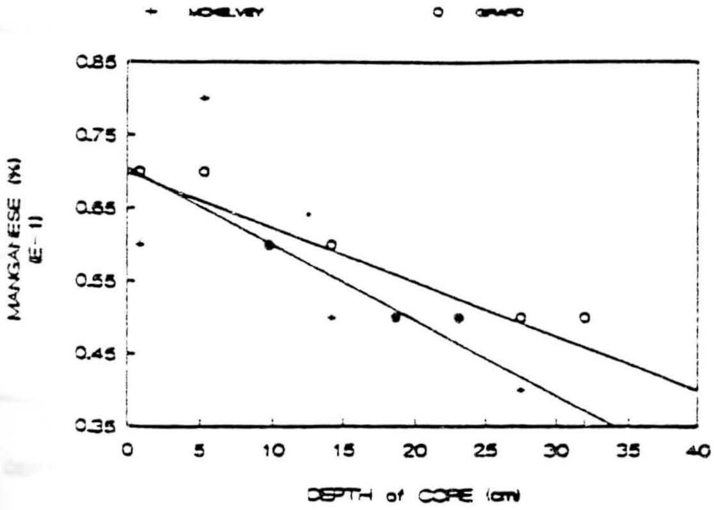
22a. MANGANESE



22b. MANGANESE

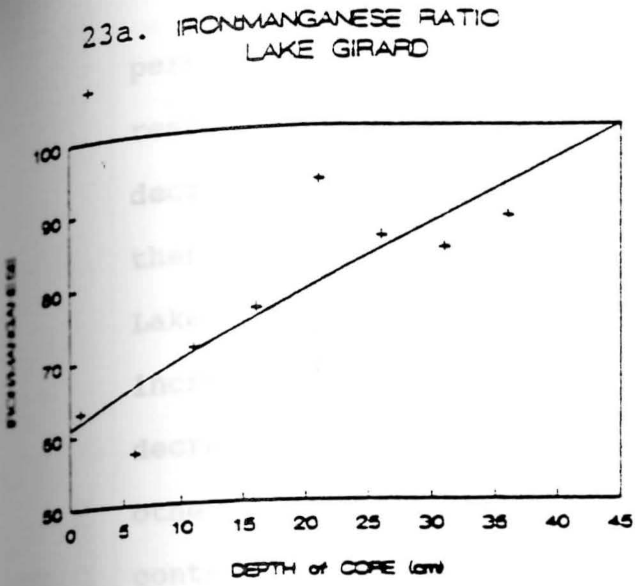


22c. MANGANESE

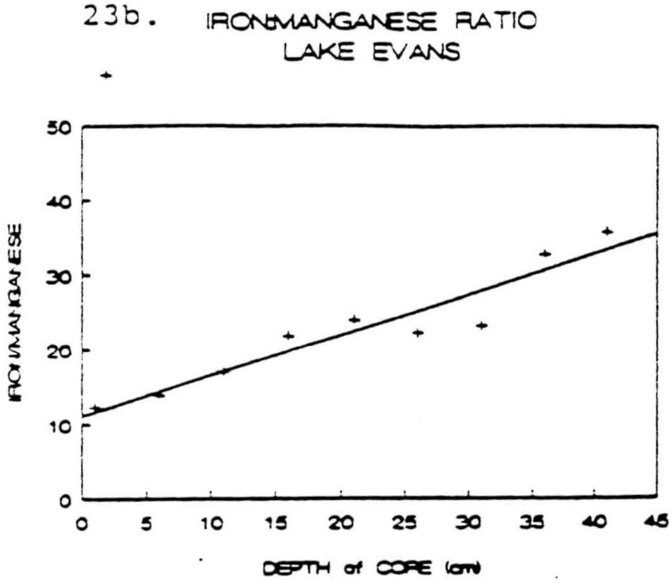


Figures 23a - 23f. Linear Regression Analysis of Iron:Manganese Ratio with Sediment Depth in Six OWS Reservoirs.

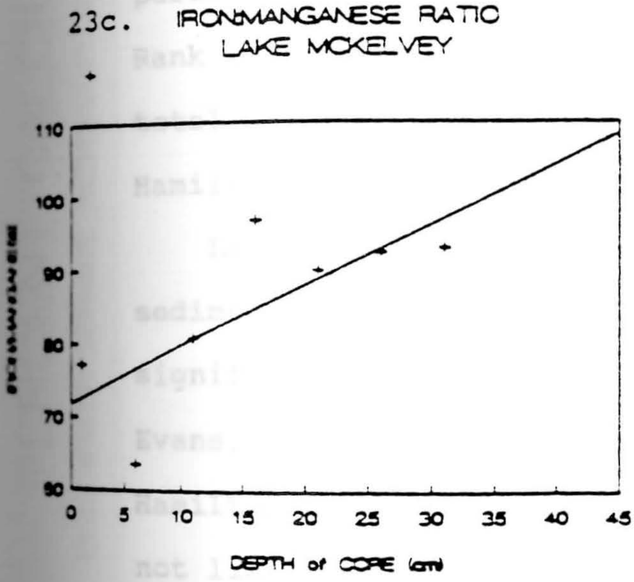
23a.



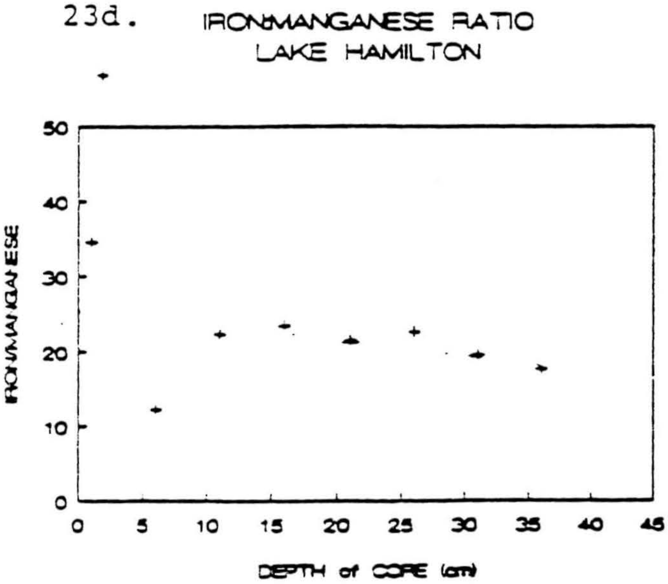
23b.



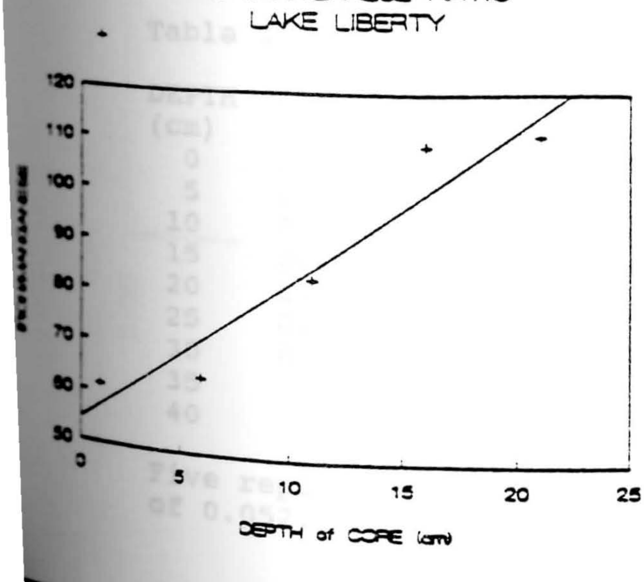
23c.



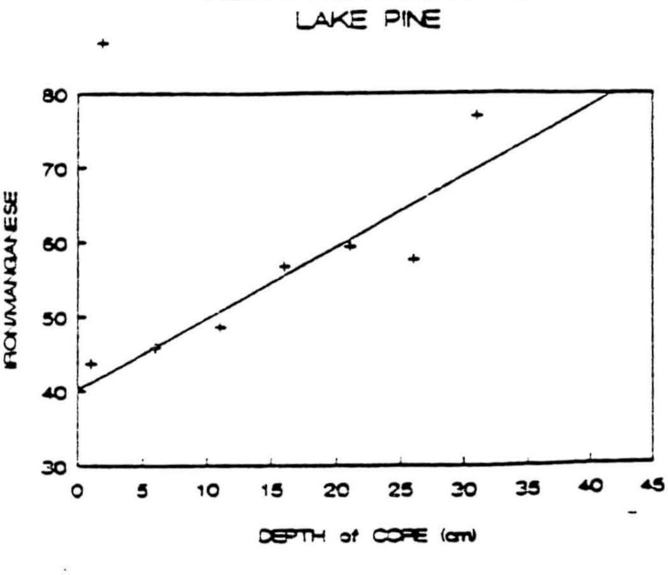
23d.



23e.



23f.



percent more calcium than the surface of other reservoirs (Table 17, Figure 24). Calcium in Hamilton decreases sharply from 0 - 5 cm (from 4.22 - 2.43 %), then fluctuates until the end of the core. Evans Lake, has the second highest percent calcium, increasing from 0 - 5 cm (from 1.17 - 1.49 %), then decreasing gradually until the end of the core. The other four reservoirs are nearly equal in calcium content, with Pine Lake having a somewhat greater percentage than either Liberty, Girard or McKelvey. Rank order based on One-way ANOVA, $p < 0.05$, of the total weighted mean calcium content (Appendix A) is: Hamilton > Evans > Pine $\geq$ Liberty = Girard = McKelvey

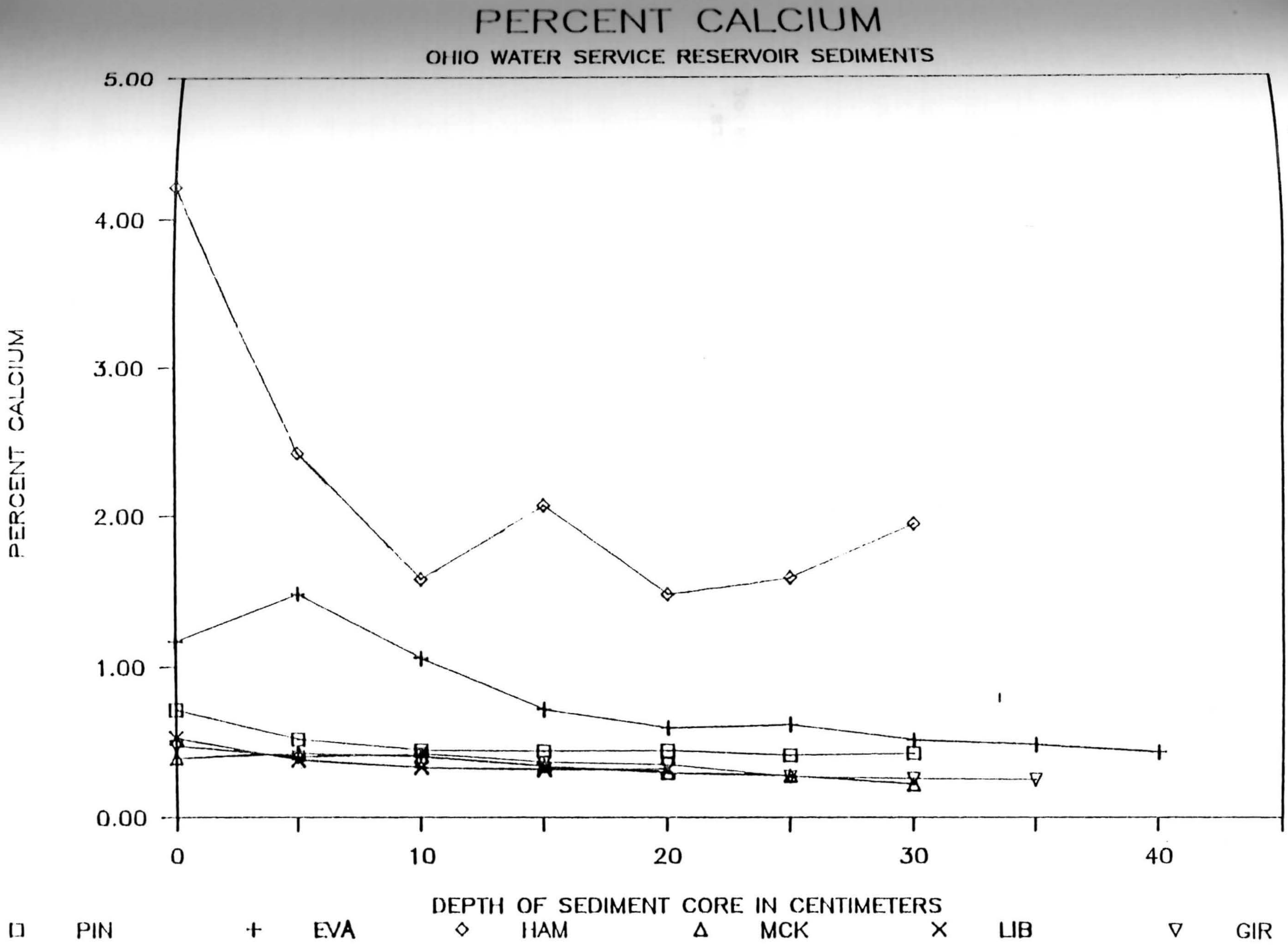
Linear regression analyses of percent calcium with sediment depth (Table 10, Figures 25a - 25f) show significant inverse relationships in Lakes Pine, Evans, McKelvey and Girard. Lakes Liberty and Hamilton show decreases in calcium with depth that are not linear.

Table 17. Percent Calcium in Six OWS Reservoir Sediments.

DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	0.72	1.17	4.22	0.40	0.54	0.48
5	0.53	1.49	2.43	0.44	0.39	0.41
10	0.45	1.06	1.59	0.41	0.34	0.43
15	0.45	0.73	2.08	0.35	0.32	0.38
20	0.45	0.61	1.49	0.30	0.33	0.36
25	0.42	0.63	1.60	0.28		0.28
30	0.43	0.53	1.95	0.23		0.27
35		0.50				0.26
40		0.44				

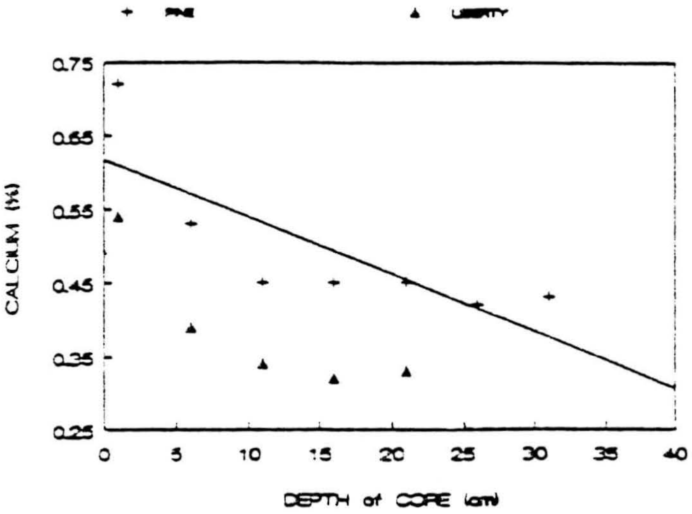
Five replicate sample analyses give a coefficient of variance of 0.052.

Figure 24. Percent Sediment Calcium in Six OWS Reservoirs.


PERCENT CALCIUM
OHIO WATER SERVICE RESERVOIR SEDIMENTS
5.00
4.00
3.00
2.00
1.00
0.00
PERCENT CALCIUM
0
10
20
30
40
DEPTH OF SEDIMENT CORE IN CENTIMETERS
□ PIN
+ EVA
◇ HAM
Δ MCK
× LIB
▽ GIR

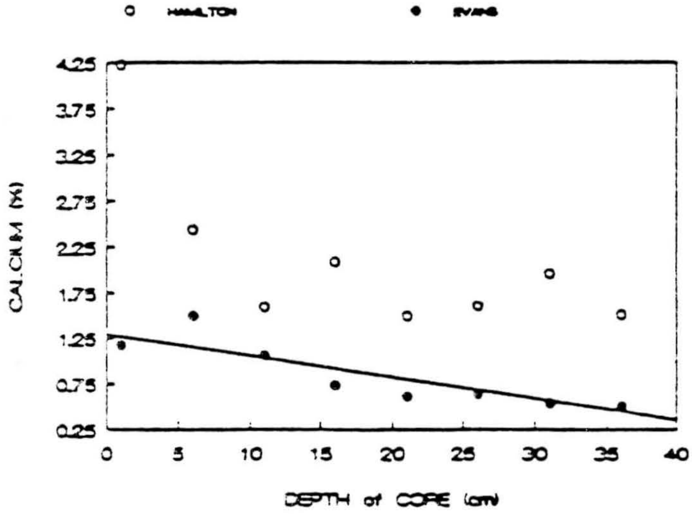
Figures 25a - 25c. Linear Regression Analysis of Calcium with Sediment Depth in Six OWS Reservoirs.

25a.



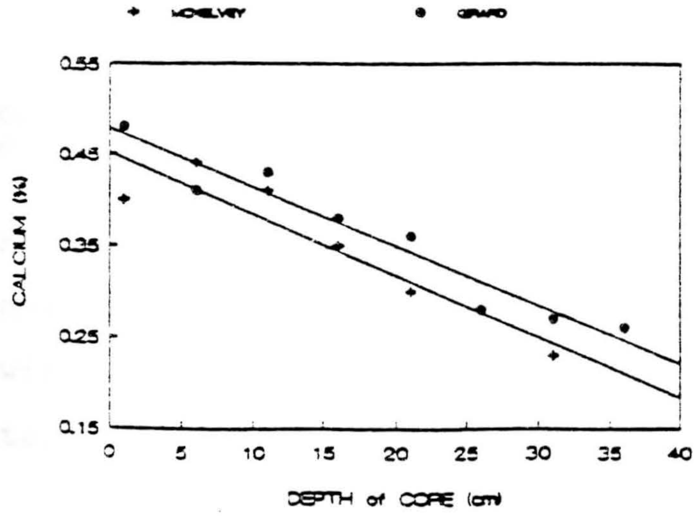
CALCIUM

25b.



CALCIUM

25c.



CALCIUM

Percent Magnesium:

Clearly, Lake Hamilton has the greatest percent magnesium throughout the length of its core (Table 18, Figure 26). Liberty and Girard are similar in magnesium distribution with depth. Pine essentially has the lowest percent magnesium and McKelvey the second lowest concentration. Rank order based on Oneway ANOVA, $p < 0.05$, of the total weighted percent mean magnesium content between cores (Appendix A) is:

Hamilton > Evans = Liberty = Girard > McKelvey > Pine

No significant correlations exist between magnesium and depth in any reservoir (Table 10, Figures 27a - 27f).

Table 18. Percent Magnesium in Six OWS Reservoir Sediments.

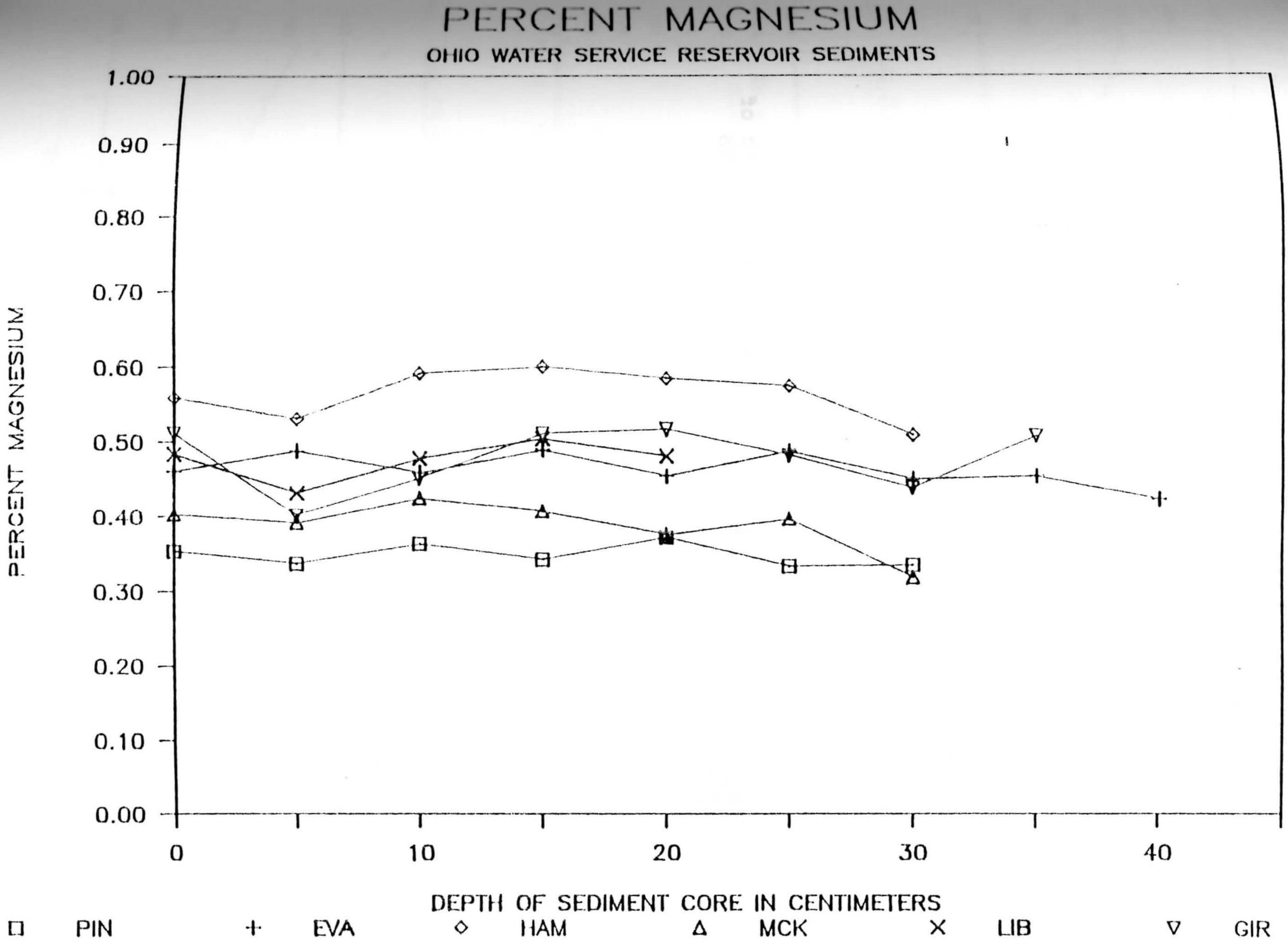
DEPTH (cm)	PINE	EVANS	HAMILTON	MCKELVEY	LIBERTY	GIRARD
0	0.35	0.46	0.56	0.40	0.48	0.51
5	0.34	0.49	0.53	0.39	0.43	0.40
10	0.36	0.46	0.59	0.43	0.48	0.45
15	0.34	0.49	0.60	0.41	0.50	0.51
20	0.37	0.46	0.59	0.38	0.48	0.52
25	0.33	0.49	0.58	0.40		0.48
30	0.34	0.45	0.51	0.32		0.44
35		0.46				0.51
40		0.42				

Five replicate sample analyses give a coefficient of variance of 0.061.

Calcium : Magnesium Ratio (Ca:Mg) with DEPTH:

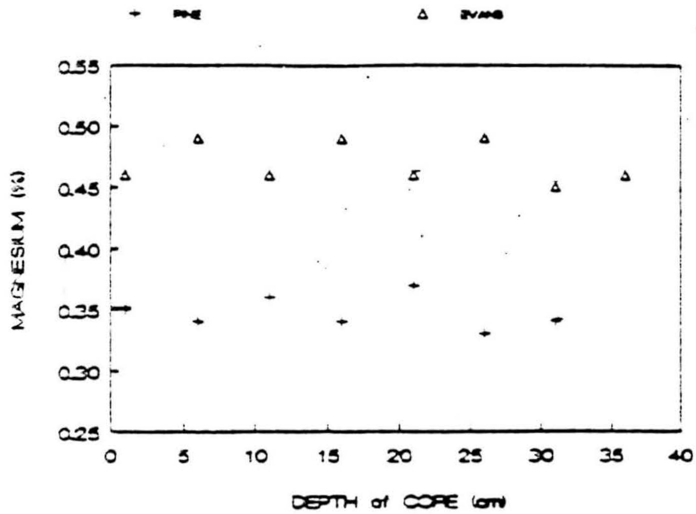
Linear regression analysis of Calcium : Magnesium ratio with depth (Table 10, Figures 28a - 28f) indicates that Ca:Mg is directly related to depth,

Figure 26. Percent Sediment Magnesium in Six OWS Reservoirs.

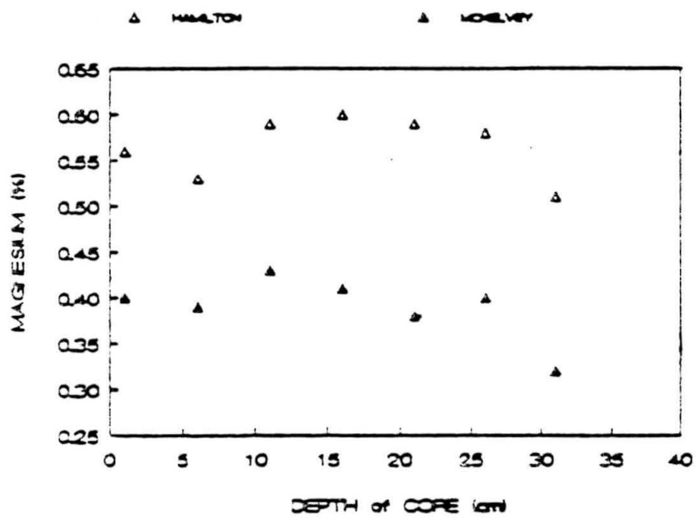

PERCENT MAGNESIUM
OHIO WATER SERVICE RESERVOIR SEDIMENTS
PERCENT MAGNESIUM
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
DEPTH OF SEDIMENT CORE IN CENTIMETERS
□ PIN
+ EVA
◇ HAM
△ MCK
× LIB
▽ GIR

Figures 27a - 27c. Linear Regression Analysis of Percent Magnesium with Sediment Depth in Six OWS Reservoirs.

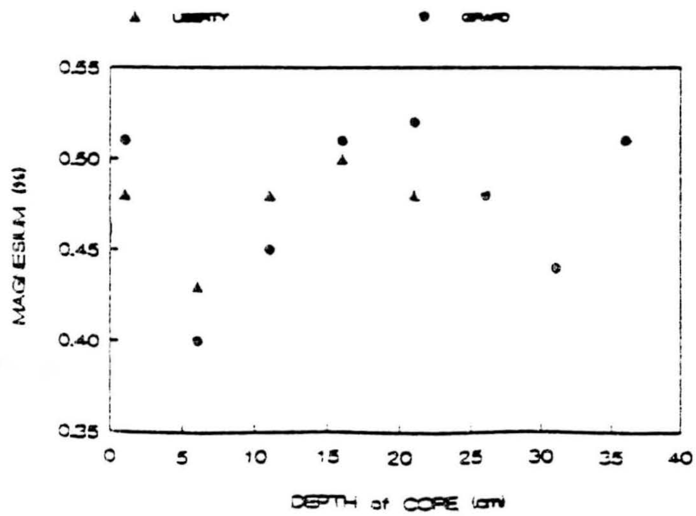
27a. MAGNESIUM



27b. MAGNESIUM

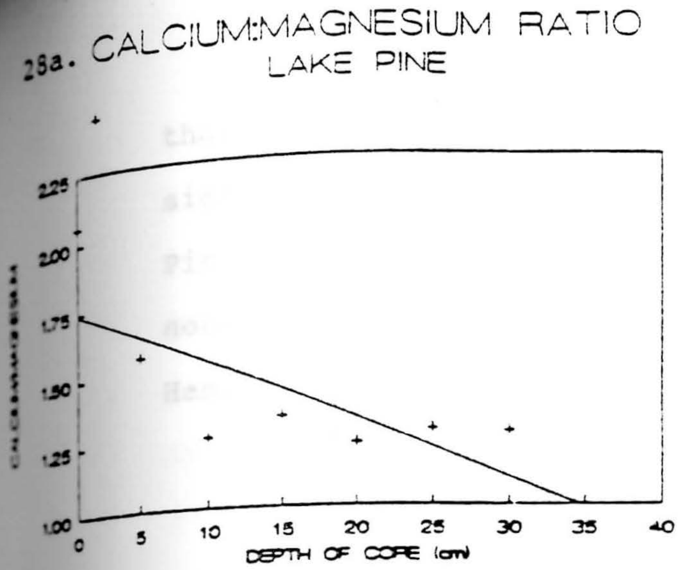


27c. MAGNESIUM

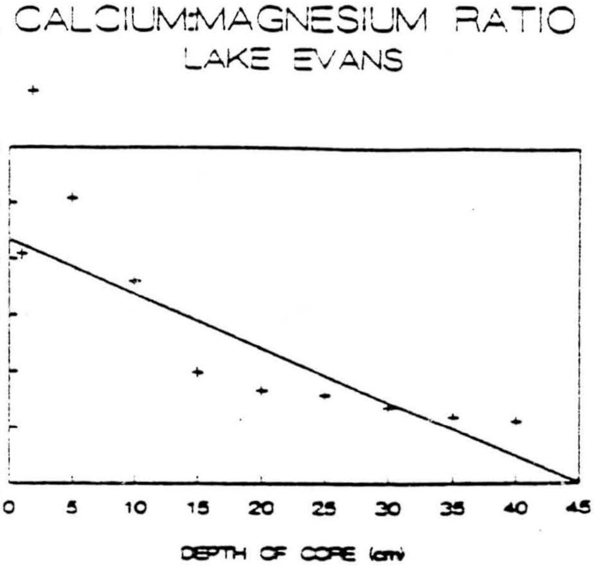


Figures 28a - 28f. Linear Regression Analysis of Calcium:Magnesium Ratio with Sediment Depth in Six OWS Reservoirs.

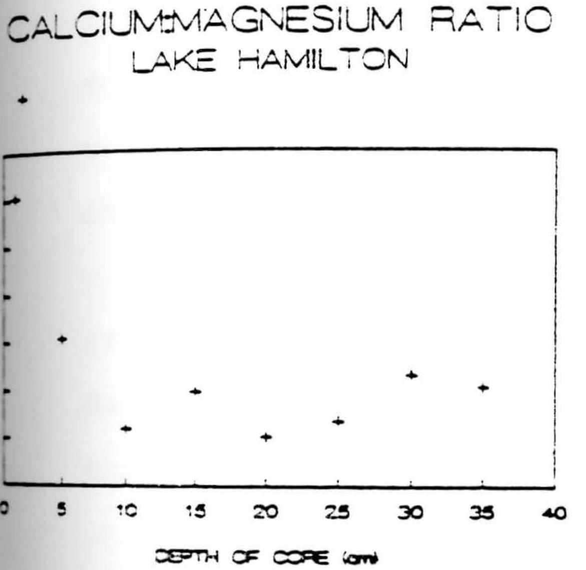
28a.



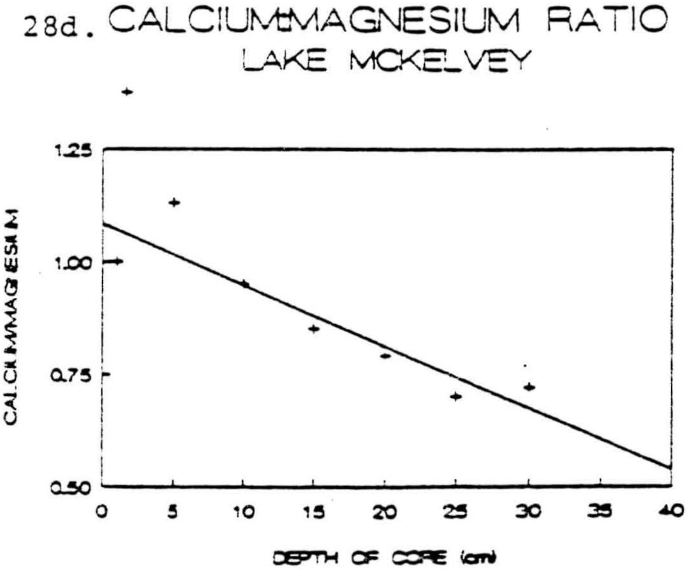
28b.



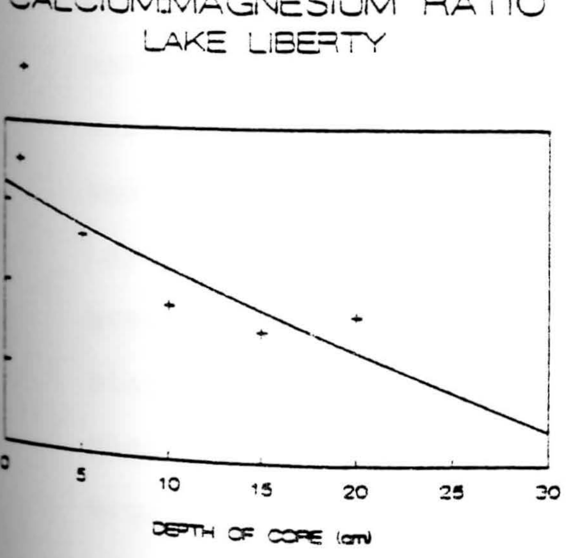
28c.



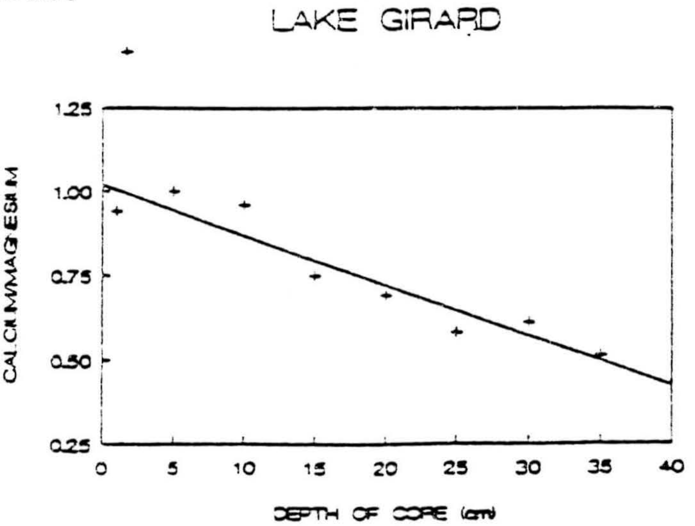
28d.



28e.



28f.



that is less magnesium relative to calcium is significantly present in deeper sediments in Lakes Pine, Evans, McKelvey, Liberty and Girard. A nonlinear relationship between Ca:Mg occurs in Lake Hamilton.

DISCUSSION

Water content decreases with depth of core in all reservoirs; however, Hamilton Lake exhibits an increase of nearly three percent water in the last 15 cm of sediment. Water content is expected to decrease with increasing depth, correlating with decreases in organic content, decreases in bioturbation, and increased compaction at depth (Hakanson 1983). Sharp decreases at 33 cm in Pine and 34 cm in Girard suggest core penetration into soil below lake sediments. It does not appear that the high percentage of water at 0 - 3 cm in Liberty is related to organic content (Figure 6). Rather, the degree of compaction, the degree of bioturbation and the mineral content affect the water content.

Organic matter in sediments originates allochthonously and autochthonously, from the production of algae and macrophytes. The latter are among the major inputs of organic matter in Lakes Pine and Evans, where sediment C:N ratios are within 12:1, and whose WSA:LSA are relatively low (Table 3). Pine Lake is the shallowest reservoir and provides the greatest area for macrophyte development. Water depth plays a role in organic matter sedimentation, as shallow areas receive "significant quantities of organic matter" from the decomposition of macrophytes and leaf litter (Clay and Wilhm 1979). Comparison of four lakes by Januszkiewicz (1983/1984) revealed that the concentration of organic matter in the shallowest of them, Lake Wierzcholek, maximum depth 3.1 meters, was greatest of all lakes studied. Organic matter is significantly greater in Pine Lake than any other OWS Reservoir. Increased levels of organic matter in bottom sediments have been correlated with increased trophic state (Zdanowski 1983), and have been found to vary seasonally (Olszewski and Mowinska 1985). Pine Lake, with the highest trophic state (TSI = 61.3 ± 1.8), was expected to have a significantly higher content of sediment organic matter. The relationships of organic matter with depth in Pine and Evans parallel each other, with Evans having a significantly lower total concentration, but a similar slope (b = -0.047 and -0.042), for Evans and Pine, respectively (Table 10). Lakes Girard, Liberty, McKelvey and Hamilton have much steeper slopes, exceeding b = -0.13, suggesting more rapid sedimentation of organics in recent times. With Pine Lake in an increased trophic state and potentially experiencing continuous macrophyte sedimentation, it is not surprising that the input of organic matter has not changed as dramatically as in the other four reservoirs. This suggests Pine has had little change in trophic state. Lake Evans, on the basis of sediment organic matter alone, also does not appear to be increasing in trophic state as rapidly as Girard, Liberty, McKelvey or Hamilton. The supply of particulate and dissolved organics from Yellow Creek (originating from Pine Lake) may partly explain the similar pattern of organic distribution in the cores of Lakes Pine and Evans.

Hamilton Lake has significantly higher total organic matter than all lakes except Pine, and a strong negative correlation between organic content and sediment depth where b = -0.133 (Table 10). With its steep sides, Hamilton has little area for significant littoral plant development. Rather, detrital matter is derived from algae in the water column, as C:N ratios are within 12:1. Like Hamilton, McKelvey does not have the shallow areas for macrophyte development; rather, the organic input is primarily derived from production in the water column. The significant increases in organic matter over time in all lakes, more importantly in Hamilton, McKelvey, Girard and Liberty, suggests eutrophication.

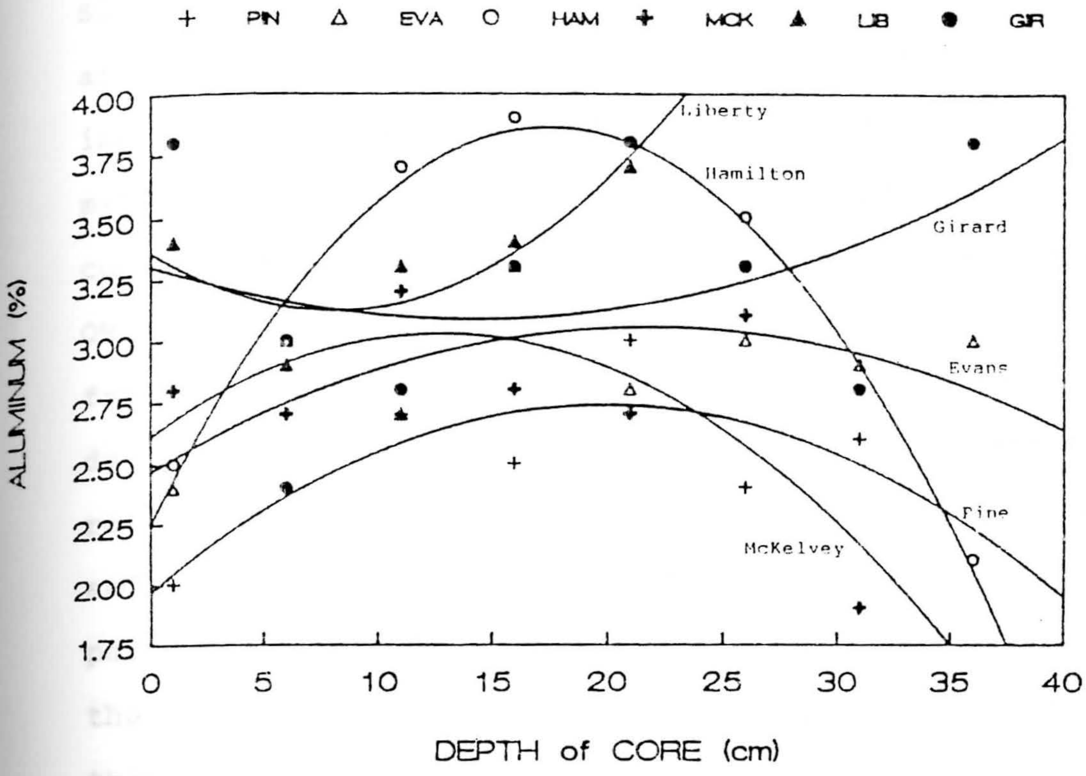
Aluminum is not an endogenic component of lake sediments; rather, it is carried to the sediment from various parts of the catchment area (Januszkiewicz 1983/1984). The distribution of aluminum with sediment depth is being used as an indicator of the constancy of runoff. Linear regression analysis of aluminum to depth indicates no significant correlation in any reservoir. However, second order polynomial curves show some interesting relationships (Figure 29). A pronounced increase towards the center of the core with decreases on either side are apparent in Hamilton, and to a lesser degree in McKelvey, Evans and Pine. Increases toward the terminal end of the core in Lake Liberty, and to a lesser degree, in Lake Girard are apparent. This suggests a time period of increased surface runoff. Because the pattern is apparent in reservoirs of close proximity, Hamilton and Evans, construction, mining and runoff may have influenced the aluminum peaks at midcore. Consequently, Girard and Liberty, in the same watershed, are expected to show similar distributions of aluminum with depth. That no significant increase over time (towards recent sediments) has occurred suggests all lakes have moderately constant minerogenic supply from runoff and erosion. It should be noted, however, that seasonal variations in aluminum and other minerals from runoff may occur, i.e., during the spring thaw. Data on percent aluminum from every centimeter of Lake Evans suggests these seasonal fluctuations (Figure 30), but no significant increase or decrease over time (depth of core) is observed.

The ratio of organic matter to aluminum has been used to verify the source of sediment organic matter.

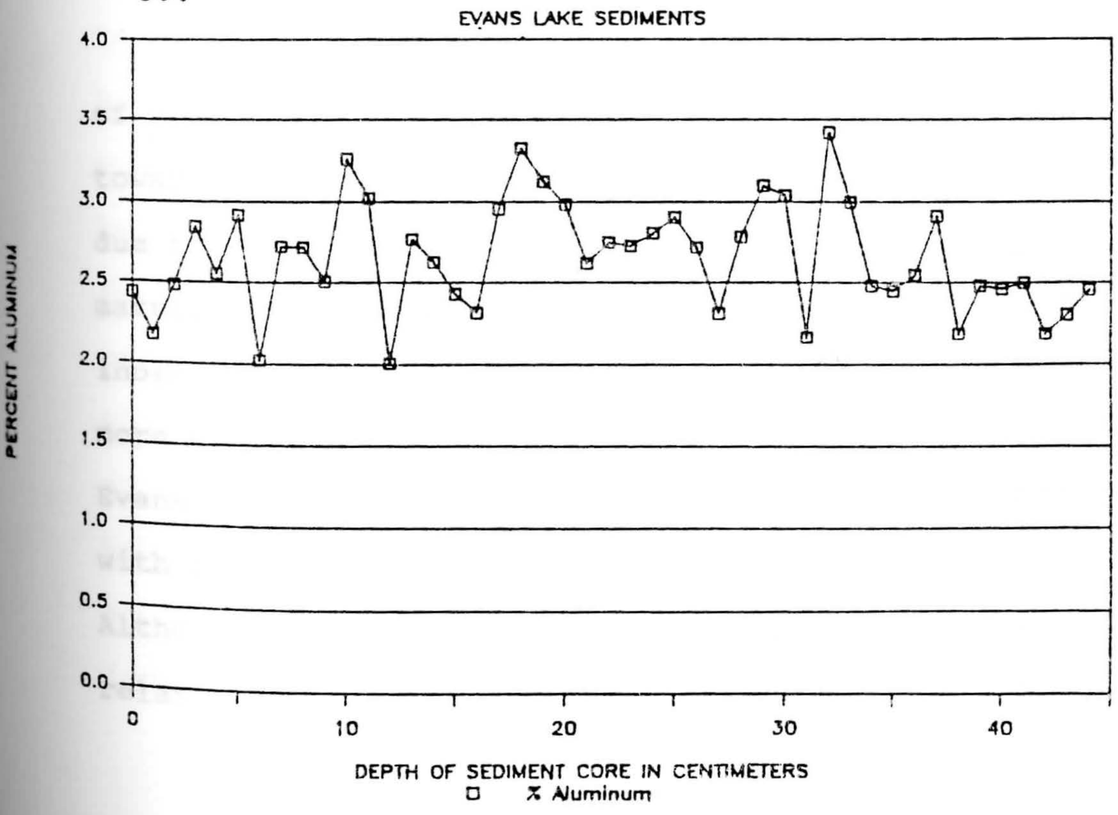
Figure 29. Second Order Polynomial Curves of Percent Aluminum with Sediment Depth in Six OWS Reservoirs.

Figure 30. Percent Sediment Aluminum in Lake Evans.

29. ALUMINUM



30. PERCENT ALUMINUM



significant indirect relationships of OM:Al with depth are prevalent in Lakes Pine, Evans and Girard and are implied in Lakes Liberty and McKelvey. More organic matter is being deposited relative to aluminum in contemporary sediments in these reservoirs. Increased OM:Al ratios in recent sediments results primarily from the continual decomposition of organic matter at depth, and of increased algal production, increased rooted plant development, the sedimentation of algae and macrophytes, increased allochthonous supply of particulate organic matter and its sedimentation. At the surface, sediments receive more organic matter than is decomposed, hence the indirect association between organics and depth. In Lake Hamilton, the atypical regression curve of OM:Al with depth is a result of the aluminum deposition pattern (Figure 9).

In Lakes undergoing eutrophication, the percentage of sediment carbon content is expected to increase towards surface sediments. Sedimentation of carbon is due to both an increase in the supply of organic matter (organic carbon) and to the sedimentation of inorganic carbon as carbonates. The latter is much more prevalent in hard-water reservoirs, such as Lakes Evans and Hamilton. Significant increases in carbon with time are apparent in all reservoirs except Pine. Although Lake Hamilton shows a significant linear relationship, it is obvious that a nonlinear curve better describes the relationship between carbon content and depth (Figure 31). Nonlinear patterns are used to exemplify the limitations of linear regression analysis and to show possible alternatives. It is beyond the scope of this research to apply a statistical analysis to the nonlinear relationships.

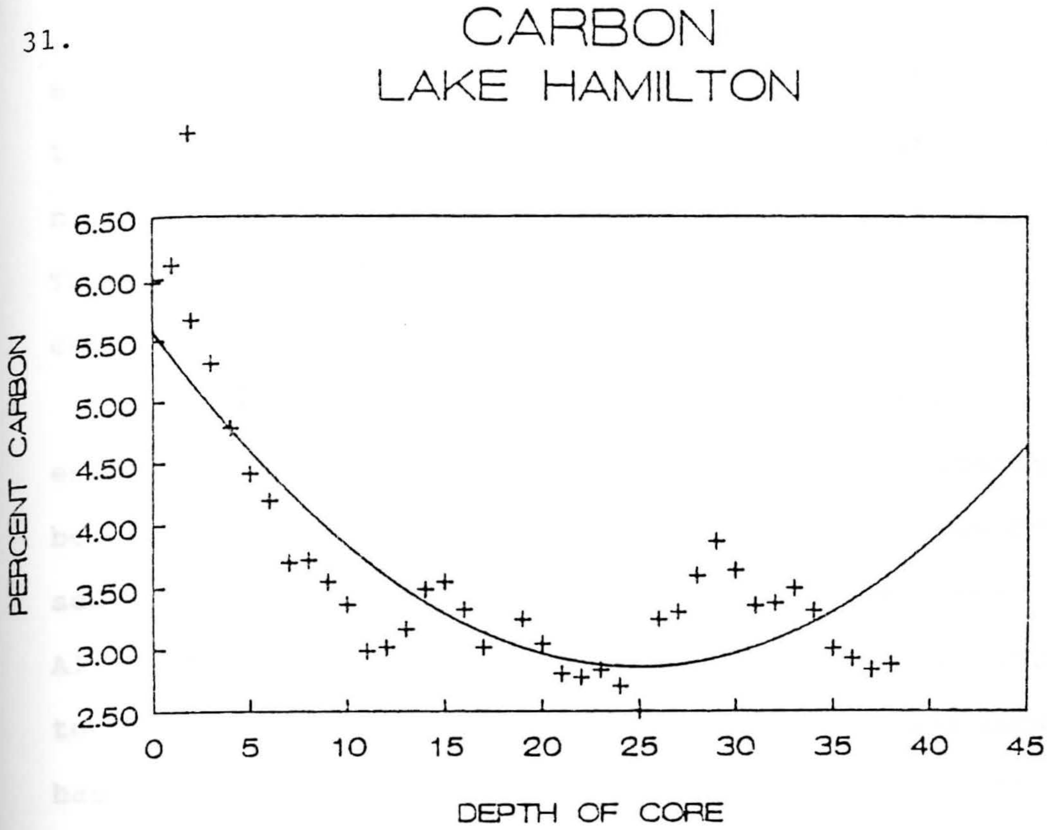
Eutrophication is thought to be primarily responsible for the increases in carbon, because carbon is not a dynamic element; that is, it is not readily exchanged at the sediment water interface as are nutrients such as nitrogen and phosphorus. Its sedimentation is not directly redox or pH dependent as are iron and manganese. The concentration of carbon in sediments is related to the refractory carbon skeletons sedimented during decomposition, minus the loss of carbon as $CO2$ during decomposition. Decomposition decreases with depth, thus, lakes that have experienced increased eutrophication, are expected to show significant negative correlations between carbon content and depth of sediment. Furthermore, the slope values of C:DP linear regressions should be indicative of lake trophic state, and should be steeper in lakes undergoing eutrophication. In descending order, slope values for C:DP are Liberty (-0.097), Girard (-0.069), McKelvey (-0.067), Hamilton (-0.054), Evans (-0.026) and Pine (-0.004).

Sediment nitrogen "is chiefly connected with organic matter" (Januszkiewicz 1983/1984), and "is closely linked with energy" (Job and Kannan 1980). Consequently, the concentration of nitrogen in the OWS sediments is directly correlated to that of organic matter in all OWS reservoirs except Pine (Appendix A). With the onset of lake eutrophication, sediments change from an inorganic to a more organic character (Wetzel 1983). With greater quantities of organic matter, more nitrogen is available for release and reutilization in the photic zone. This is a positive feedback system, as sediments are the site of much nitrogen metabolism (Wetzel 1983). All OWS Reservoirs exhibit significant indirect relationships of percent nitrogen with increased sediment depth. Such phenomena have been related to change in lake trophic state (Bortleson and Lee 1972, Pennington 1973). As with carbon, the nitrogen with depth relationship in Lake Hamilton is better described by a nonlinear curve (Figure 32). The nitrogen variation with depth in the OWS Lakes is related partly to increased lake eutrophication, and primarily to the selective removal and release of nitrogen as soluble NH4-N. Nitrogen concentrations in sediments, along with phosphorus, have been found to be more concentrated in eutrophic as opposed to oligotrophic reservoir sediments (Fish and Andrew 1980). Total core nitrogen is not

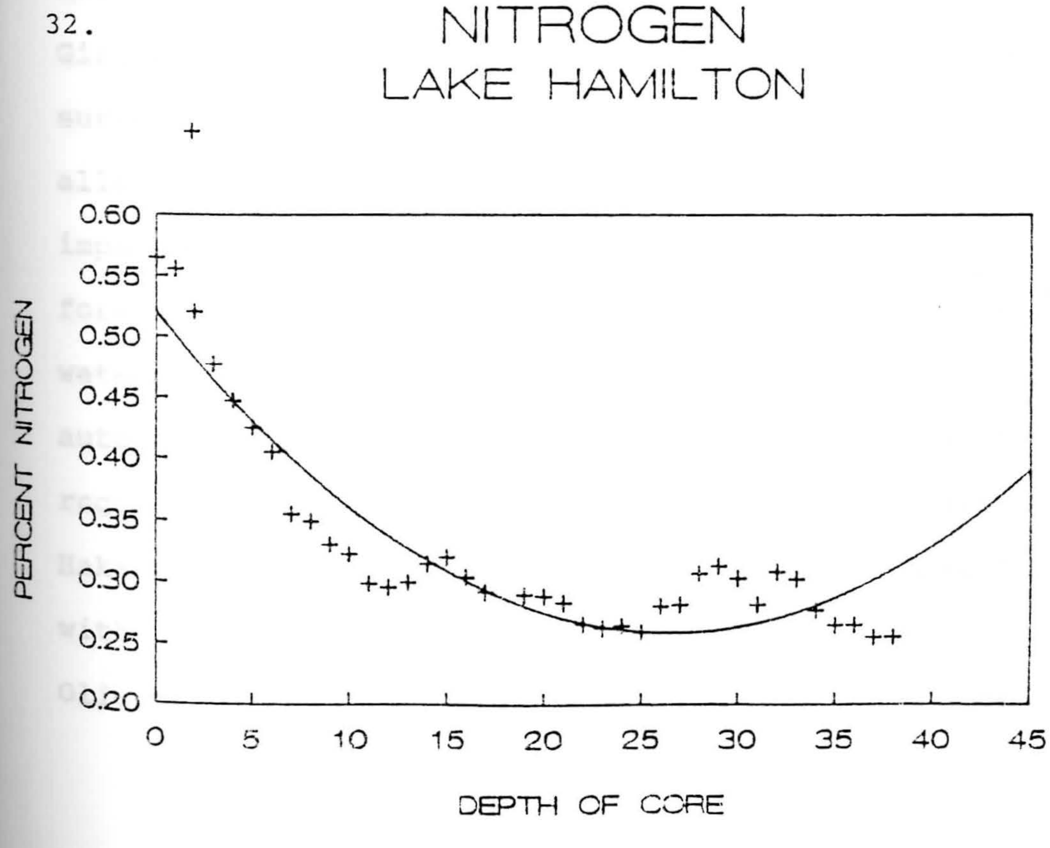
Figure 31. Second Order Polynomial Curve of Percent Sediment Carbon in Lake Hamilton.

Figure 32. Second Order Polynomial Curve of Percent Sediment Nitrogen in Lake Hamilton.

31.


CARBON
LAKE HAMILTON
PERCENT CARBON
6.50
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
0
5
10
15
20
25
30
35
40
45
DEPTH OF CORE

32.


NITROGEN
LAKE HAMILTON
PERCENT NITROGEN
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
5
10
15
20
25
30
35
40
45
DEPTH OF CORE

significantly different among the OWS Reservoirs, with the exception of Pine Lake, which has markedly higher nitrogen throughout its sediment core (Figure 13). This concurs with the high carbon and organic concentrations in Pine Lake.

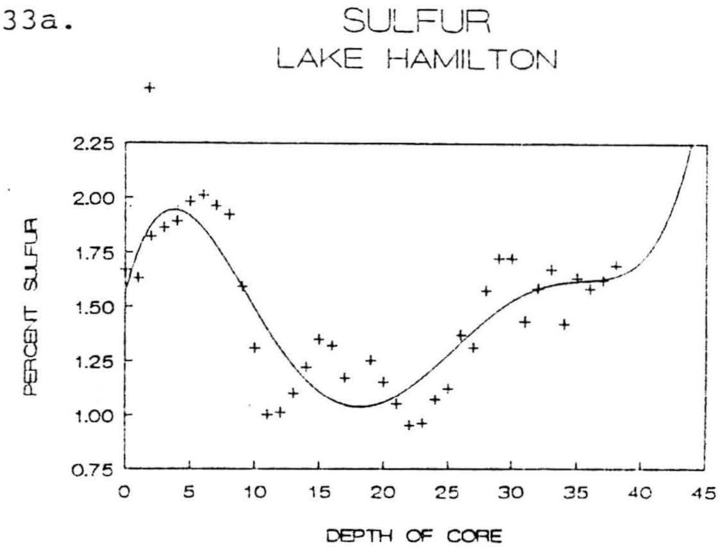
Carbon to nitrogen ratios have been used to estimate lake type, humic content and to differentiate between allochthonous and autochthonous supplies of sediment organic matter (Hansen 1961, Wetzel 1984). Allochthonous organic matter has a C/N ratio of 45:1 to 50:1, while organic matter produced autochthonously has a C/N ratio of 12:1. With this classification, the supply of organic matter to all OWS Reservoirs is regarded chiefly as autochthonous, as C/N ratios are close to 12:1. However, the presence of forested areas around Lakes Hamilton, McKelvey, Liberty and Girard, in addition to the high watershed to lake surface area ratios of these lakes, may make allochthonous supply of organic matter more important. In the same respect, the absence of forestation about Evans and Pine Lake and the low watershed to lake surface area ratios, make autochthonous contributions more important. With regard to the classification of sediment humosity, Hakanson (1983) utilizes the C:N ratio in conjunction with mineral and organic content of sediments. Oligotrophic lakes, which are dominated by minerogenic materials, would have sediments with high C:N ratio and low organic content. Eutrophic lakes, dominated by humus, would also have sediments with high C:N ratio, but here the organic content would be high. Pine and Hamilton have high C:N ratios, and also have significantly greater concentrations of organic matter. This would classify their sediments as more polyhumic, corresponding to their higher trophic levels (Table 5), (Hakanson 1983). The four other reservoirs do not have significant differences in organic content, thus their sediment humosity is similar.

Sulfur has both organic sources, incorporated in algae, macrophytes and particulate matter, and inorganic sources as metal sulfides, hydrogen sulfide, elemental sulfur and sulfate, forms which are dependent upon the oxygen and redox conditions at the sediment/water interface. King and Klug (1982) conclude "the sulfur content of surface profundal sediments is largely a reflection of the degree of bacterial mineralization of seston inputs," and that in one lake they studied, the bulk of sediment sulfur was organic. If most sulfur originates organically, it is reasonable that a positive correlation should exist between organic content and sediment sulfur. An interesting association was found between the concentration of sulfides and of organic acids in bottom sediments; Maeda and Kawai (1986) explain, "while in the mineralization process of organic matter under anaerobic conditions, organic acids are produced as the intermediates by heterotrophic bacteria." These associations may explain the significant direct correlations between OM and sulfur in Lakes Evans, McKelvey and Girard (Appendix A).

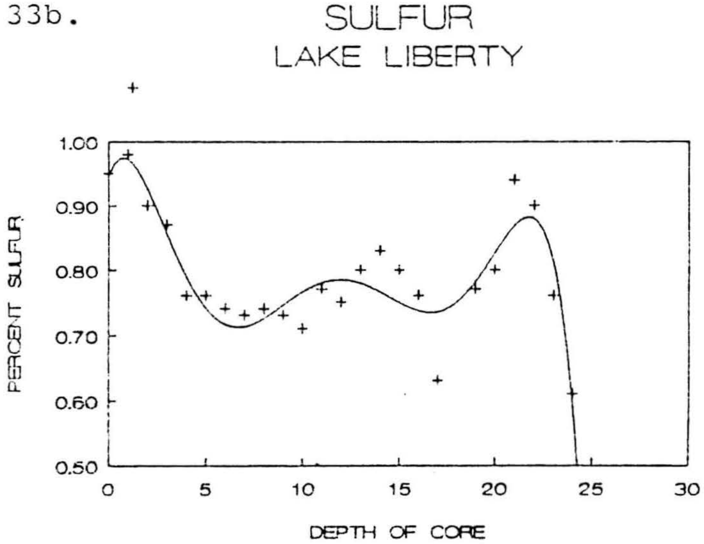
Soluble sulfate is connected to insoluble sulfide in anoxic sediments (Mitchell et al 1983). Thus, eutrophic lakes, having longer durations of hypolimnetic anoxia and greater organic concentrations should exhibit a higher percent of sediment sulfur. In these reservoirs, there is a net movement of sulfur to the sediments (Wetzel 1975). These sulfur movements have been related to the release of phosphorus from sediments, the nutrient primarily responsible for lake eutrophication (Nakajima et al. 1979). Lakes undergoing eutrophication would have more total sulfur in contemporary sediments. This is apparent in Lakes McKelvey and Girard. No such relationships of sulfur with depth occur in the four other reservoirs. However, periodic fluctuations are apparent in Lakes Hamilton (Figure 33a), Liberty (Figure 33b) and Evans (Figure 33c). These fluctuations may be related to the change in hypolimnetic oxygen conditions, seasonal variations in metal sulfide input and to periodic increases in

Figure 33a - 33c. Sixth Order Polynomial Curves of Percent Sediment Sulfur in Lakes Hamilton, Liberty and Evans.

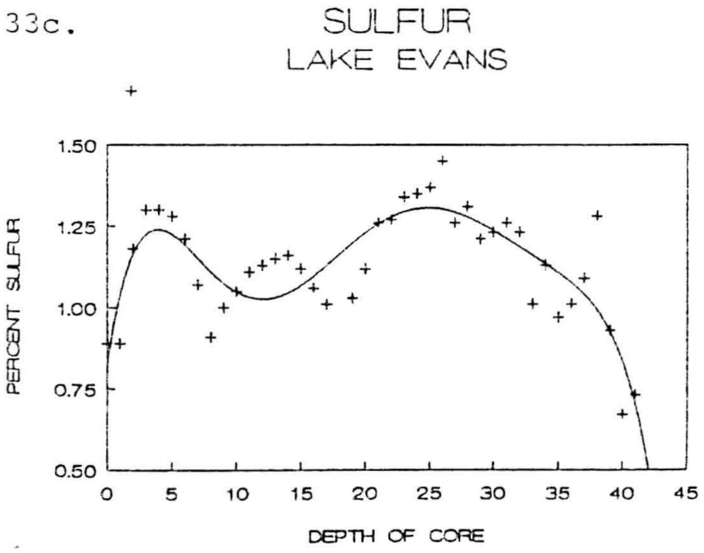
33a.


SULFUR
LAKE HAMILTON
PERCENT SULFUR
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0
5
10
15
20
25
30
35
40
45
DEPTH OF CORE

33b.


SULFUR
LAKE LIBERTY
PERCENT SULFUR
1.00
0.90
0.80
0.70
0.60
0.50
0
5
10
15
20
25
30
DEPTH OF CORE

33c.


SULFUR
LAKE EVANS
PERCENT SULFUR
1.50
1.25
1.00
0.75
0.50
0
5
10
15
20
25
30
35
40
45
DEPTH OF CORE

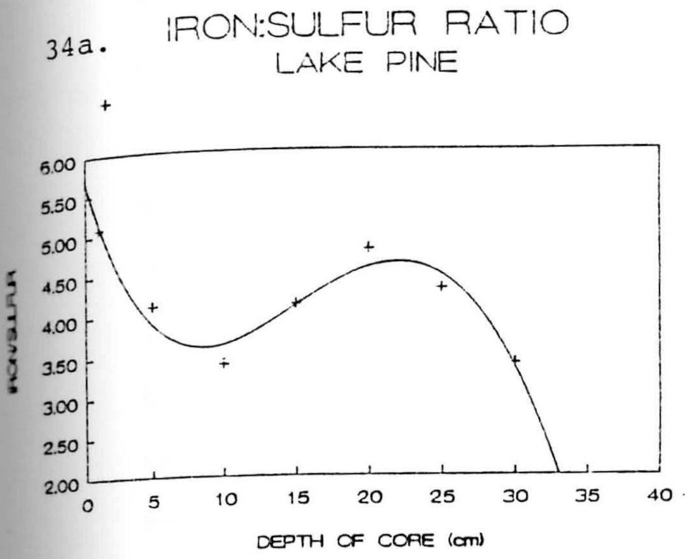
organic sedimentation, such as after an algal bloom. Significant direct linear relationships between FE:S and depth occur in McKelvey and Girard, suggesting more FeS deposition in recent years. Nonlinear relationships better describe the FE:S relationship in Lakes Pine, Evans, Hamilton and Liberty (Figures 34a, 34b, 34c, and 34d respectively). Pine Lake has two maxima, one at the surface and a second at 20 cm and is increasing towards recent sediments. Likewise, Lake Hamilton has a maximum at the surface and a second at 20 cm. Lake Liberty shows only one maximum increase, and Evans has two maxima, one at 10 cm and another at the bottom of the core. These patterns suggest periodic deposition of FeS in Pine, Evans, Hamilton and Liberty.

Hamilton Lake is greatly influenced by its watershed (WSA:LSA = 85), and nearly all parameters examined thus far are unusual. The high concentrations of sulfate Hamilton receives from strip-mined watershed creeks and from Yellow Creek may have some bearing on iron and sulfur deposition in the Lake.

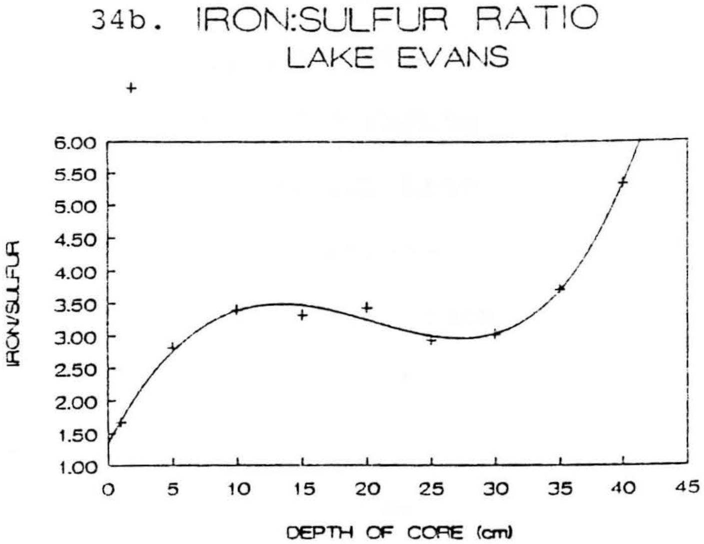
In addition to the supply from the watershed, the precipitation of iron and manganese is influenced by pH and redox conditions. Manganese is much more sensitive to the latter, and will be reduced at higher redox potential than iron (< 200 mV). Under intensive

Figures 34a - 34d. Polynomial Curves of Iron:Sulfur Ratio with Sediment Depth in Lakes Pine, Evans, Hamilton and Liberty.

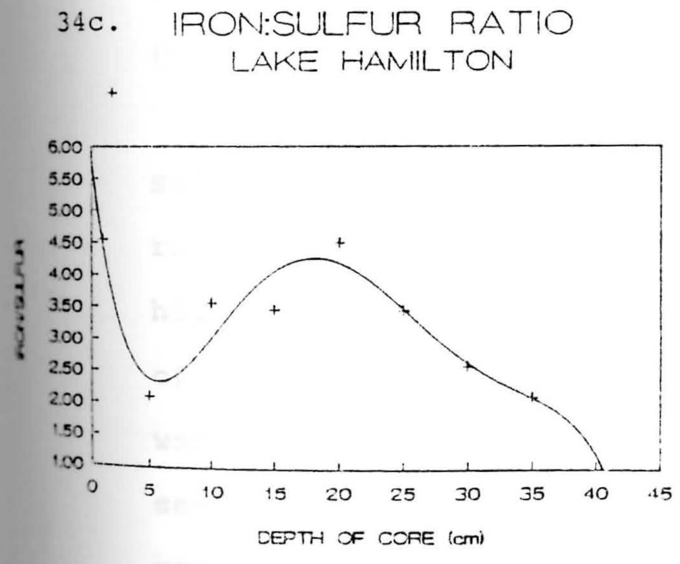
34a.



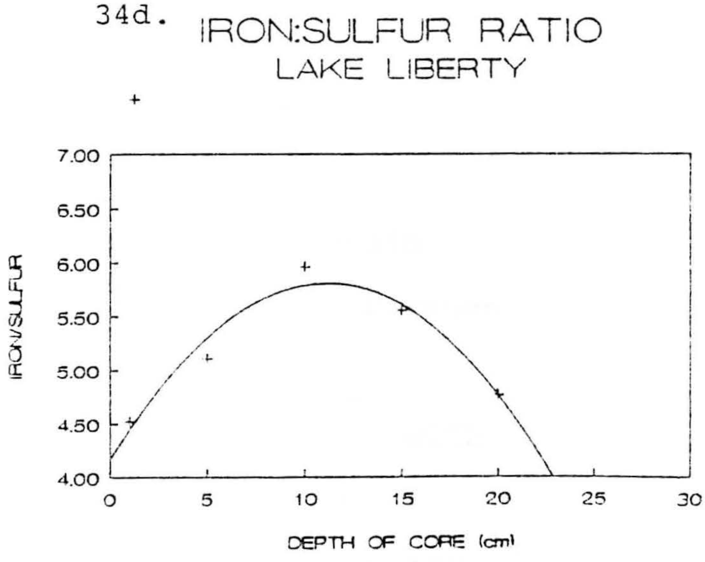
34b.



34c.



34d.



anoxia, manganese is continually released while iron is released and reprecipitated with sulfur. Presumably, sediments of eutrophic reservoirs should have greater Fe:Mn ratios with increasing depth due to increased anoxia. In five Wisconsin Lakes of varying trophic state, Weber Lake, the only oligotrophic lake, exhibited the lowest total Fe and Mn concentrations (Bortleson and Lee 1974). A relationship between lake trophic state and iron and manganese deposition in sediments is inferred. The OWS Lakes of highest trophic state, and those undergoing eutrophication, should have positive correlations between Fe:Mn and depth. This occurs, in order of ascending R^2 value, in Lakes McKelvey, Girard, Pine, Evans and Liberty (Table 10).

The calcium and magnesium concentrations in sediments are associated with hardness of the reservoir. Hamilton and Evans undoubtedly contain high concentrations of calcium in the sediment because of the hardness loading from the strip mined watershed. Decreases in carbonate sedimentation with sediment depth have been related to diminished productivity (Serruya 1971). Thus, increases in the calcium content as calcium carbonate in recent sediments are related to production, as formation of $CaCO_3$ is favored during photosynthesis. This may be particularly important in Lake Evans, a reservoir that has hard-water and stratifies less effectively than all reservoirs except Pine. Biogenically formed $CaCO_3$ in Evans has a lesser possibility of redissolving than it would in Lake Hamilton or Girard, reservoirs that have extended periods of anoxia in their hypolimnions (Table 4). If most of the calcium carbonate formed in Evans in the trophogenic zone reaches the sediments, increases in calcium in more contemporary sediments may be indicative of eutrophication in Lake Evans. In fact, significant increases in calcium occur in all reservoirs (Figure 26).

Magnesium has considerably less predictive value for hardness and production because it does not precipitate substantially. Calcium is a better indicator of productivity because it is associated with deeper areas of the lake (Clay and Wilhm 1979), and magnesium predominates near the lake shore and is associated with larger grain sizes (Gupta and Pant 1983). Total core magnesium may reflect the watershed input of Lake Hamilton, as magnesium content is significantly higher in Hamilton than in all other Reservoirs (Appendix A). One of the softest reservoirs, Pine, has significantly lower magnesium than all other reservoirs. Significant negative correlations of CA:MG with depth in Pine, McKelvey, Evans, Liberty and Girard are best explained by the differential solublity of calcium and magnesium under anaerobic conditions. This may also be related to increased reservoir production, favoring $CaCO_3$ deposition and magnesium dissolution.

CONCLUSIONS

An examination of the sediment profiles in six OWS Reservoirs has shown the interrelationships between lake trophic state and sediment structure. The eutrophic status and lake morphometry of Pine Lake relate well to the quality and character of the sediments. Of high organic, carbon and nitrogen content, the sediments reflect the shallowness of Pine, and the lake's potential to sustain a significant macrophyte population. The C:N ratio within the range of 12:1, coupled with increases in organic matter relative to aluminum, indicates sediment organic matter originating autochthonously. Such intensive autochthonous supplies of organic matter provide nutrients, recycled during decomposition, for increased trophic development. Neither carbon nor sulfur has increased significantly towards recent sediments, although metal sulfides are not expected to increase where sediment/water interfaces are relatively oxic. Nitrogen has increased with time, primarily in association with the increase in sediment organic matter. Total concentrations of iron and manganese are relatively low in Pine; however, the direct association between Fe:Mn and depth is evidence of its high trophic state. Sediments beneath the zone of bioturbation retain iron and release manganese in response to the low oxygen and low redox environment. $CaCO^3$ precipitation is favored in this shallow, eutrophic reservoir. Consequently, the Ca:Mg ratio is indirectly related to depth. The differential solubility of calcium and magnesium verifies an anoxic environment in buried sediments. It appears Pine Lake has the greatest potential for hypereutrophic advancement. It does not appear that this advancement has yet occurred with great intensity, primarily because the organic and carbon contents were highest and their change with depth lowest of all reservoirs. The Fe:S ratio is increasing towards recent sediments and may indicate oxic conditions in this shallow reservoir. These conditions suggest Pine Lake has been continuously productive, and has experienced little change in lake trophic state.

Evans Lake, of significantly lower trophic state index than Pine, has sediments of much lower organic content. Evans' low sediment organic content and its significant, but moderate increase towards recent sediments are mainly due to increased autochthonous supply and to decomposition of organic matter at depth. Unlike Hamilton, McKelvey, Girard, and Liberty, little area around Evans is forested and Evans also has the second smallest watershed:lake surface area ratio; thus, the organic matter supply from the watershed is negligible. The C:N ratio, coupled with the OM:Al ratio, classify Lake Evans sediments as autochthonous. Significant changes have occurred over time (towards recent sediments) in the concentration of carbon and nitrogen. Sulfur has not increased significantly; however, periodic depositional patterns are obvious. As with Pine, Fe:Mn ratios are significantly and directly correlated with depth; however, the Fe:Mn with depth slope (b = .546) is not nearly as great as in a more eutrophic reservoir, like Pine, where b = .953. Calcium and magnesium are considerably more concentrated in Evans than in all other reservoirs except Hamilton. Calcium has increased with respect to magnesium in recent sediments. Increased photosynthetic activity in the upper waters of Evans contributes to the formation of $CaCO^3$, and the weak stratification favors sedimentation. The differential solubility of calcium and magnesium under anoxic conditions in buried sediments explains the negative correlation between Ca:Mg and depth. In summary, Evans has shown signs of eutrophication, such as in the increasing concentrations of organic matter, carbon, nitrogen and calcium towards recent sediments. The low percentage of organic matter throughout the sediments shows that Evans does not have the same potential for eutrophication as Pine.

Hamilton has the most interesting sediment profile of all reservoirs. With a high watershed to lake surface area ratio (85), Hamilton Lake is significantly affected by the quality and conditions of the watershed. This is apparent in the organic, carbon and nitrogen content distributions in the sediments, decreasing dramatically from the surface (from about 0 - 15 cm), then leveling off, and even increasing in concentration in deeper sediments. Increases in sulfur are also obvious in recent sediments and concur with low iron:sulfur ratios. These patterns coincide with decreases in aluminum, suggesting that Lake Hamilton has recently experienced increased productivity, and that this increase is related to the conditions of the watershed. Aluminum decreasing towards surface sediments indicates lower inputs from the watershed. At mid core, the opposite patterns exist. There are decreases in organic matter, carbon, nitrogen and sulfur and increases in aluminum and iron (products of the watershed). This suggests periods of increased runoff, increased mining, construction or development in the watershed of Lake Hamilton. Towards the end of the core, sulfur increases, the Fe:S ratios are low and aluminum decreases. Slight increases are also apparent in both carbon and nitrogen, suggesting Hamilton had a peak in productivity early in its development. Hamilton does not have the typical Fe:Mn relationship with depth.

The linear regression curve of Fe:Mn may have been skewed by the high surface value of iron (7.58%) and by the high concentrations of manganese throughout the core. As in Evans, the calcium and magnesium concentrations are indicative of the water hardness and the strip mined watershed. Significantly high concentrations of both of these elements occur in the sediments, and the Ca:Mg ratio is inversely related to depth. In conclusion, the lowermost sediments of Hamilton show some increased productivity, while mid core sediments actually reflect decreasing productivity. The most recent sediments indicate an increase in production has occurred. All of these patterns appear to be related to the quantity and quality of the watershed input to Lake Hamilton. With substantial concentrations of organic matter in sediments, more nutrients are available for increased eutrophication.

Of all the Ohio Water Service Reservoirs, McKelvey is the least eutrophic, classified as mesotrophic by Carlson's Index (1977). McKelvey Lake is most influenced by its morphometry and to a lesser extent by its watershed. C:N ratios are less than 12:1, and a positive correlation of OM:AL with depth verifies the authochthonous origin of organic matter. However, the forestation along McKelvey's shore may affect the organic input to the sediments. Increases in carbon, nitrogen and sulfur are all significant towards recent sediments, suggesting McKelvey has undergone eutrophication. The increases in sulfur towards recent sediments correspond to the negative correlation of FE:S with depth. These data suggest increased durations of hypolimnion anoxia, permitting FeS precipitates. Indirect correlations between FE:MN with depth, where (b = .816), confirm the deposition of iron and the release of manganese in anoxic, buried sediments. The high intercept value of Fe:Mn (a = 71.8), for Lake McKelvey suggests an external supply of iron from the watershed. Calcium and magnesium are low in Lake McKelvey sediments, representing the softer water conditions of this reservoir. In conclusion, McKelvey displays signs of eutrophication, particularly evident in the increasing concentration of carbon, nitrogen, sulfur, organic matter and Ca:Mg towards surface sediment, and in the inverse correlations of Fe:S and Fe:Mn with depth. Increased eutrophication of McKelvey Lake will depend primarily on the nutrient loading, duration of stratification, and on the morphometry of the reservoir.

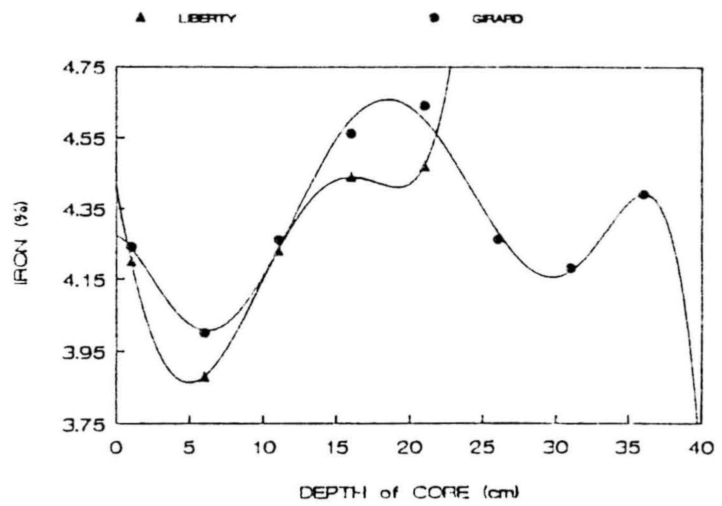
Liberty and Girard, of similar water quality and lake morphometry, also have similar in sediment profile structures. Organic matter in both lake sediments is regarded chiefly as autochthonous by C:N ratios, and by the negative correlations between OM:Al with depth. It is possible that the forested shorelines also make an organic contribution to lake sediments. Increases in carbon and nitrogen (more so in Liberty than in Girard) and increases in sulfur in Lake Girard show some increase in lake productivity has occurred. Girard Lake also shows an inverse relationship between Fe:S with depth. This is related to increased anoxia in the hypolimnion in recent years. The iron and manganese concentrations are similar in these reservoirs, and the iron profiles are very similar, particularly when a polonomial curve is applied to the data points (Figure 35). Fe:Mn ratios represent advanced trophic state, particularly in Liberty where Fe:Mn slope (b = 2.95), and to a lesser extent in Girard, where (b = 0.867). Calcium and magnesium again represent the softer water conditions of these reservoirs. Like iron, the magnesium distributions in Liberty and Girard are similar (Figure 36). The Ca:Mg is indirectly related to depth and supports the conclusion that both lakes have experienced increases in trophic state. Based on these analyses, Lakes Liberty and Girard show signs eutrophication, Girard more so than Liberty Lake. These increases are represented in sediments by significant increases in organic matter, carbon, nitrogen, sulfur (in Girard) and Ca:Mg towards recent sediments, and by the indirect associations between

Figure 35. Sixth Order Polynomial Curve of Percent Sediment Iron in Lakes Liberty and Girard.

Figure 36. Sixth Order Polynomial Curves of Percent Sediment Magnesium in Lakes Liberty and Girard.

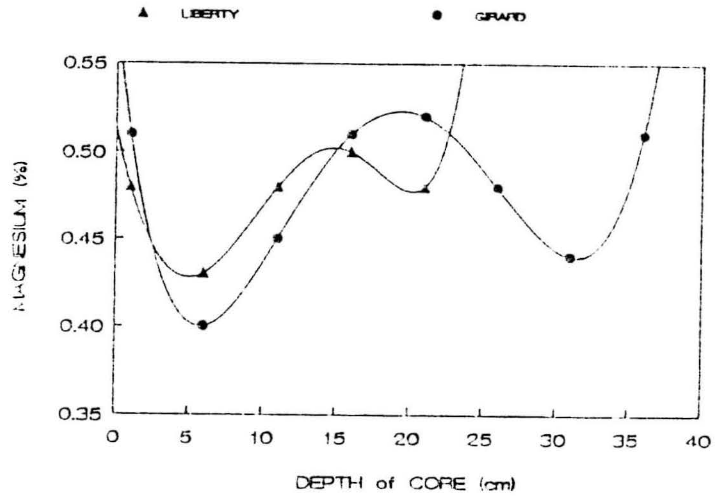
35.

IRON



36.

MAGNESIUM



Fe:S (in Girard) and of Fe:Mn with depth. Both lakes have the potential for increased eutrophication. Such advancements may depend on the nutrient input from the watershed, and on the recycling of existent nutrients in sediments.

SUMMARY

Sediments cores were collected from six Ohio Water Service Reservoirs (Pine, Evans, Hamilton, McKelvey, Liberty and Girard) to show the relationship between sediment chemitry and lake trophic state. The cores were sectioned into centimeter sections and analyzed for water and for total carbon, nitrogen and sulfur by gas chromatography. Every centimeter section of Lake Evans and every fifth centimeter section of all other reservoirs was analyzed for aluminum, iron, manganese, calcium and magnesium by inductively coupled plasma analysis. Every fifth centimeter section of all reservoirs was analyzed for weight loss on ignition as a measure of sediment organic matter. Total concentration of these elements, linear regression analysis and ratio analysis were incorporated to gain insight into past trophic conditions.

Analysis of Pine Lake sediments shows the reservoir has been in a continuous state of high productivity. This is related to the shallowness of the lake that permits substantial quantities of macrophyte development. Sediments are in constant contact with the entire water column, as it rarely stratifies. Thus nutrients are readily recycled from sediments and incorporated into algae and macrophytes. The high organic, carbon and nitrogen

concentrations and the indirect relationship of Fe:Mn ratio with depth reflect the advanced trophic state of Pine.

Lake Evans sediments represent the low trophic state of this reservoir. Significant increases towards recent sediments in the concentration of organic matter, carbon, nitrogen and calcium suggest eutrophication. Sulfur shows periodic depositions with depth. A direct association between Fe:Mn and depth represents an increase in productivity, but the slope of the regression curve indicates a lower trophic state than Pine. Evans does not have nearly the potential for eutrophication that Pine does; however, increased nutrient loading may contribute to the eutrophication of Lake Evans.

Hamilton Lake sediments represent the strong influence of the watershed on lake conditions. Recent increases in trophic state are apparent and may be related to decreases in runoff. The hardness of the water and the high inputs of metals from the watershed are represented by the significantly high concentrations of calcium, magnesium, iron and manganese in the sediments of Lake Hamilton. Hamilton has potential for increased eutrophication.

McKelvey Lake shows signs of eutrophication, although it is still considered a mesotrophic reservoir. Organic matter, sulfur, carbon, nitrogen, Fe:S, Fe:Mn, and Ca:Mg distributions in McKelvey all suggest an increasing lake trophic state. Though the sediments reflect the potential for increased eutrophication, the deepness of the reservoir, its nutrient loading and the degree of hypolimnion anoxia will primarily influence eutrophication.

Liberty Lake and Girard Lake are similar in water chemistry, trophic state, morphometry and sediment structure. Both reservoirs have significant increases in organics, carbon and nitrogen in recent sediments, and Girard has significant increases in sulfur. The latter suggest increasing hypolimnion anoxia in Girard. The distribution of the data points of iron and magnesium with depth in the cores of Liberty and Girard shows the similarity of the lakes. Both have potential for increased trophic development, Girard slightly more than Liberty, and these advances may be dependent upon nutrient loading and recycling of existent sediment organic matter.

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APPENDIX A

Table 1: Analysis of Varience (ANOVA) by Student-Newman-Deuls Procedure at the 0.050 Level for the Weighted Mean Values of Organic Matter, Aluminum, Carbon, Nitrogen, Sulfur, Iron, Manganese, Calcium and Magnesium in the Sediment Cores of Six Ohio Water Service Reservoirs. Means with the same letters are not significantly different at $p < 0.05$.

ORGANIC MATTER

MEAN	LAKE	SIGNIFICANT DIFFERENCE
8.4	EVANS	A
9.8	MCKELVEY	A B
10.4	LIBERTY	A B
10.5	GIRARD	A B
10.8	HAMILTON	B
15.3	PINE	C

ALUMNIMUM

MEAN	LAKE	SIGNIFICANT DIFFERENCE
2.5	PINE	A
2.7	MCKELVEY	A
2.8	EVANS	A
3.2	HAMILTON	B
3.3	GIRARD	B
3.3	LIBERTY	B

CARBON

MEAN	LAKE	SIGNIFICANT DIFFERENCE
2.62	EVANS	A
3.18	GIRARD	B
3.34	MCKELVEY	B
3.56	LIBERTY	C
3.59	HAMILTON	C
6.25	PINE	D

NITROGEN

NO TWO GROUPS ARE SIGNIFICANTLY DIFFERENT AT THE 0.050 LEVEL.

SULFUR

MEAN	LAKE	SIGNIFICANT DIFFERENCE
0.66	PINE	A
0.79	LIBERTY	B
0.91	GIRARD	C
0.99	MCKELVEY	C
1.13	EVANS	D
1.47	HAMILTON	E

TABLE 1 CONTINUED:

IRON

MEAN	LAKE	SIGNIFICANT DIFFERENCE
2.92	PINE	A
3.602	EVANS	B
4.262	LIBERTY	C
4.339	GIRARD	C
4.607	MCKELVEY	C
4.703	HAMILTON	C

MANGANESE

MEAN	LAKE	SIGNIFICANT DIFFERENCE
0.052	LIBERTY	A
0.054	PINE	A
0.056	MCKELVEY	A
0.058	GIRARD	A
0.199	EVANS	A B
0.223	HAMILTON	C

CALCIUM

MEAN	LAKE	SIGNIFICANT DIFFERENCE
0.34	MCKELVEY	A
0.36	GIRARD	A
0.38	LIBERTY	A
0.64	PINE	A B
0.91	EVANS	B
2.11	HAMILTON	C

MAGNESIUM

MEAN	LAKE	SIGNIFICANT DIFFERENCE
0.34	PINE	A
0.40	MCKELVEY	B
0.48	GIRARD	C
0.48	LIBERTY	C
0.49	EVANS	C
0.55	HAMILTON	D

Table 2. Correlation Analysis of Organic Matter with Depth, Carbon, Nitrogen and Sulfur in Six Ohio Water Service Reservoirs.

ORGANIC MATTER	DEPTH	CARBON	NITROGEN	SULFUR
PINE	.5444	.9986**	-.1589	.6756
EVANS	-.9678**	.9245**	.9297**	.7577*
HAMILTON	-.9628**	.8454*	.8795*	.3884
MCKELVEY	-.8939*	.9437**	.9692**	.8371*
LIBERTY	-.8799	.9627*	.9741*	.2607
GIRARD	-.9175**	.9647**	.9488**	.9730**

* = .01 ** = .001