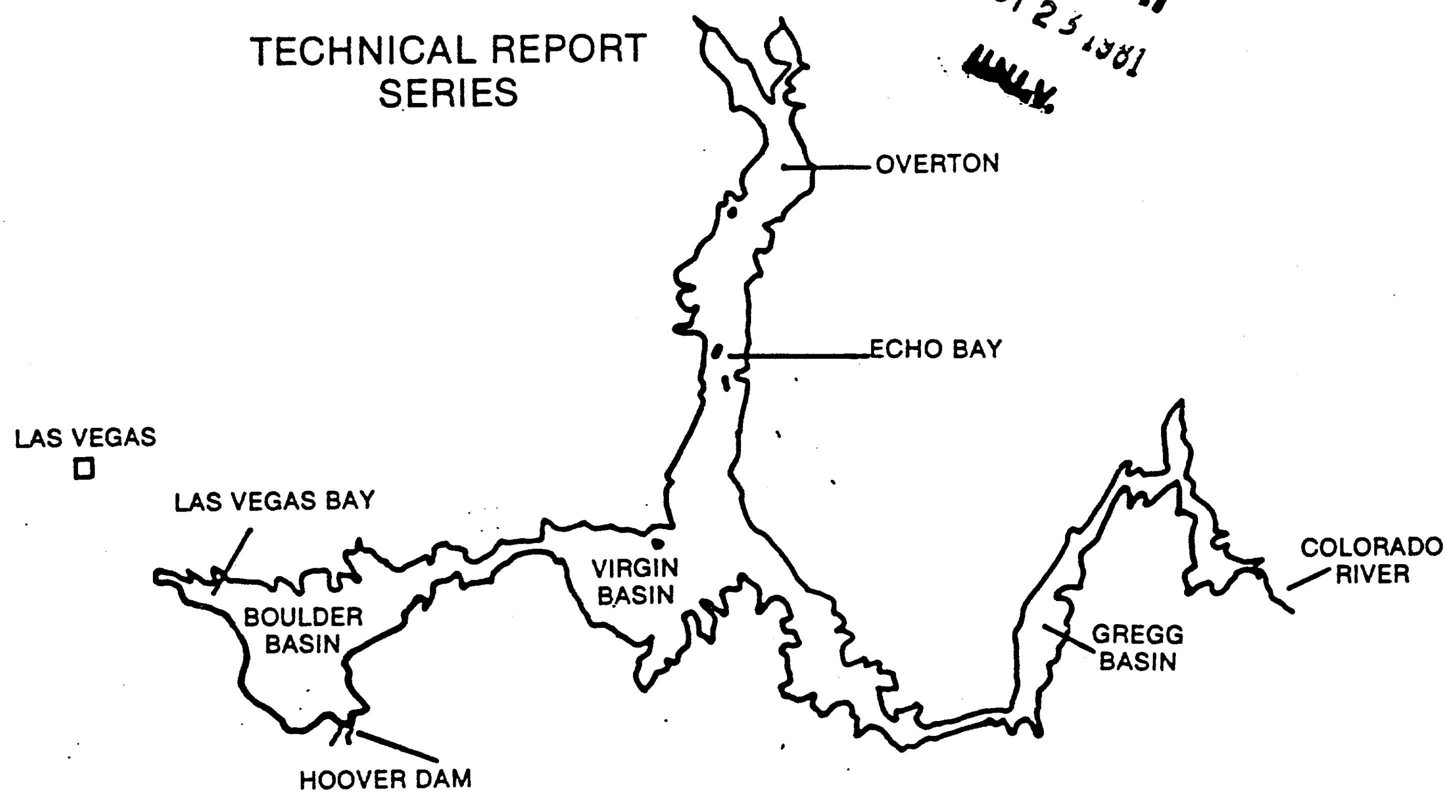
LAKE MEAD LIMNOLOGICAL RESEARCH CENTER

Chemical and Biological Structure of Lake Mead Sediments

Richard T. Prentki, Larry J. Paulson, and John R. Baker

Technical Report #6

TECHNICAL REPORT SERIES



DEPARTMENT OF BIOLOGICAL SCIENCES
UNIVERSITY OF NEVADA
LAS VEGAS

CHEMICAL AND BIOLOGICAL STRUCTURE OF LAKE MEAD SEDIMENTS

Richard T. Prentki, Larry J. Paulson and John R. Baker

Lake Mead Limnological Research Center
Department of Biological Sciences
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Technical Report No. 6

Final Report to
the Water and Power Resources Service
on Lake Mead Sediment Investigations
(Contract NO. 14-06-300-2218)
Larry J. Paulson: Principal Investigator

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EXECUTIVE SUMMARY

A) The largemouth bass *(Micropterus salmoides)* population in Lake Mead has undergone a serious decline since Glen Canyon Dam was constructed 450 km upstream in 1963.

B) State fisheries management agencies are concerned that the decline was caused by water level fluctuations and more severe drawdowns during the bass spawning season, when the operation of Hoover Dam was altered during the post-Lake Powell period.

C) The construction of Glen Canyon Dam and formation of Lake Powell in 1963 drastically altered the natural discharge and temperature cycles and decreased suspended sediment and nutrient loading in the Colorado River inflow to Lake Mead. Recent studies indicate that these changes in nutrient loading have caused a decrease in the fertility and productivity of Lake Mead, and this, in turn, could have contributed to the decline in the largemouth bass fishery.

D) The Water and Power Resources Service initiated a detailed investigation of the chemical and biological properties of Lake Mead sediments in order to: (i) resolve questions regarding historical changes in fertility and productivity of the reservoir, (ii) better assess the cause(s) for the decline in the largemouth bass fishery and (iii) predict future impacts associated with the proposed power modifications to Hoover Dam and operation of pump-storage hydroelectric units.

E) Sediment cores were collected with a Vibra-corer by a commercial, oceanographic drilling firm in non-delta areas of the inner Las Vegas Bay, middle Las Vegas Bay, Boulder Basin, Virgin Basin, Bonelli Bay and the Overton Arm. Sediments were dated by ^{137}Cs assays and analyzed for organic content, organic carbon, total nitrogen, total phosphorus, organic phosphorus, NaOH -extractable phosphorus, calcium carbonate, bulk density and water of hydration.

F) Individual-basin (Lower and Upper Basins) and reservoir-wide sedimentation rates were estimated for autochthonous and allochthonous organic carbon and calcium carbonate, nitrogen and phosphorus and dry weight during three periods ($\leq$1954, 1955-1962, $\geq$1963) of Lake Mead history. Autochthonous organic carbon sedimentation in the post-Lake Powell period was used with recent measurements of phytoplankton productivity to develop a regression model for predicting historic rates of productivity.

G) Reservoir-wide sedimentation rates and productivity in Lake Mead were relatively low during the period prior to 1954. Increased nutrient loading in years of high runoff during the 1955-1962 period caused a sharp increase in reservoir-wide sedimentation and productivity. The Upper Basin was especially productive during this period due to large inputs of suspended sediments and phosphorus. Phosphorus loading in the Colorado River decreased by over 90% in the post-Lake Powell period and caused a severe reduction in productivity in the Upper Basin. Increased phosphorus loading from the discharges of secondary-treated sewage effluents into Las Vegas Bay, combined with relatively high nitrogen loading from the Colorado River, elevated productivity in the Lower Basin. However, this was not sufficient to offset reductions that occurred in the Upper Basin, and reservoir-wide productivity decreased by 77% during the post-Lake Powell period and was equivalent to productivity in the period prior to 1954.

H) This decline in productivity was accompanied by a decrease in abundance of zooplankton, which comprise the principal food source for largemouth bass fry. Survival of bass fry appears to have decreased in the face of low zooplankton abundance, and this may be the cause for the historic decline of the largemouth bass fishery.

I) The fertility and productivity of Lake Mead could be improved to benefit the bass fishery if: (i) Hoover Dam were operated from a surface, rather than deep, discharge, (ii) pump-storage hydroelectric units were operated to recirculate nutrients in the reservoir, (iii) nutrient loading from Las Vegas Wash were maintained at current levels or allowed to increase with some type of diffuser system to minimize the point source problem in the inner Las Vegas Bay.

1.0 INTRODUCTION

Lake Mead was impounded in 1935 by the construction of Hoover Dam. The Colorado River was unregulated prior to then and therefore was subjected to extreme variations in flow and suspended sediment loads. Hoover Dam stabilized flows and reduced suspended sediment loads downstream (Dill 1944), but Lake Mead still received silt-laden inflows from the upper Colorado River Basin. The Colorado River contributed 97% of the suspended sediment inputs to Lake Mead, and up to 140×10^6 metric tons (MT) entered the reservoir in years of high runoff (Paulson and Baker 1981). Most of the sediments were deposited in the river channel and formed an extensive delta in upper Lake Mead (Gould 1960b; Lara and Sanders 1970). However, sediments were also transported into the Virgin Basin and Overton Arm by the overflow that occurred during spring runoff (Anderson and Pritchard 1951). The limnology of Lake Mead is thought to have been strongly influenced by this turbid overflow until Glen Canyon Dam was constructed 450 km upstream in 1963.

The construction of Glen Canyon Dam and formation of Lake Powell drastically altered the characteristics of the Colorado River inflow to Lake Mead (Paulson and Baker 1981). The operation of Glen Canyon Dam stabilized flows, reduced river temperatures and cut the suspended sediment loads by 80% (Paulson and Baker 1981). Nitrate loads decreased initially during 1963 and 1964, then increased through 1970, but have since decreased again to a lower steady state (Paulson 1981). Phosphorus loads were greatly reduced due to reductions in suspended sediment inputs (Paulson and Baker 1981). Lake Powell now retains 70% of the dissolved phosphorus (Gloss, Mayer and Kidd 1980) and 96% of the total phosphorus (Gloss, Reynolds, Mayer and Kidd 1981) inputs that once flowed into Lake Mead. The Colorado River still provides 85% of the inorganic nitrogen to Lake Mead, but Las Vegas Wash now contributes 60% of the phosphorus inputs (Baker and Paulson 1981).

Wastewater discharges from Las Vegas Wash into Las Vegas Bay increased steadily during the post-Lake Powell period. The morphometry and hydrodynamics of Lake Mead are such that the Las Vegas Wash inflow is confined to the Lower Basin where historically it has elevated phytoplankton productivity. However, high phosphorus loading and productivity have resulted in decreases in nitrate concentrations, and the Las Vegas Bay and parts of Boulder Basin have become nitrogen limited since 1972 (Paulson 1981). A unique situation has therefore developed in Lake Mead in that the Upper Basin has become more phosphorus limited and the Lower Basin more nitrogen limited since the formation of Lake Powell. Paulson and Baker (1981) theorized that these changes in nutrient loading and limitation must also have been accompanied by decreases in reservoir-wide productivity. This, in turn, could explain the apparent improvements in water quality of Las Vegas Bay that have occurred since 1968 (Paulson 1981).

Chlorophyll-a concentrations in the inner Las Vegas Bay have decreased considerably since the first measurements were made in 1968 (Hoffman, Tramutt and Heller 1971) and during the period of the Lake Mead Monitoring Program (Deacon and Tew 1973; Deacon 1975, 1976, 1977). Improvements in water quality of the bay have confounded efforts to establish water quality standards on effluent discharges and are contrary to predictions made in the early 1970 s that water quality would continue to degrade with increased phosphorus loading (EPA 1971). The trophic state of Lake Mead is generally low and below that predicted by phosphorus loading models (Vollenweider 1968). Rather, it appears that the reservoir has undergone a decline in productivity, and this may have had an adverse impact on the largemouth bass fishery (Paulson, Baker and Deacon 1979).

Lake Mead has historically supported an excellent largemouth bass fishery (Hoffman and Jonez 1973). However, the total catch has decreased from about 800,000 in 1963 to current levels of 105,000 (NDFG 1980), despite increased angler pressure over this period. The causes for this have not been conclusively established, but the decline could be related to changes in the fertility of Lake Mead since Lake Powell was formed (Paulson et al. 1979). The Arizona and Nevada Departments of Wildlife are concerned that the fishery may also have been adversely affected by more severe spring draw-downs of the reservoir with changes in the operation of Hoover Dam in the post-Lake Powell period. There is also concern that the proposed modification to upgrade Hoover Dam and installation of pump-storage hydroelectric units in Lake Mead could cause further declines in the fishery. The Water and Power Resources Service therefore initiated an investigation to: (i) better evaluate the historical decline of the largemouth bass fishery and (ii) predict future impacts of modifications to Hoover Dam and installation of pump-storage units in the reservoir.

It was therefore necessary to conduct a detailed analysis of the chemical and biological properties of Lake Mead sediments in order to resolve questions regarding historical reservoir productivity as related to changes in fertility caused by the formation of Lake Powell.

1.1 STUDY OBJECTIVES

The objectives of this investigation were to:

I. Analyze the chemical and biological composition of sediments from various locations and compare these data with historical nutrient data for Lake Mead.

II. Determine if the historical nutrient data reflect historical patterns in phytoplankton productivity of Lake Mead.

III. Compare the chemical and biological composition of sediments with our recent estimates of phytoplankton productivity (Paulson et al. 1980) at the same locations to determine if there have been any major changes in the spatial patterns of phytoplankton productivity in Lake Mead.

IV. Determine the age of sediment profiles in Lake Mead by ^{137}Cesium radioactive assays in order to date the sediment layers and compute average rates of organic matter sedimentation in the reservoir.

V. Integrate information from this study with that of previous limnological studies of Lake Mead and the Colorado River and determine future impacts of the various alternative modifications to Hoover Dam and pump-storage systems on the limnology of Lake Mead to year 2000.

VI. Recommend how the limnological status of Lake Mead can best be served in the framework of the proposed alternative power generation modifications.

VII. Discuss the results of this study in relation to the declining largemouth bass fishery in Lake Mead and try to answer the following questions: (i) is there a relationship between the declining bass fishery and nutrient loading and phytoplankton productivity? (ii) was impoundment of Lake Powell by Glen Canyon Dam the cause of the problem or was the fishery already declining, along with the productivity, prior to formation of Glen Canyon Dam? (iii) is the process of declining fishery unique to Lake Mead or a natural process that occurs in other reservoirs? and (iv) are there any design features that can be installed or modified in hydroelectric facilities to prevent a further decline in the fishery, or reverse the decline?

2.0 METHODS

2.1 Sampling Locations

The productivity and siltation patterns in Lake Mead are extremely heterogeneous due to the irregular reservoir morphometry and variable influence of nutrient loading from Las Vegas Wash and the Colorado River (Paulson et al. 1980). In order to insure that this heterogeneity was adequately represented in the survey, we collected sediment cores from several locations in the reservoir. The location of the drilling sites are shown in Fig. 1. Station locations were surveyed with an echo sounder, and the final sites were selected to provide a

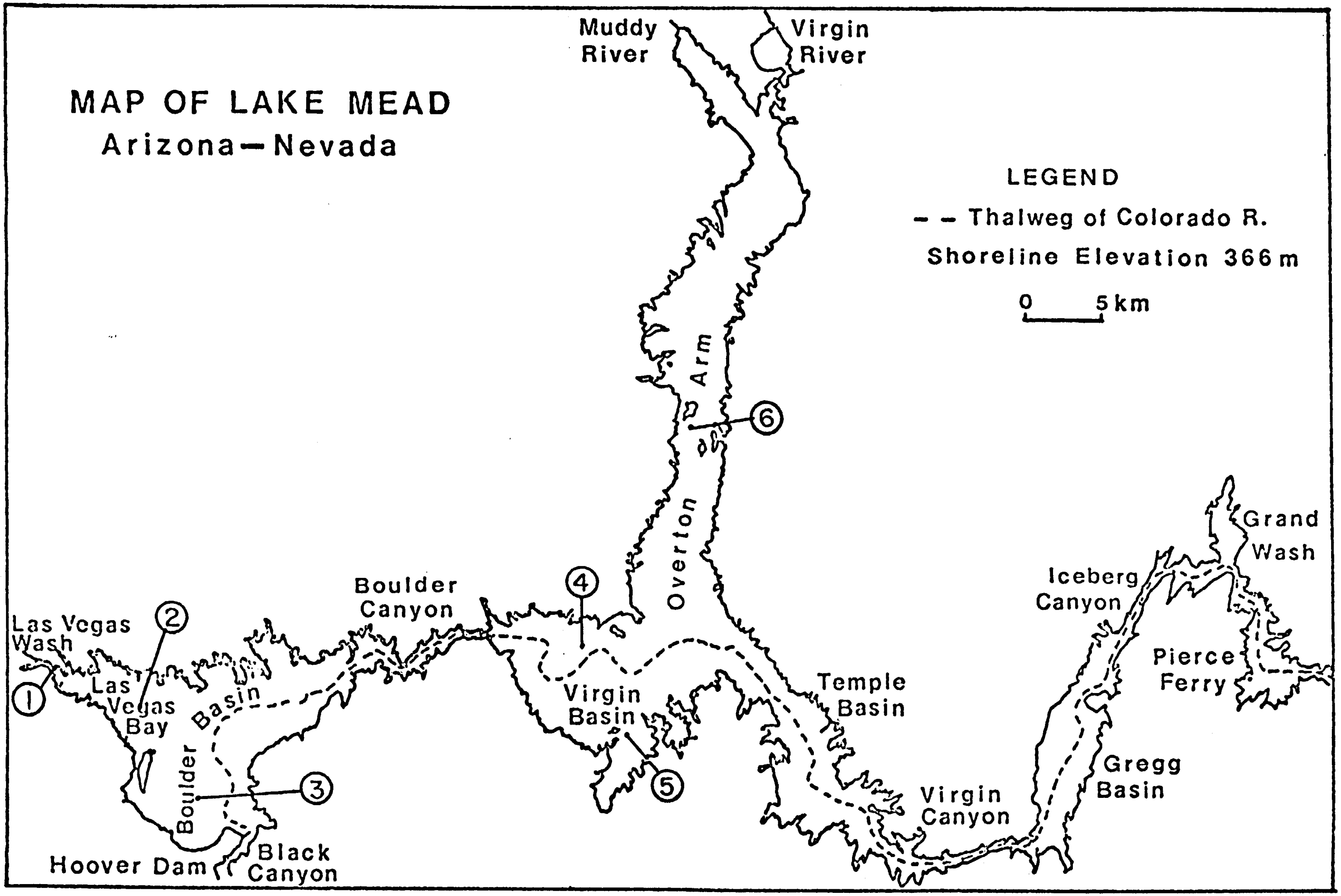

Figure 1. Map of Lake Mead.

reasonably flat, undisturbed sediment surface. We purposely placed the stations outside the old river channel to avoid possible sediment disturbances from the Colorado River density current. Station 1 was located in a small embayment of the inner Las Vegas Bay, near the point of the sewage inflow from Las Vegas Wash. The depth at this station was 14 m (Table 1). Two other stations were placed in the Lower Basin; one in the middle Las Vegas Bay (Station 2) at a depth of 60 m and one in Boulder Basin (Station 3) at a depth of 90 m. Two stations were also placed off the old river channel in the Upper Basin. The Virgin Basin (4) and Bonelli Bay (5) stations were located at depths of 90-100 m. The sixth station was located in the Overton Arm, near Echo Bay, in 75 m of water.

2.2 Sediment Coring

The actual sediment coring was conducted by a commercial, oceanographic drilling company (Ocean/Seismic/Survey Inc., Norwood, New Jersey). This company specializes in deep coring of lakes and reservoirs and has had extensive experience in coring sediments for chemical and biological analyses. Ocean/Seismic/Survey Inc. used a specially-designed, hydraulically-operated vibra-corer to obtain undisturbed sediment cores from Lake Mead. The vibra-corer utilizes two contra-rotating weights to produce an axial vibratory movement of the core barrel. The power head was operated hydraulically from a diesel-driven power pack at the surface. The core barrel was 20 ft. (6.1 m) in length and the effective diameter was 3.4 in. (8.6 cm). Lexan liners were inserted into the core barrel

Table 1. Physical characteristics at sediment coring stations in Lake Mead.

Station	Water Depth m (ft)	Number of cores*	Date of submersion	Pre-reservoir material
1**	14 (46)	8	6/38	gravel
2	60 (197)	11 (8)	7/35	gravel
3	90 (300)	6 (4)	7/35	gravel
4	85-95 (280-310)	10	7/35	soil
5	102 (335)	11	7/35	sand
6***	75 (246)	8	7/35	sand

* total number of cores, number of cores pooled for physical and chemical analyses given in parentheses

** this station was dry in low water years

*** fine sediment was not deposited above sand until 3/1940 which was fitted with a "flap-valve" type core catcher. The power head and core barrel were supported in a tripod A-frame and lowered to the reservoir floor from a 12 ft. (3.7 m) x 30 ft. (9.1 m) barge. The corer was allowed to rest on the bottom during the coring. Coring rates were monitored with a penetration recorder on the barge. Coring was terminated when coring rates indicated that contact had been made with the old reservoir floor. The corer was retrieved with a diesel-operated winch mounted on the barge. The core liners were removed and inspected for signs of marbling or other disturbance. Undisturbed cores were immediately capped and stored upright on the barge. They were transferred to a walk-in freezer on the UNLV campus within 10 hours of collection. Six to eleven cores were collected from each station. The coring was conducted over a ten-day period during mid-October, 1979.

2.3 Sediment Analyses

2.3.1 Physical Analyses

Sediment bulk density (g dry wt. cm^{-3}) was calculated by measuring the volume of the wet sediment sample (cm^3), drying the sample at 125°C, and weighing. The weight (g) is then divided by the wet sediment volume (cm^3).

2.3.2 Chemical Analyses

A detailed description of procedures used for chemical analyses of sediments was presented in Kellar, Paulson and Paulson (1980) and therefore will only be discussed briefly in this report. Organic carbon and nitrogen contents of sediment were determined with an elemental analyzer (Perkin Elmer Model

240B). Sediments were first treated with 1 N HCl and heated at 105°C to drive off residual carbonates (Froelich 1980). Duplicate, 20-60 mg subsamples were then combusted in the elemental analyzer at 950°C. Total phosphorus digestions were made by combusting sediments at 550°C for a 1.5 hour period. Inorganic phosphorus was then extracted from the residue with 1 N H_2SO_4. The phosphorus extract was subsequently analyzed with methods of John (1970). NaOH-extractable phosphorus (NaOH-IP) was measured on wet sediment samples using methods of Williams et al. (1980).

Sediment organic content, water of hydration and carbonate were determined as follows: sediments were combusted at 550°C for 1.5 hrs., allowed to cool and then weighed. The residue was then wetted with distilled water and dried at 105°C. Organic content and water of hydration were calculated with equations (2) and (3).

$$\text{Organic content (\%)} = \frac{(\text{dry wt.}_{105°C} - \text{combusted wt.}_{550°C})\ 100}{\text{dry wt.}_{105°C}} \tag{2}$$

and

$$\text{Water of hydration (\%)} = \frac{(\text{re-wetted wt.}_{550°C} - \text{combusted wt.}_{550°C})\ 100}{\text{dry wt.}_{105°C}} \tag{3}$$

Sediment carbonates were determined by combustion at 950°C for 3 hrs. (Dean 1974; Wetzel and Manny 1978), and calculated by equation (4) : (4)

$$CaCO_3\text{-equivalent } (\%) = \frac{(\% \text{ wt. loss}_{950°C} - (\% \text{ organic wt.} + \% \text{ water hydration})) \times 100.07}{44}$$

Sediment pore waters were also analyzed for nutrients in 2.5 cm-sections of cores collected in Boulder Basin. Sediments were placed in a sediment press (Robbins and Gustunis 1976), and water was extruded under a pressure of 80 PSI with 99.999% helium gas. The pore waters were analyzed for ammonia, nitrate and phosphate with methods described in Kellar et al. (1980).

2.3.3. Cesium Analysis

The ^{137}Cesium counting was performed by Controls for Environmental Pollution Inc. (CEP), a commerical laboratory in Santa Fe, New Mexico. A few samples were also counted by the U.S. Environmental Protection Agency, Office of Radiation Programs, Las Vegas, Nevada, and by the Southern Plains Watershed and Water Quality Laboratory, Durant, Oklahoma, for quality assurance purposes.

3.0 RESULTS

3.1 Sediment Core Dating

^{137}Cesium radioactivity from atmospheric bomb fallout has been widely used to date reservoir sediments (McHenry et al. 1976, 1980; Ritchie et al. 1973). ^{137}Cs is strongly adsorbed by fine soil particles, and, if eroded from the watershed, will be deposited in reservoir sediments. The ^{137}Cs activity of sediment profiles will therefore reflect the intensity of ^{137}Cs fallout from atmospheric nuclear testing (McHenry et al. 1976). The first occurrence of ^{137}Cs activity in the bottom of a sediment profile indicates that layer was deposited after the first testing in 1954. American bomb testing in the period from 1957-1959 resulted in increased deposition of ^{137}Cs, but the maximum peaks occurred during 1962-1964 with the atmospheric nuclear testing conducted by the Russians. The Chinese and French have since conducted tests, but ^{137}Cs fallout has decreased steadily since 1963 (McHenry et al. 1976). The historical patterns in bomb fallout are ideal for our purposes because the peak fallout occurred during the period when Lake Powell was formed, thus providing an excellent sediment marker in Lake Mead. Sediments deposited prior to 1954 should have no ^{137}Cs activity, providing a secondary marker in the reservoir.

The ^{137}Cs concentrations in Lake Mead sediments were generally low and differed somewhat between the Upper and Lower Basins (Fig. 2). The slightly higher activity in Upper Basin sediments apparently reflects greater inputs and deposition of suspended sediments from the Colorado River. The bottom sediment layers where ^{137}Cs activity first appeared were evident in all cores from deep stations and were assigned the 1955 marker. The ^{137}Cs profiles in middle Las Vegas Bay, Boulder Basin, Virgin Basin and the Overton Arm generally followed the classic pattern that has been found in other reservoirs. ^{137}Cs activity increased after 1955, reached a peak and then decreased again in

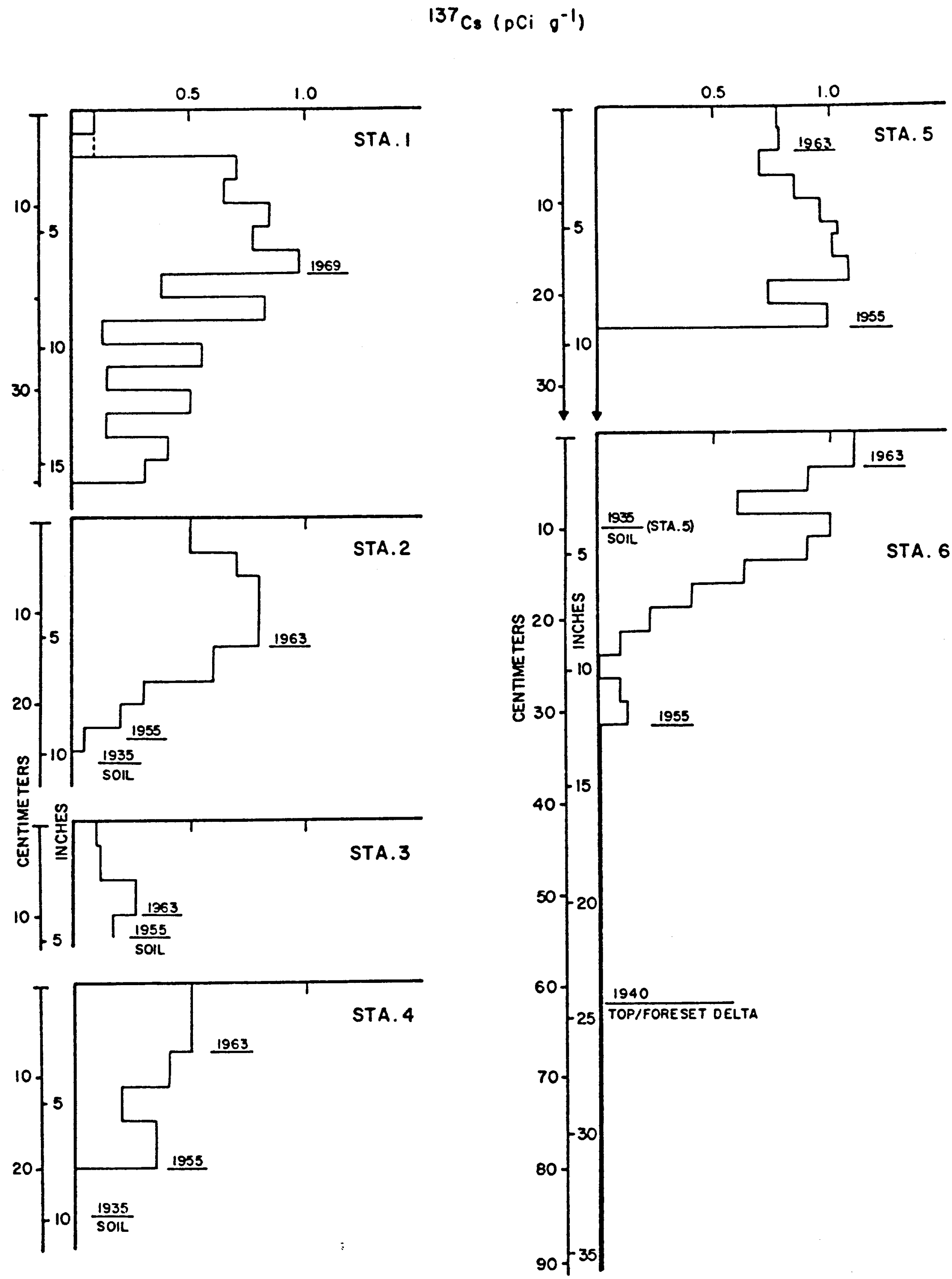

Figure 2. ^{137}Cesium profiles of Lake Mead sediments and dates of various sediment layers.

the recent sediments. The peak activity layer in these cores was assigned the 1963 marker.

Data collected in Bonelli Bay and the inner Las Vegas Bay were, however, more difficult to interpret. In Bonelli Bay, peak ^{137}Cs activity occurred at 17-19 cm sediment depth, far below that found at the other Upper Basin Stations. In Virgin Basin, the peak activity occurred at 8-9 cm, and in the Overton Arm, it occurred at 3-4 cm sediment depth. In order to resolve the obvious discrepancies with other Upper Basin cores, we assigned the 1963 marker to the secondary ^{137}Cs maximum that occurred 3-4 cm from the sediment surface in Bonelli Bay. This is consistent with changes in other chemical parameters of this layer and reasonable in terms of known reductions in suspended sediment loading and siltation in the Upper Basin after 1963.

The ^{137}Cs profile in the inner Las Vegas Bay was also difficult to interpret because activity was found in gravel layers deep in the core. This station was shallow and in the past has been subject to water level fluctuations and periodic desiccation. This area was dry until 1938, very shallow (1-2 cm) during 1947 and from 1951-1957, and then dry again from 1964-1969. Because of possible reworking of sediments during dry or low water years, we were unable to use the disappearance of ^{137}Cs activity to indicate the 1955 marker. Moreover, the peak in ^{137}Cs activity must reflect 1969 rather than 1963, because this area was dry over the period from 1963-1969.

Apart from some difficulties in interpreting ^{137}Cs profiles in Bonelli Bay and the inner Las Vegas Bay, the ^{137}Cs data provide reliable markers of the 1955 and 1963 sediment layers. It is also possible to establish a third marker, the old reservoir floor of 1935, by obvious discontinuities between pre-reservoir soils and post-reservoir sediments. Post-reservoir sediments were underlain by gravel in the middle Las Vegas Bay, gravel and soft rock in Boulder Basin, unconsolidated desert soils in Virgin Basin and sand in Bonelli Bay. These layers were distinguished from reservoir sediments by marked increases in sediment bulk density (Fig. 3). A similar discontinuity existed in the Overton Arm, but the sediment depth here was also influenced by delta deposits from the Virgin River as the reservoir was filling. Gould (1960a) reported that in 1935 and 1936, the mouth of the Virgin River was located at Bitter Wash, a few kilometers upstream from our station. He was, therefore, unable to distinguish between sand deposited by the river and that in the pre-reservoir deposits. Clay sediments were deposited once lake levels increased and caused the point of river inflow to recede up the Overton Arm. This occurred in 1940 and was reflected by a marked decrease in sediment bulk density above 25 cm (Fig. 3). Layers below that represent siltation from the Virgin River inflows during 1935-1940.

3.2 Sediment Chemical Structure

3.2.1. Nutrient and Organic Matter Profiles

The nitrogen content of Lake Mead sediments was very low compared to values given for other lakes and reservoirs (Table 2) and ranged from 0.03% of sediment dry weight in old ($\leq$1955) reservoir sediments to 0.2% in recent ($\geq$1963) sediments (Fig.

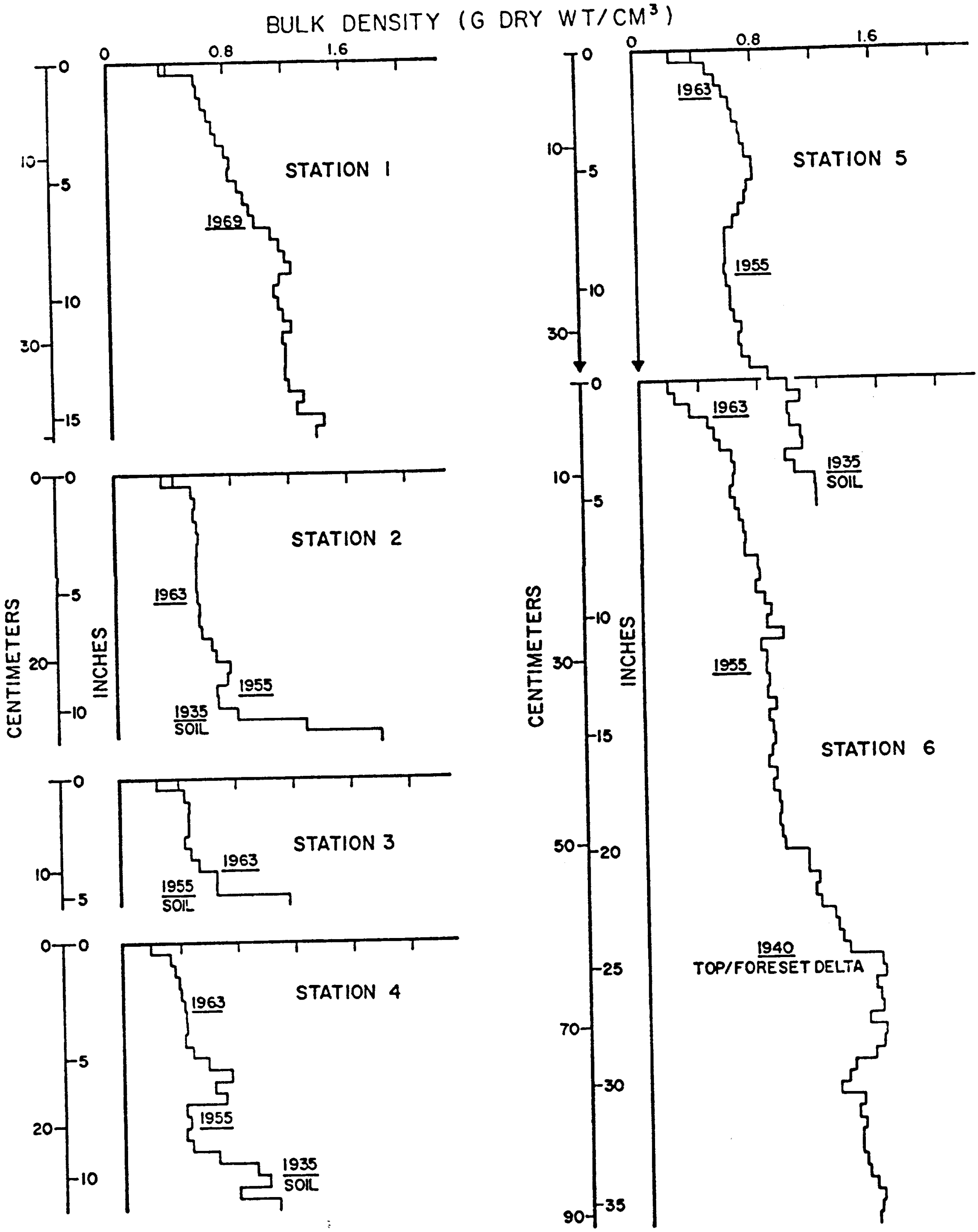

Figure 3. Bulk density profiles of Lake Mead sediments.

Table 2. Chemical characteristics of recent lake and reservoir sediments. Values given are percent of sediment dry weight.

LAKE/RESERVOIR	TROPHIC STATUS	ORGANIC MATTER	ORGANIC CARBON	NITROGEN	PHOSPHORUS		REFERENCES
Shagawa Lake, Minnesota	Eutrophic	25.3	12.0[1]	-	-		Gorham and Sanger (1976)
10 lakes in NE Minnesota	Oligotrophic-mesotrophic	25.7	-		-		" " " "
						C:N:P[2]	
Lake George, Uganda	Eutrophic	60.0	35.0	2.73	0.214	164:12.8:1	Viner (1977)
Tuttle Creek Reservoir, Kansas		1.34-5.09	-	-	-		Schwartz and Marzolf (1972)
Sugarloaf Lake, Michigan		16.0-50.0	-	-	-		Beatty and Hooper (1958)
Barataria Bay, Louisiana		0.0-7.6	-	-	-	C:N:P[3]	Krumbein and Caldwell (1939)
Lake Huron (Canada/U.S.)		-	3.56-4.65[3]	0.44-0.55[3]	0.10-0.20	34:4.1:1	Kemp and Thomas (1976)
Lake Erie (Canada/U.S.)		-	2.30-5.24	0.25-0.68	0.09-0.19	26:3.2:1	" " " "
Lake Ontario (Canada/U.S.)		-	3.23-6.28	0.29-0.80	0.14-0.22	31:4.5:1	" " " "
Long Lake, Washington	Eutrophic	8.5-15.5	-	0.18-0.65	0.12-0.44		Thomas and Soltero (1977)
Lake McIlwaine, Rhodesia	Eutrophic	-	0.5-12.8	0.04-1.04	0.02-0.425		Nduku (1976)
Lake Mendota, Wisconsin	Eutrophic					C:P	
Core-89		-	8.41	0.65-1.0	0.16	52.6	Bortelson and Lee (1972)
Core-86		-	7.74	-	0.15	51.6	" " " "
Core-84		-	9.23	-	0.12	76.9	" " " "
Lake Taupo, New Zealand	Oligotrophic	-	-	-	0.06-0.22		Rawlence and Reay (1976)
Poland Lakes (17)	Eutrophic (14)	18.2-39.4	-	-	0.11-0.34		Kufel (1976)
	Mesotrophic (3)	17.7-26.2	-	-	0.13		" "
Blelham Tarn, England		-				C:N:P	Pennington et al. (1976)
Core A			1.08	0.093	0.029	37:3.2:1	
Core B			1.17	0.096	0.031	38:3.1:1	
Core C			1.00	0.082	0.026	38:3.0:1	
Core D			1.06	0.102	0.027	30:2.9:1	
Core E			1.20	0.094	0.035	34:2.7:1	
Castle Lake, California	Oligo-Mesotrophic	-	12.7	0.95	-		Kimmel and Goldman (1977)
Lake Texoma, Oklahoma		-	0.1-2.1				Hyne (1978)
Fort Gibson Reservoir, Oklahoma		-	0.1-2.5				"
Lake Tahoe, California-Nevada	Ultraoligotrophic	-	<1.0-6.0				"
Lake Mead, Arizona-Nevada	Mesotrophic	-	0.3-1.7	0.03-0.2	0.03-0.10		This Study

1 Computed by dividing organic matter by 2.1 (Gorham and Sanger 1976)

2 Data given are means of values for 0-40 cm sediment depth.

3 Data are averages of values for surficial (0- ≤ 2 cm) sediments.

4). The nitrogen content of surficial sediments was higher in the Lower Basin than Upper Basin stations, but the spatial differences across the reservoir were still relatively small. There was a general pattern of decreasing nitrogen content with increasing sediment depth. This was especially evident in the inner Las Vegas Bay where the nitrogen content of sediments has increased steadily since 1969. It was also evident in the middle Las Vegas Bay until 1963, but thereafter nitrogen did not vary appreciably, as was also the case in Boulder Basin. In Virgin Basin, Bonelli Bay and the Overton Arm, sediment nitrogen content decreased after 1955 but then increased again or remained stable during subsequent years.

Organic carbon in Lake Mead sediments was also very low, approximately one-fourth the values reported for other lake sediments (Table 2). Values ranged from 0.3% of sediment dry weight in early sediments to 1.7% in recent sediments (Fig. 5). The same general trends that occurred in nitrogen profiles also existed for organic carbon profiles. However, there were some notable differences that were reflected in the organic carbon:nitrogen ratios (C/N) (Fig. 6). The C/N ratios of recent sediments in the Lower Basin were usually lower than those in the Upper Basin. These differences were largely due to higher sediment nitrogen content in the Lower Basin. Increased nitrogen content of the inner Las Vegas Bay sediments also caused a decrease in the C/N ratios after 1969. It is not known why the Lower Basin sediments are higher in nitrogen, but this may be due to higher productivity in the basin since 1963.

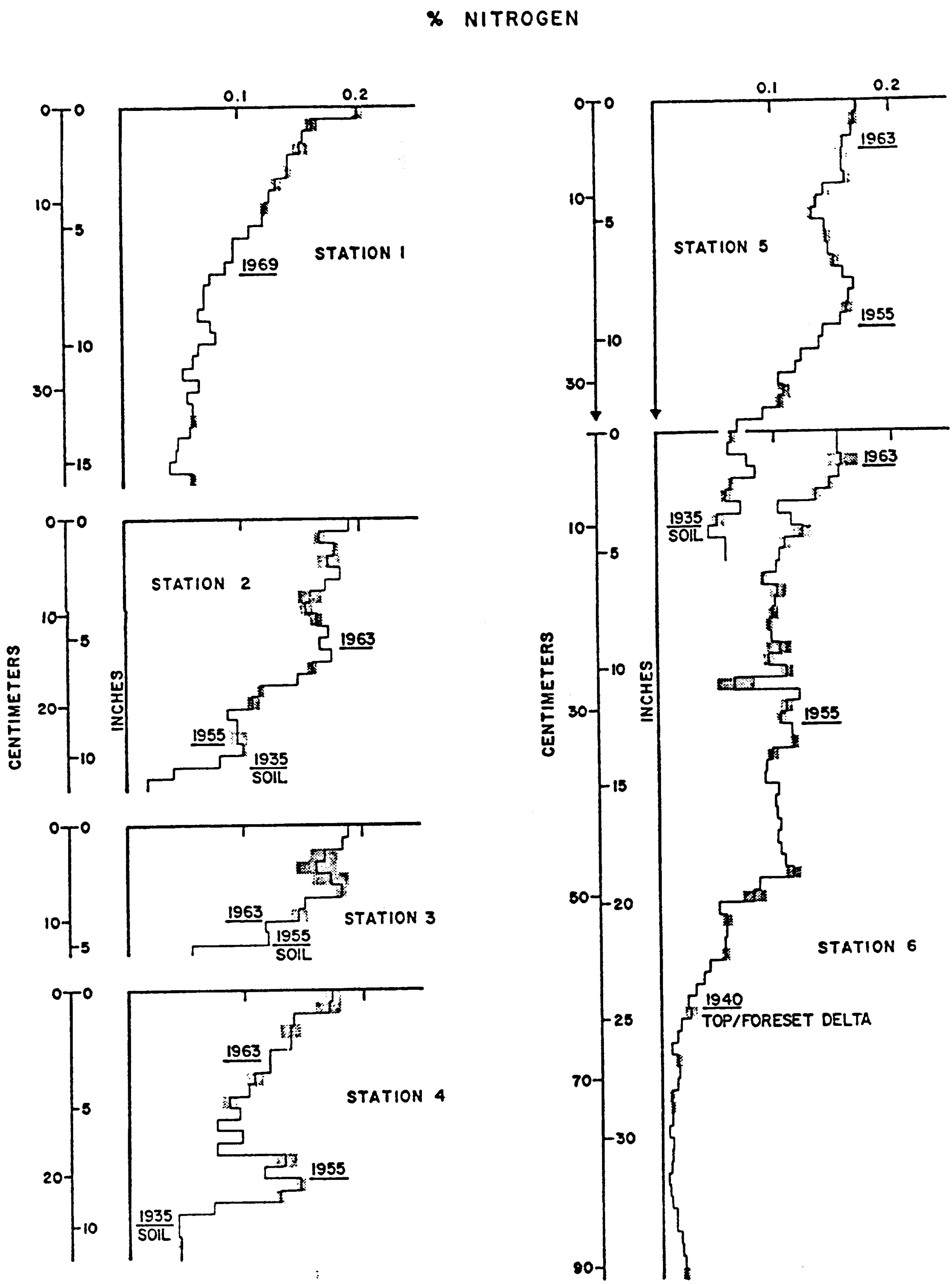

Figure 4. Nitrogen content of Lake Mead sediments (error bars shown by shading).

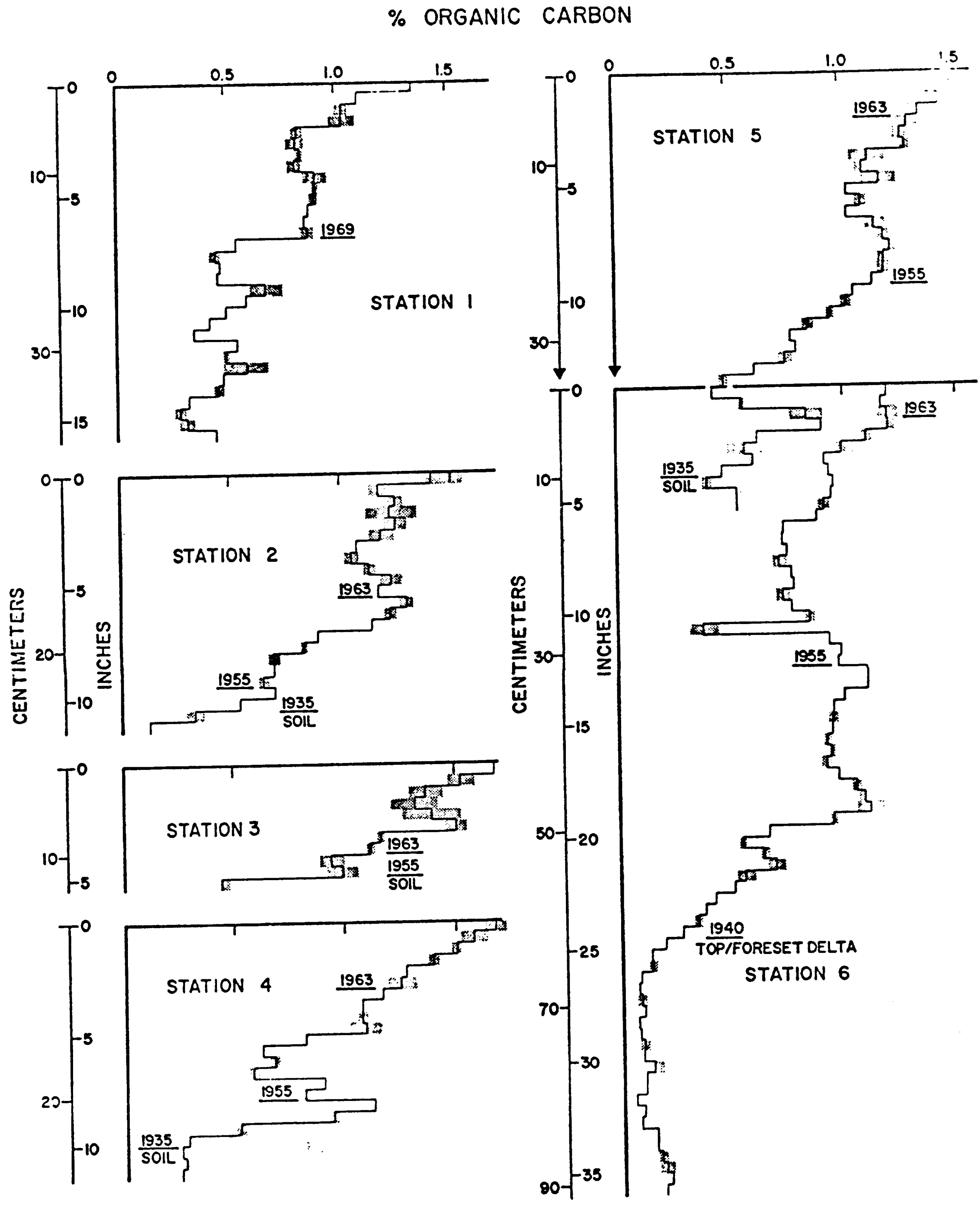

Figure 5. Organic carbon content of Lake Mead sediments (error bars shown by shading).

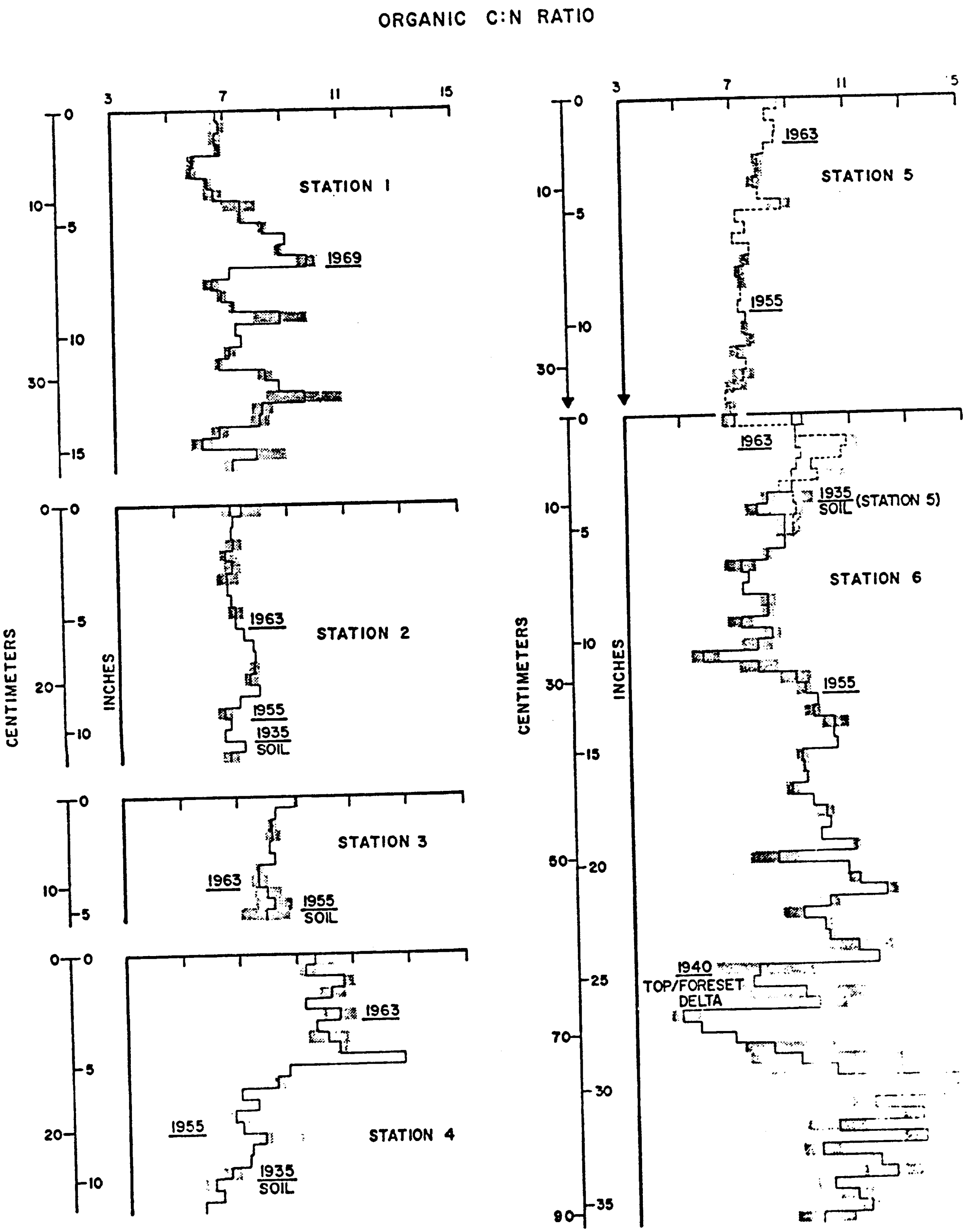

Figure 6. Organic carbon:organic nitrogen ratios of Lake Mead sediments (error bars shown by shading).

The organic matter content of Lake Mead sediments (Fig. 7) was also low, but still higher than what would be expected on the basis of organic carbon concentrations. The overall average organic matter content to organic carbon ratio was twice that reported for other lake sediments (Table 2). Regression of organic content on organic carbon gave an R^2 value of only 0.64. Organic matter content must therefore measure something in addition to organic carbon in Lake Mead sediments. Organic content measurements were corrected for losses of water of hydration (Fig. 8), and this therefore could not account for the discrepancy. Organic carbon measurements made with the elemental analyzer were corrected for carbonate loss, but organic matter determinations were not. Combustion of acidified and unacidified sediments in a muffle furnace at 550°C revealed that carbonate losses caused a 20% overestimate of our organic matter measurements (Kellar et al. 1980). Although appreciable, carbonate losses still cannot account for the discrepancy between organic carbon and organic matter content of Lake Mead sediments. We suspect that this may be caused by sulfate reduction that occurs in the sediments and results in production of some volatile organic sulfur compounds (Nriagu 1968) that are lost in combustion for organic matter content, but are not reflected in organic carbon measurements.

Calcium carbonate measurements were made in our study in order to correct organic carbon determinations and evaluate historical patterns of carbonate precipitation in the reservoir (Fig. 9). The most notable feature of the calcium carbonate profiles is the marked enrichment in Lower Basin sediments.

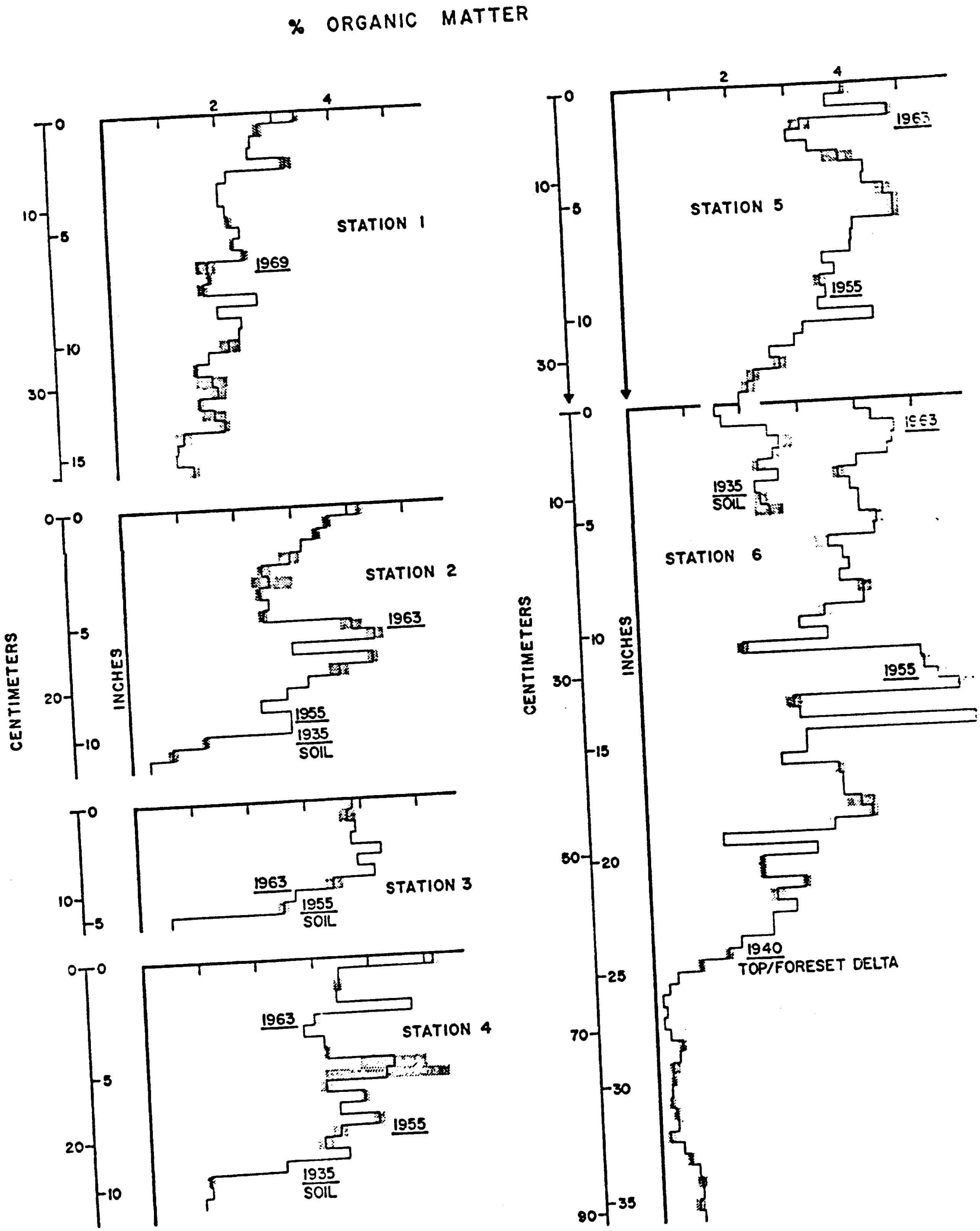

Figure 7. Organic matter content of Lake Mead sediments (error bars shown by shading).

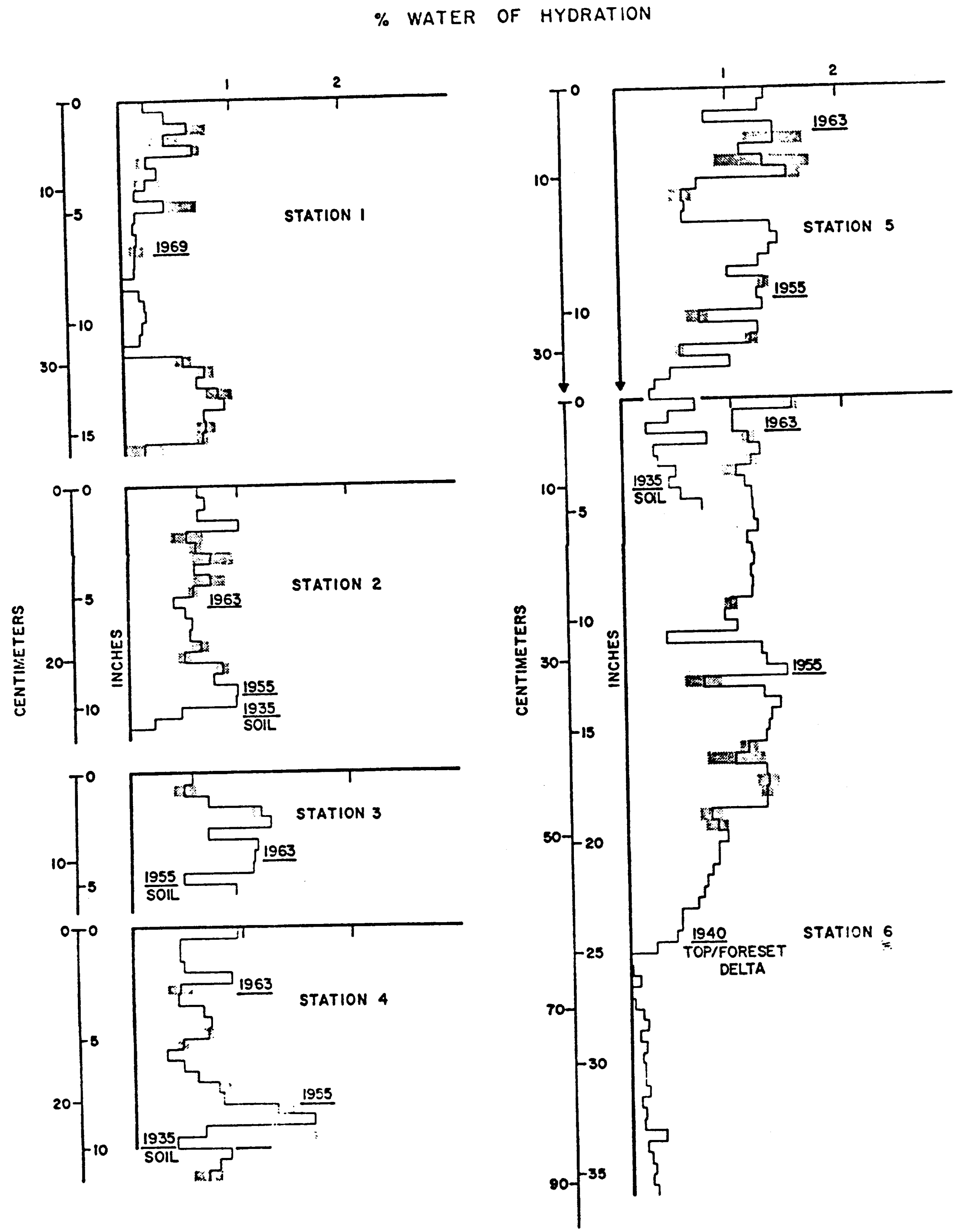

Figure 8. Water of hydration profiles of Lake Mead sediments (error bars shown by shading).

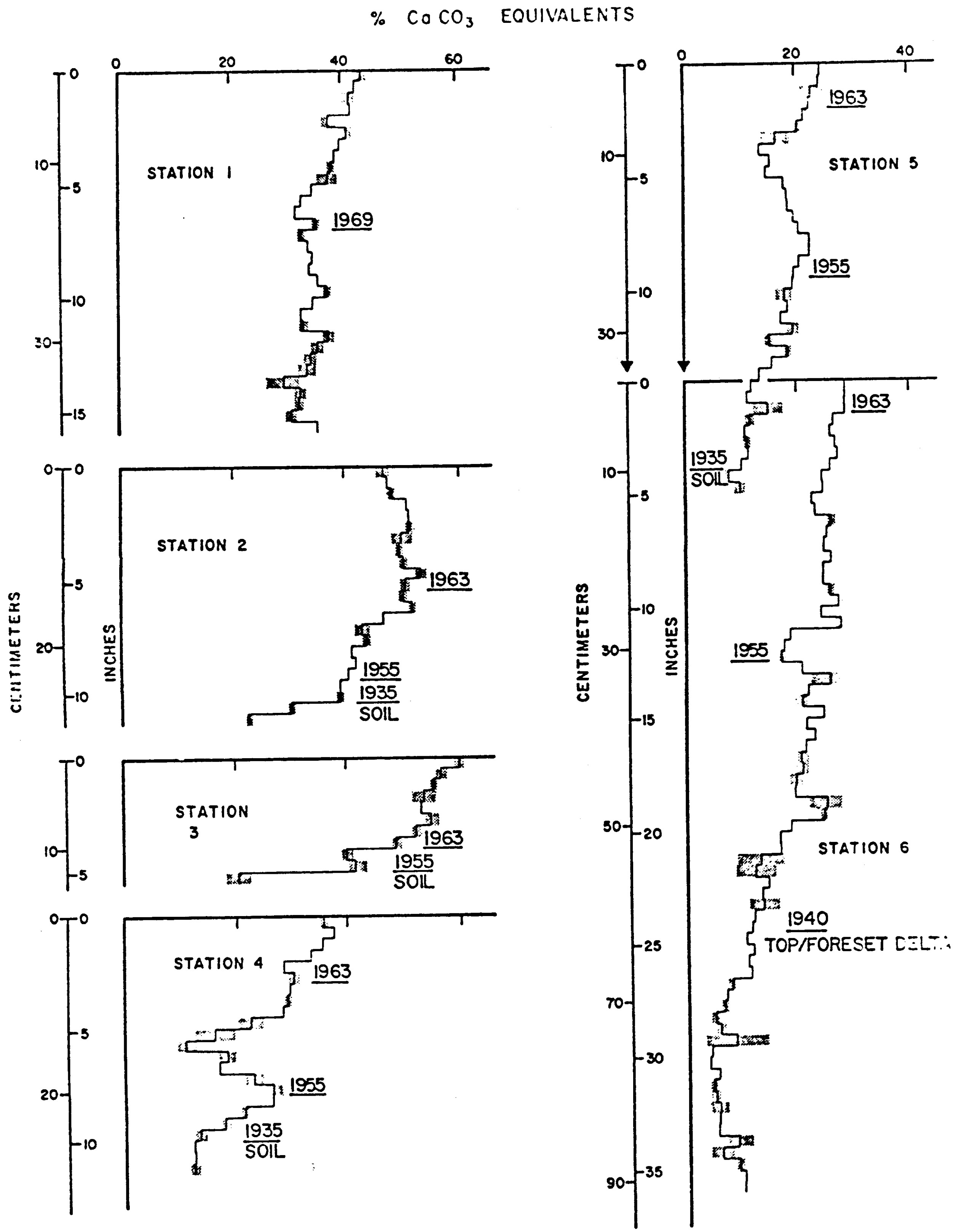

Figure 9. Calcium carbonate content of Lake Mead sediments (error bars shown by shading).

Calcium carbonate was on the order of 40-50% in Lower Basin sediments compared to only 20-25% in the Upper Basin.

The Upper Basin sediments have always had lower concentrations of calcium carbonate than the Lower Basin. Prior to the formation of Lake Powell, this was probably caused by inhibition of carbonate precipitation by inflow of organic compounds from the Colorado River. Reynolds (1978) reported that polyphenols in the Colorado River inhibit calcium carbonate precipitation in the upper end of Lake Powell. However, polyphenol concentrations are diluted in the reservoir and calcium carbonate does precipitate in lower Lake Powell.

The spatial differences in calcium carbonate of Upper and Lower Basin sediments prior to 1963 indicate that this also occurred in Lake Mead when it received unregulated flows from the Colorado River. However, polyphenol concentrations appear to still be sufficient to inhibit precipitation in the Upper Basin of Lake Mead. There was some increase in calcium carbonate in recent sediments in Virgin Basin and Bonelli Bay, but it was still much lower than that in the Lower Basin. This is probably also related to changes in productivity of the Upper Basin in the post-Lake Powell period.

Total phosphorus concentrations of Lake Mead sediments were appreciable and ranged from 300 ppm (mg kg dry weight^{-1}) in old reservoir sediments to 1000 ppm in recent sediments (Fig. 10). In the inner and middle Las Vegas Bay phosphorus increased steadily in sediments deposited after 1963, but elsewhere phosphorus concentrations decreased or remained stable. The

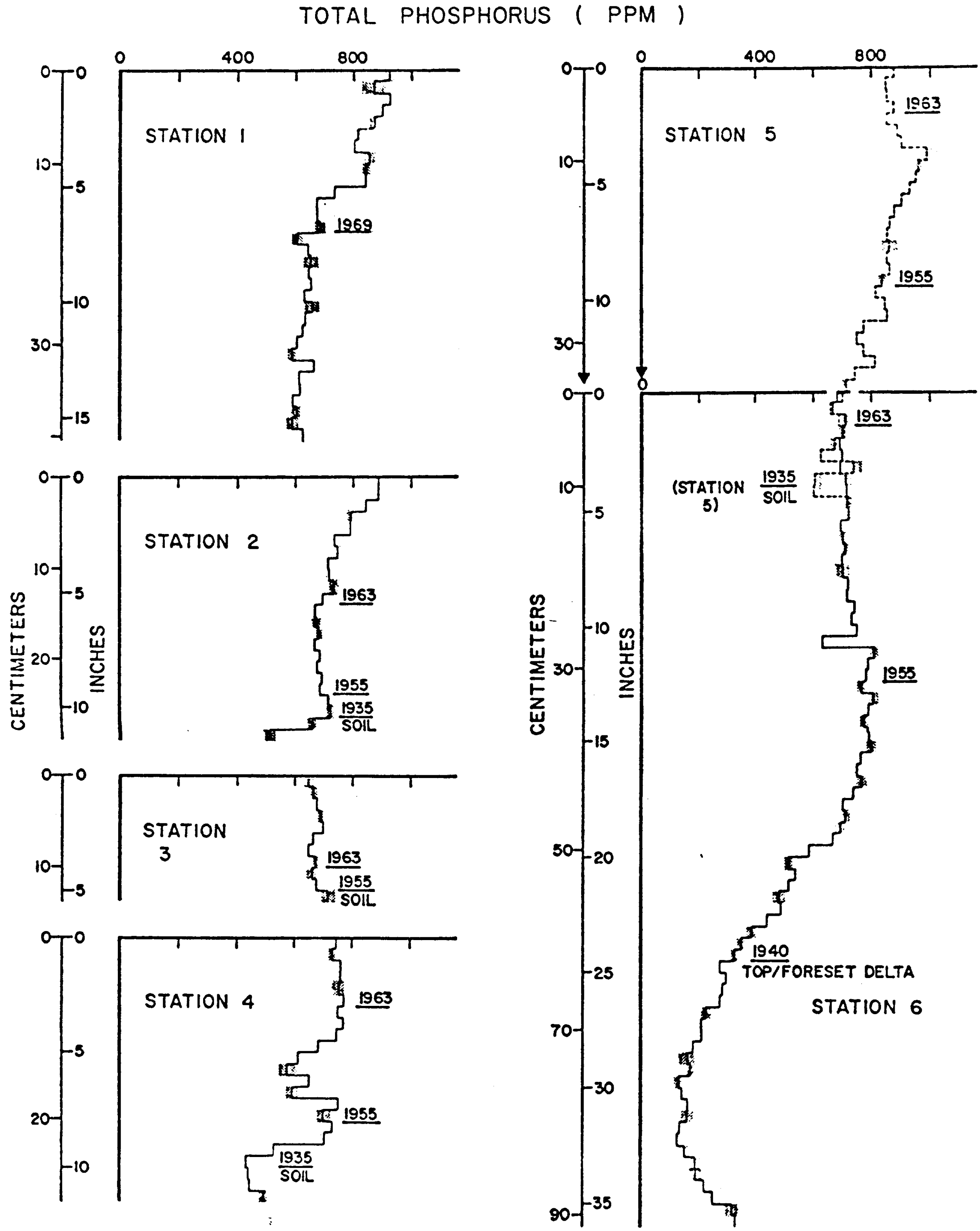

Figure 10. Total phosphorus concentration of Lake Mead sediments (error bars shown by shading) (mg kg^{-1} dry weight, ppm).

Table 3. Phosphorus chemistry of sediment cores (mg kg dry wt. $^{-1}$).

Station	Depth into core cm (in)	Total P	Inorganic P	NaOH IP	Organic P
1	0-1.3 (0-0.5)	923	786	94	137
1	16.5-17.8 (6.5-7.0)	680	---	36	---
2	0-1.3 (0-0.5)	885	736	105	149
3	0-1.3 (0-0.5)	642	633	80	9
4	0-1.3 (0-0.5)	743	596	45	147
5	0-1.3 (0-0.5)	874	769	42	105
6	0-1.3 (0-0.5)	683	565	42	118

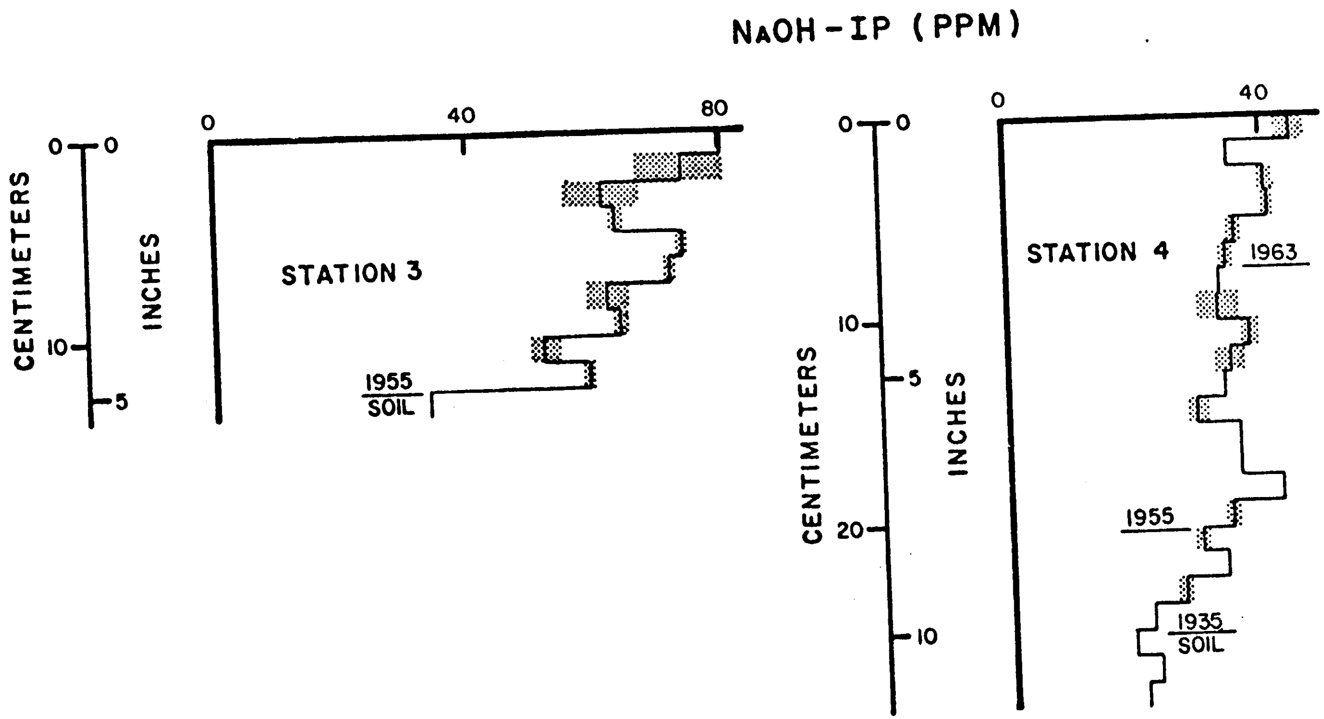

Figure 11. NaOH-inorganic phosphorus concentrations of sediments in Boulder Basin and Virgin Basin of Lake Mead (error bars shown by shading).

be 125 and the N/P 15 which is much closer to ratios expected for phytoplankton (Vallentyne 1974).

We also analyzed sediment pore waters in Boulder Basin to provide better insights into post-depositional nutrient transformations and interactions across the sediment-water interface. There was no measureable nitrate in either oxidized or reduced layers of the pore waters, despite high concentrations in the hypolimnion water (Table 4). This indicates that nitrate diffusing into the sediments is rapidly lost due to denitrification. Ammonia concentrations were high throughout the core indicating that rates of nitrification are extremely low.

Phosphate concentrations in pore waters were also high throughout the core and did not appear to be related to redox conditions (Table 4). It is commonly assumed that carbonates control phosphorus solubility (Stumm and Morgan 1970; Wetzel 1975) in calcareous sediments. Williams et al. (1971), however, demonstrated that iron, not calcium, controlled phosphorus concentration in calcareous sediments of several Wisconsin lakes. If iron controls phosphorus solubility in Lake Mead, then ratios of NaOH-IP:phosphate or total phosphorus:phosphate should be higher in oxidized than reduced layers of the sediments. The ratios run 11-12 in oxidized zones and 12-59 in reduced zones for NaOH-IP and 651-678 in oxidized zones and 657-715 in reduced zones for total P. These data indicate that either carbonates or possibly aluminum clays, or both, control phosphorus chemistry in Lake Mead sediments. Phosphate concentrations in pore waters

Table 4. Inorganic nitrogen and phosphorus analyses of hypolimnion water and sediment pore waters in Boulder Basin, October 1979.

Station	Depth into core cm (in)	Redox	NO_3-N		NH_3-N		PO_4-P	
			ppb in pore water	ppm in dry wt	ppb in pore water	ppm in dry wt	ppb in pore water	ppm in dry wt
3*	water column @ 70 m		244	---	3	---	3.5	---
3	0-2.5 (0-1)	oxidized	$\leq$ 1	0.00	2110	5.7	2380	6.4
	2.5-5.1 (1-2)	oxidized	$\leq$ 1	0.00	2280	3.9	1920	3.3
	5.1-7.6 (2-3)	reduced	$\leq$ 1	0.00	2750	4.9	3330	5.9
	7.6-10.2 (3-4)	reduced	$\leq$ 1	0.00	2950	4.5	2770	4.2
	10.2-12.7 (4-5)	reduced	$\leq$ 1	0.00	2230	2.5	1580	1.8
	12.7-15.2 (5-6)	reduced (relic soil)	$\leq$ 1	0.00	2030	0.9	1300	0.6

*unpublished data, Lake Mead Limnological Research Center, University of Nevada, Las Vegas are considerably higher than in overlying waters. Moreover, there is no concentration gradient from the bottom to the top of the core to indicate any appreciable diffusion of phosphate into the water column.

3.2.2. Spatial and Temporal Patterns in Sedimentation

The ^{137}Cs data and chemical analyses enabled us to estimate annual sedimentation rates for dry weight, organic carbon, nitrogen, total phosphorus and calcium carbonate during three periods of reservoir history (1935-1954, 1955-1962 and 1963-1977). In addition, it was possible to partition autochthonous (in-reservoir) and allochthonous (river-borne) components of organic carbon and calcium carbonate on the basis of previous analyses of bottomset delta deposits made during the 1948-49 sediment survey in Lake Mead (Gould 1960a). A 15-30 m delta, comprised primarily of fine clay materials, was formed in the Colorado River thalweg of Virgin and Boulder Basins during the first 13 years of impoundment. The bottomset delta deposits were fairly uniform in organic carbon (0.65%) and calcium carbonate (16%) (Gould 1960a) and were comprised of nearly pure allochthonous material due to the enormous rate of siltation. Siltation in non-thalweg areas of the reservoir are much lower, since we found at most, 46 cm of sediments in either basin. These non-thalweg deposits are comprised of both autochthonous and allochthonous materials. However, it is possible to partition these materials by measuring organic carbon and carbonate concentrations in various layers of the non-thalweg sediments, and subtracting out that reported in bottomset delta sediments by Gould (1960a). The calculations for this are given in equations 6 and 7 for autochthonous and allochthonous organic carbon and in equations 8 and 9 for calcium carbonate.

Autochthonous organic C ($g\ m^{-2} yr^{-1}$) = (6)

$$\frac{1}{t} \sum_{i=1}^{n} \frac{OC_i/100}{CC_i} - 0.65/100 \times \rho_i CC_i \times D_i \times k_i$$

Where t = time (yr) to deposit ith through nth sediment interval

OC_i = percent organic carbon content of bulk density in ith sediment interval, not corrected for $CaCO_{3i}$ content

0.65 = percent carbonate-free organic carbon of bottomset sediments from Gould (1960a)

CC_i = 1 - (% $CaCO_{3i}$/100), where % $CaCO_{3i}$ is precent calcium carbonate content of bulk density in ith sediment interval

ρ_i = bulk density of ith sediment interval ($g\ interval^{-1} cm^{-3}$)

D_i = length of sediment interval (constant = 1.27 cm)

k_i = unit conversion factors

The summation is performed for those intervals in which:

$$\frac{OC_i/100}{CC_i} \geq 0.65/100$$

The first term in equation 6 is the percent organic carbon present in excess of bottomset delta concentration, expressed on a carbonate-free basis for the ith sediment interval. The last term corrects bulk density for calcium carbonate content.

Allochthonous organic C ($g\ m^{-2} yr^{-1}$) =

$$\frac{1}{t} \sum_{i=1}^{n} OC_{Tot_i} - OC_{Aut_i} \times D_i \times k_i \tag{7}$$

Where t = time (yr) to deposit ith through nth sediment interval

OC_{Tot_i} = total organic carbon ($g\ C\ cm^{-3}$) in ith sediment interval

OC_{Aut_i} = autochthonous organic carbon ($g\ C\ cm^{-3}$) in ith sediment interval

D_i = length of sediment interval (constant = 1.27 cm)

k_i = unit conversion factors

Autochthonous $CaCO_3$ ($g\ m^{-2} yr^{-1}$) =

$$\frac{1}{t} \sum_{i=1}^{n} (\%CaCO_{3i} - 16)/100 \times \rho_i \times D_i \times k_i \tag{8}$$

Where t = time (yr) to deposit ith through nth sediment interval

$\%CaCO_{3i}$ = percent calcium carbonate content of bulk density in ith sediment interval

16 = percent concentration of calcium carbonate of bottomset delta sediments from Gould (1960a)

ρ_i = bulk density of ith sediment interval ($g\ interval^{-1} cm^{-3}$)

D_i = length of sediment interval (constant = 1.27 cm)

k_i = unit conversion factors

Allochthonous $CaCO_3$ ($g\ m^{-2} yr^{-1}$) =

$$\frac{1}{t} \sum_{i=1}^{n} CaCO_{3_{T_i}} - CaCO_{3_{Aut_i}} \times D_i \times k_i \tag{9}$$

Where t = time (yr) to deposit ith through nth sediment interval

$CaCO_{3_{T_i}}$ = total calcium carbonate ($g\ cm^{-3}$) in ith sediment interval

$CaCO_{3_{Aut_i}}$ = autochthonous calcium carbonate ($g\ cm^{-3}$) in ith sediment interval

D_i = length of sediment interval (constant = 1.27 cm)

k_i = unit conversion factors

There was considerable spatial and temporal variation in sedimentation patterns in Lake Mead (Fig. 12). In the period from 1935-1954, dry weight, nutrient and calcium carbonate sedimentation were highest in the Overton Arm and Bonelli Bay, but then decreased in Virgin Basin and remained low in the Lower Basin. Phosphorus sedimentation was extremely high in the Upper Basin (up to 17 kg $m^{-2} yr^{-1}$) and closely related to dry weight and allochthonous carbon sedimentation. The low C/P (ca.12:1) and N/P (ca.1:1) ratios of sedimenting material indicated that most of the sediment phosphorus was inorganic and derived from suspended sediment inputs in the Colorado River.

Nitrogen sedimentation was also related to dry weight and allochthonous carbon sedimentation, but the more optimum C/N ratio (ca 10:1) and small variation in C/N ratios across the reservoir sediments (Fig. 6) indicated that sediment nitrogen

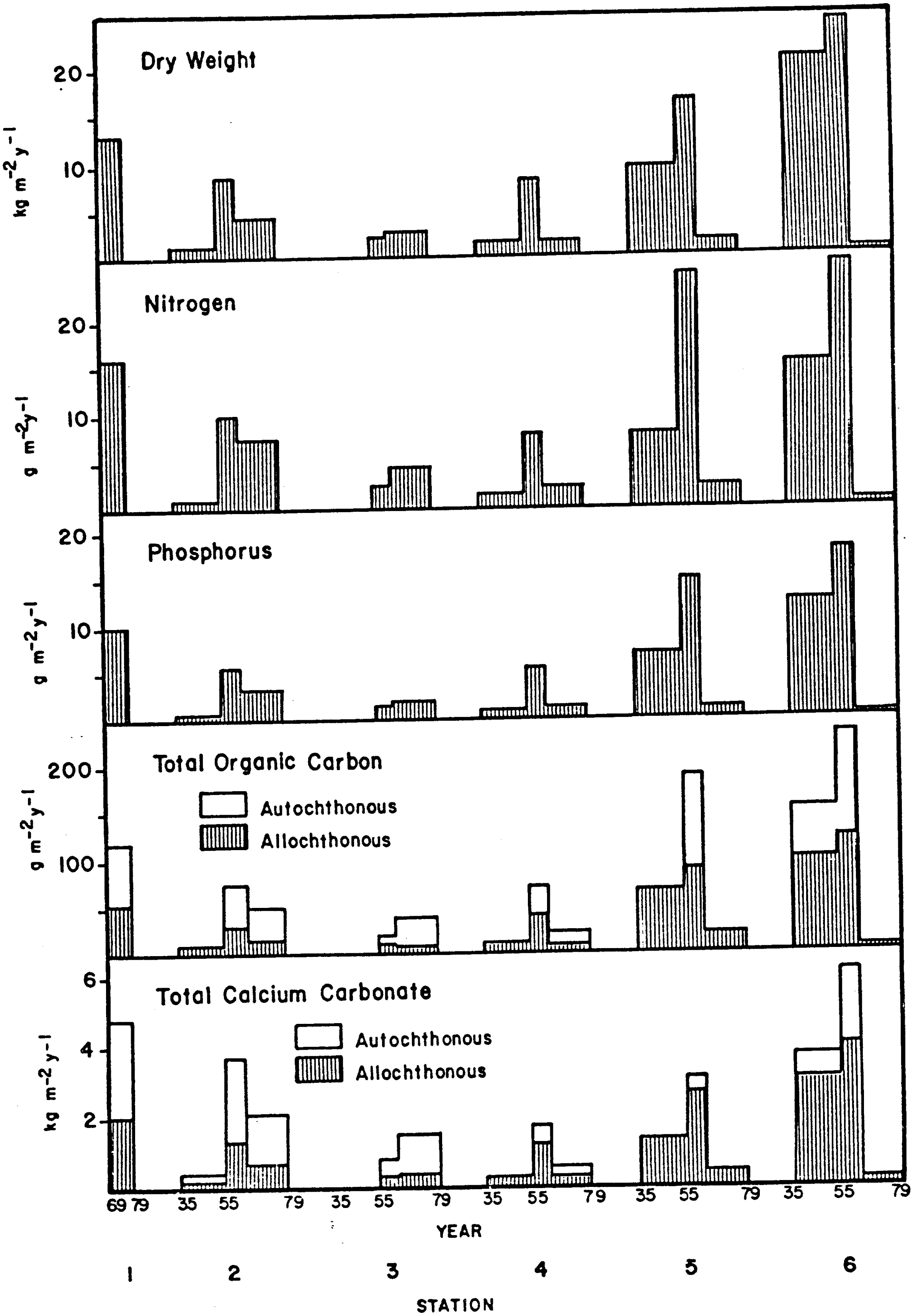

Figure 12. Sedimentation rates for nutrients, organic carbon, and calcium carbonate during three periods (≤1954, 1955-1962, ≥1963) of Lake Mead history.

was primarily organic and derived from sedimenting plankton remains. Nitrogen, therefore, is a much better measure of in-reservoir plankton sedimentation than phosphorus which is derived primarily from deposition of suspended sediments. Sedimentation rates were extremely low in the Lower Basin during this period. There was no measurable accumulation of sediments in Boulder Basin prior to 1955. Similarily, in Las Vegas Bay sedimentation rates were extremely low in the early history of Lake Mead.

Sedimentation rates increased in the Upper Basin during the period from 1955-1962 (Fig. 12). This was especially evident in Bonelli Bay and Virgin Basin where nitrogen and autochthonous carbon sedimentation increased two-fold over the preceding period. Phosphorus, dry weight and carbonate sedimentation also increased in the Upper Basin but not as drastically as what was observed for nitrogen and carbon. It is somewhat surprising that sedimentation rates increased during this period because average suspended sediment loading decreased by 34%. The suspended load in the Colorado River averaged 110 x 10^6 MT yr^{-1} prior to 1955 but then decreased to 73 x 10^6 MT yr^{-1} during the 1955-1962 water years (USBR 1976). Dry weight sedimentation rates, however, increased by 20% in the Overton Arm and 400% in Virgin Basin indicating that there must have been a significant change in the distribution of suspended sediment inputs across the Upper Basin.

The Colorado River has historically formed an overflow during spring and a shallow interflow during summer in the Upper

Basin (Anderson and Pritchard 1951). During spring runoff, this resulted in dispersal of fine suspended sediments across the Upper Arm of Lake Mead (Gregg Basin, Temple Basin). High spring runoff and flooding occurred in the Colorado River during 1956-1958 and in 1962 (USGS data), and this apparently caused greater dispersal of suspended sediments into non-delta areas of the Virgin Basin, Bonelli Bay and the Overton Arm. The magnitude of spring runoff and seasonal frequency of flooding appear to be more important factors than is average, annual suspended sediment loading in determining sedimentation in non-delta areas of the reservoir. However, even during years of extreme spring runoff, it does not appear that much Colorado River suspended sediment is transported into the Lower Basin. There was only a slight increase in sedimentation rates in Boulder Basin during the period from 1955-1962 (Fig. 12). There was a greater increase in sedimentation in the middle Las Vegas Bay but this was probably due to increased discharge of sewage effluents into the Lower Basin.

Suspended sediment loading in the Colorado River decreased to an average of 16×10^6 MT yr^{-1} in the period after Lake Powell was formed in 1963 (USBR 1976). This was accompanied by a drastic reduction in sedimentation throughout the Upper Basin (Fig. 12). In contrast, sedimentation increased slightly in Boulder Basin, decreased in middle Las Vegas Bay and increased in the inner bay.

Sedimentation patterns in Lake Mead were reversed after 1963 in that sedimentation in the Lower Basin exceeded that in the Upper Basin. However, increased sedimentation in the Lower Basin was not sufficient to offset decreased sedimentation in the Upper Basin, and therefore reservoir-wide sedimentation decreased markedly after Lake Powell was formed in 1963.

3.2.3. Reservoir-wide Sedimentation as Related to Nutrient Loading

The sedimentation rates given in Fig. 12 provided a basis for estimating reservoir-wide sedimentation during three periods of Lake Mead history. However, it was necessary to extrapolate sedimentation rates at each station to larger areas of the reservoir using area estimates of Lake Mead from Lara and Sander's (1970) sediment survey. The areas represented by our stations are shown in Table 5. This only accounts for 77-78% of the total reservoir area because sampling was not conducted in the Upper Arm (Temple Bar, Gregg Basin, Iceberg Canyon and Grand Wash). In order to obtain an estimate of reservoir-wide sedimentation, we used data from station 5 to characterize the Upper Arm of Lake Mead.

Reservoir-wide nitrogen sedimentation averaged 2980 MT yr^{-1} prior to 1954, then increased to 8420 MT yr^{-1} from 1955-1962 but decreased to 1320 MT yr^{-1} in the post-Lake Powell period (Table 6). In the Upper Basin, nitrogen sedimentation decreased from 5320 to 421 MT yr^{-1} but increased slightly from 484 to 636 MT yr^{-1} in the Lower Basin after 1963. Phosphorus sedimentation in the Upper Basin was extremely high during the early history of Lake Mead but decreased by 93.5% after formation of Lake Powell. Phosphorus sedimentation in the Lower Basin decreased by

Table 5. Reservoir mean surface areas characterized by sediment coring stations (from Lara and Sanders 1970).

Interval	Mean+ Lake Level (m)	(ft)	Total Lake Area (km^2)	STATION 1	2	3	4	5	6
≤ 1954	350	(1148)	446.9	*	21.7	101.7	35.8	108.7	80.0
1955-62	352	(1152)	465.0	*	22.1	103.6	37.0	112.5	85.1
≤ 1963	353	(1157)	474.7	0.8	21.4	104.2	37.7	114.3	87.3

*combined with Station 2

+Lake level from Bureau of Reclamation (1976) and U.S. Geological Survey (unpublished).

Table 6. Average reservoir-wide and individual basin sedimentation of nitrogen, phorphorus and organic carbon in Lake Mead (MT $yr.^{-1}$).

Parameter	Time Interval	Whole Reservoir	Lower Basin	Upper Basin	Lower and Upper Basins
N	$\leq$ 1954	2980	19	2170	2189
	1955-62	8420	484	5320	5804
	$\geq$ 1963	1320	636	421	1067
Total P	$\leq$ 1954	2470	15	1780	1795
	1955-62	5200	273	3390	3663
	$\geq$ 1963	623	268	220	488

only 2% in the post-Lake Powell period. Reservoir-wide phosphorus sedimentation, however, decreased from an average of 5200 MT yr^{-1} during 1955-1962 to 623 MT yr^{-1} after 1963. The formation of Lake Powell, therefore, markedly reduced nitrogen and phosphorus sedimentation in the Upper Basin of Lake Mead, and these changes generally followed historical patterns of nutrient loading.

The U.S. Geological Survey has monitored nitrate concentrations in Grand Canyon and below Hoover Dam ever since Lake Mead was formed in 1935 (Fig. 13). Nitrate loading from the Colorado River was relatively low during 1935-1940 but then increased periodically with high runoff during the period from 1943-1954 (Paulson 1981). High runoff during the late 1950's and early 1960's resulted in several years of high nitrate loading to Lake Mead. However, nitrate loading was markedly reduced after 1963. Nitrate loading then increased again during the period from 1966-1969 but has since decreased to a lower steady state.

There are no comparable, long-term data available for phosphorus, but loading must have been high, particularly during 1955-1962, to account for the high rates of phosphorus sedimentation during the pre-Lake Powell years. Phosphorus loading was probably on the order of that recently measured for Lake Powell by Gloss et al. (1981). They estimated that the Colorado River currently provides 5224 MT yr^{-1} of the total phosphorus to Lake Powell. However, only 229 MT yr^{-1} of phosphorus is currently discharged from Glen Canyon Dam (Gloss

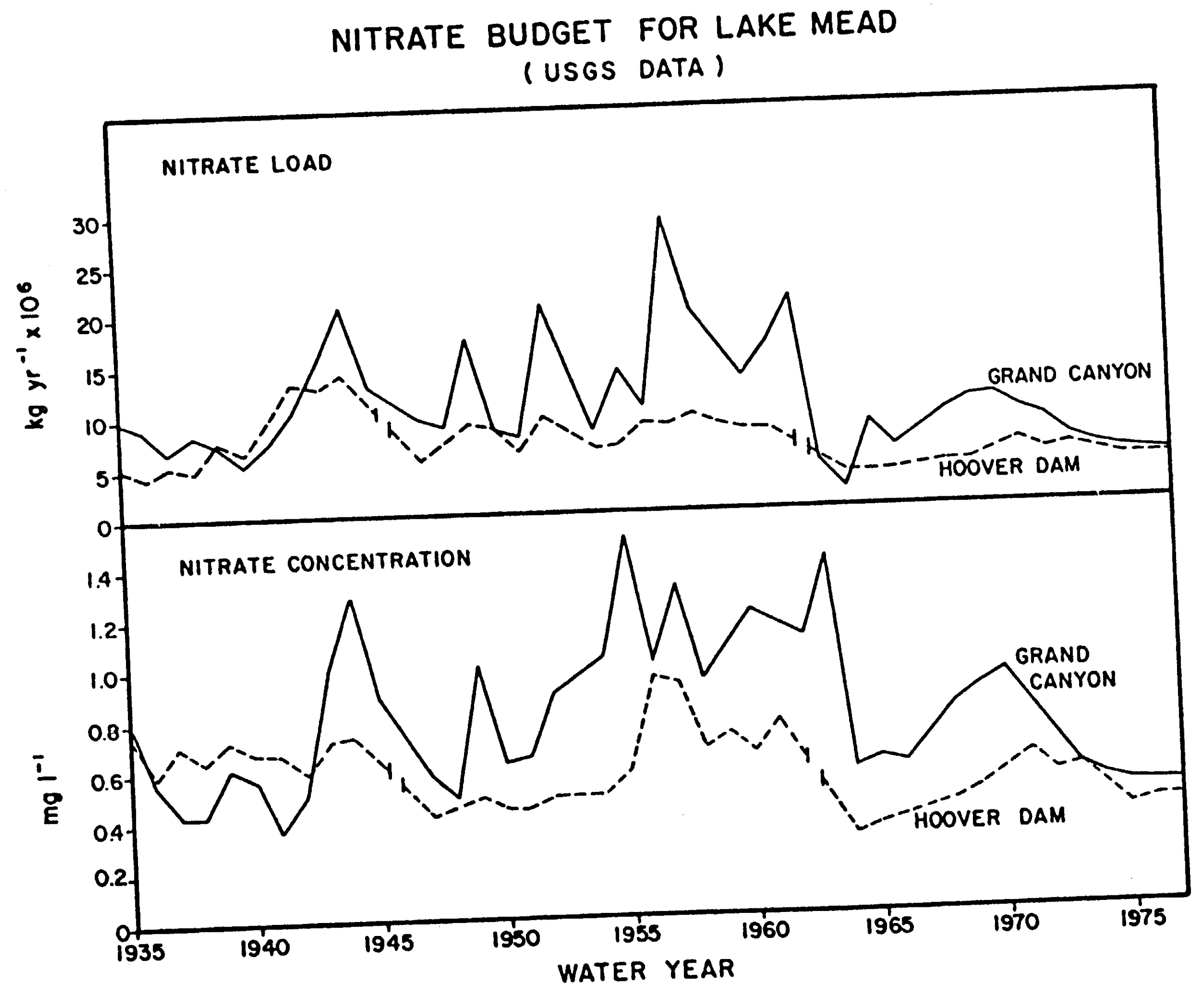

Figure 13. Historical nitrate concentrations and loads in Grand Canyon and below Hoover Dam (USGS, 1935-1977) (from Paulson 1981).

et al. 1981), and of this, only 198 MT yr^{-1} entered Lake Mead from the Colorado River (Baker and Paulson 1981). This represents a 96% reduction in total phosphorus loading into Lake Mead which accounts for the abrupt decrease in phosphorus sedimentation in the Upper Basin.

Sewage effluent discharges and nutrient loading from Las Vegas Wash, however, rose steadily in the post-Lake Powell period (Fig. 14). Las Vegas Wash now contributes 15% of the annual nitrogen and 60% of the phosphorus inputs to Lake Mead (Baker and Paulson 1980). The morphometry and hydrodynamics of Lake Mead (Paulson et al. 1980) are such that the phosphorus-rich Las Vegas Wash inflow is confined to the Lower Basin. High phosphorus loading from Las Vegas Wash and high nitrate loading from the Colorado River during the late 1960's and early 1970's combined to increase sedimentation in the Lower Basin. Nitrogen sedimentation increased from 484 to 636 MT yr^{-1}, and phosphorus sedimentation was maintained at levels equal to that in the 1955-1962 period (Table 6). However, decreased nitrate loading from the Colorado River and development of nitrogen-limitation in the Lower Basin after 1972 (Paulson and Baker 1981) have functioned to keep sedimentation rates far below that which occurred in the Upper Basin prior to the formation of Lake Powell.

The historical patterns of sedimentation in each basin of Lake Mead generally agree with historical changes in nutrient loading. However, there is a considerable difference in sedimentation estimated from nutrient budgets (apparent

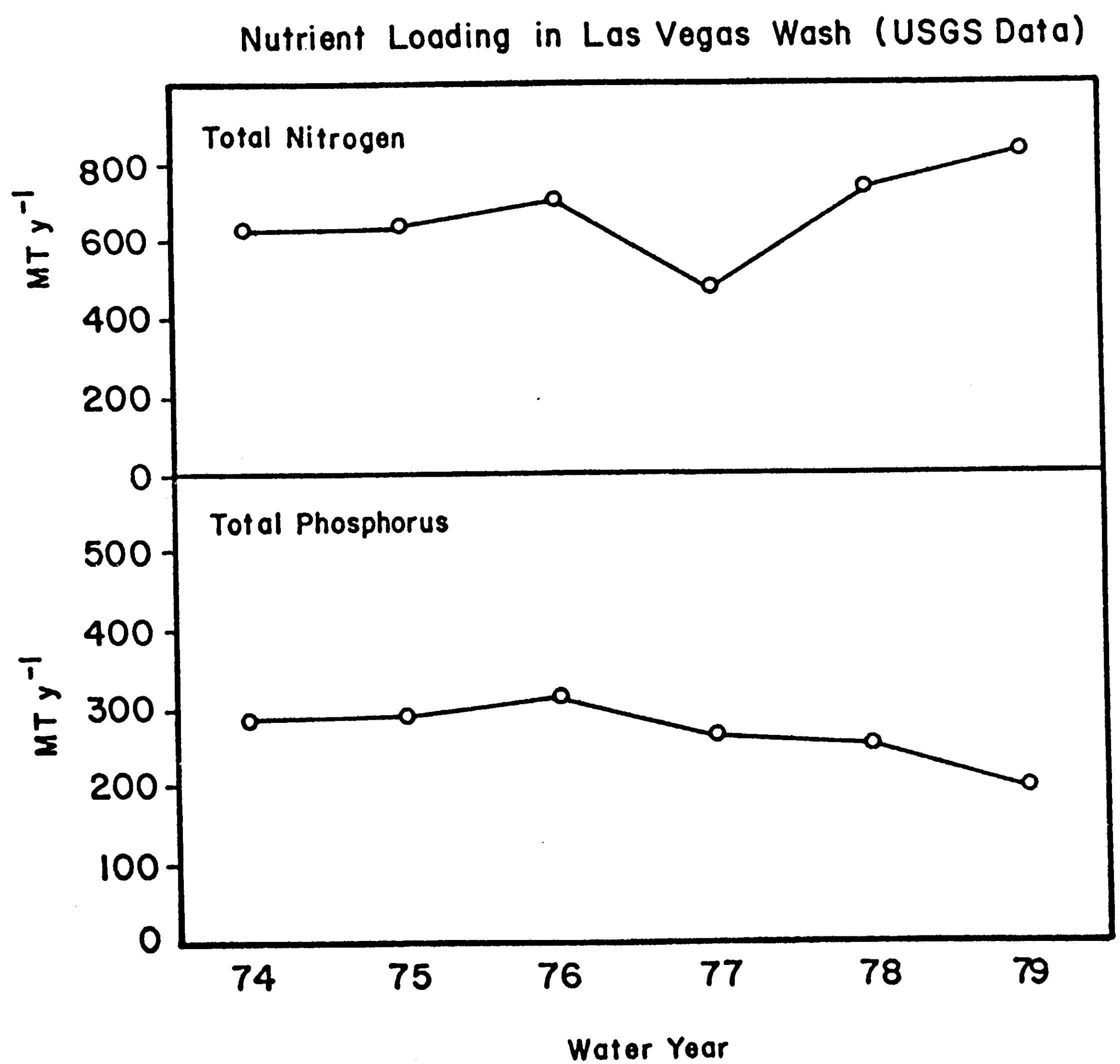

Figure 14. Total nitrogen and total phosphorus loading for Las Vegas Wash during water years 1974-1979. Measurements made at North Shore Road, 1.3 km above Lake Mead (USGS, 1974-1979).

sedimentation) (Baker and Paulson 1981), and absolute sedimentation measured in this study.

Gloss et al. (1981) estimated that steady-state total nitrogen loss from Glen Canyon Dam was 12275 MT yr^{-1}. Nitrate loss from Glen Canyon Dam or loading to Lake Mead has averaged 6910 MT yr^{-1} since 1963 (USGS data, Fig. 13), or about one-half of total nitrogen. Total nitrogen loading from Las Vegas Wash has averaged 614 MT yr^{-1} since measurements were first made in 1974 (USGS data, Fig. 14). Since the Virgin and Muddy Rivers contribute minimal nutrient inputs to Lake Mead (EPA 1977), total nitrogen loading is about 13000 MT yr^{-1}. Nitrate loss at Hoover Dam has averaged 4420 MT yr^{-1} since 1963 (USGS data, Fig. 13). There are no long-term data on total nitrogen loss, but measurements made in 1979-80 (Paulson 1981) indicate it is 1.6 times greater than nitrate loss. Total nitrogen loss for Hoover Dam, therefore, would be about 7000 MT yr^{-1}. Apparent sedimentation, or the net difference between total nitrogen inputs and outputs would be 6000 MT yr^{-1}. However, absolute sedimentation, or that actually measured in the study was only 1320 MT yr^{-1} during the post-Lake Powell period (Table 6). There must therefore be an additional loss, or storage, of 4680 MT yr^{-1} in, or from, Lake Mead.

This additional nitrogen is clearly not being stored in the water column because nitrate concentrations in Lake Mead decreased considerably during the post-Lake Powell period (Paulson and Baker 1981; Paulson 1981). A small portion, however, is stored in the sediment pore waters. Ammonia concentrations in pore waters of Boulder Basin averaged 4.8 mg kg sediment dry weight^{-1} (Table 4). If extrapolated across the reservoir sediment surface, this would account for 4.3 MT yr^{-1} of nitrogen storage. We did not analyze dissolved organic nitrogen in pore waters, but this represents another potential site of nitrogen storage. However, it is unlikely that dissolved organic nitrogen concentrations in pore waters are much higher than ammonia and therefore probably do not account for the additional nitrogen storage. There must therefore be a considerable loss of nitrogen from Lake Mead to account for the differences in apparent and absolute sedimentation.

One such mechanism of nitrogen loss would be fish harvest. Culp (1981), using catch data provided by the Arizona and Nevada Departments of Wildlife, estimated that the fish harvest for Lake Mead resulted in an annual nitrogen loss of 32 MT. This, however, is less than 1% of the difference in apparent and absolute sedimentation. There is still an additional loss of 4648 MT yr^{-1} from Lake Mead, and this appears to be caused by denitrification.

Denitrification, or the biological conversion of NO_3 to N_2, occurs naturally in sediments of lakes and reservoirs. Although rates can vary widely, denitrification often represents a major loss of nitrogen from aquatic systems (Table 7). This also appears to be the case in Lake Mead. Nitrate was non-detectable in the pore waters of Boulder Basin, despite fairly high concentrations (250-300 μg l^{-1}) in the overlying hypolimnion waters. This sharp gradient indicates that denitrification

Table 7. Rates of denitrification reported for lakes and reservoirs of different trophic states.

Lake	Mean Depth (m)	Denitrification Rate (mg N m^{-2} day^{-1})	Trophic State	Source
Aegerisee	49	2.6	oligotrophic	Vollenweider 1968
Turlersee	14	7.8	mesotrophic	"
Hallwilersee	28	6.0	eutrophic	"
Pfaffikersee	18	22.9	eutrophic	"
Greifensee	19	56.5	eutrophic	"
Baldaggersee	34	25.0	eutrophic	"
Rybinsk	--	4.0	mesotrophic	Kuznetsov 1968
Mead	55	27.0	mesotrophic	This study

occurs rapidly in Lake Mead sediments. Denitrification for Lake Mead would be 27 mg N m^{-2} day^{-1} on the basis of an annual nitrogen loss of 4648 MT yr^{-1} (Table 7). Although this is a high rate, it is well within the range of that reported for natural lakes. Direct measurements of denitrification should be done to evaluate the accuracy of our estimate, but clearly denitrification represents a major nitrogen loss from Lake Mead.

Phosphorus loading to Lake Mead from the Colorado River was 198 MT yr^{-1} in 1977-78 (Baker and Paulson 1981). This is similar to the 220 MT yr^{-1} steady-state phosphorus loss from Lake Powell estimated by Gloss et al. (1981). Phosphorus loading from Las Vegas Wash was 263 MT yr^{-1} in 1977-78 (Baker and Paulson 1981) and has averaged 268 MT yr^{-1} since monitoring was started in 1973 (USGS data, Fig. 14). Total phosphorus loading to Lake Mead is about 460 MT yr^{-1} since the Virgin and Muddy Rivers contribute minimal phosphorus to the reservoir (EPA 1977). Phosphorus loss from Hoover Dam was 123 MT yr^{-1} in 1977-78 (Baker and Paulson 1981). The fish harvest also results in an annual loss of 25 MT of phosphorus from the reservoir (Culp 1981). The combined phosphorus losses from Lake Mead would therefore be 148 MT yr^{-1}. Apparent phosphorus sedimentation would be 312 MT yr^{-1}. Absolute phosphorus sedimentation, as measured in this study, was 268 MT yr^{-1} in the Lower Basin, 220 MT yr^{-1} in the Upper Basin and 623 MT yr^{-1} in the whole reservoir during the post-Lake Powell period (Table 6). Absolute sedimentation thus exceeded apparent sedimentation by 311 MT yr^{-1}, which is the reverse of what occurred for nitrogen.

Phosphorus does not have a gaseous phase, and therefore inputs and outputs to a lake or reservoir are controlled primarily by the inflows and outflows. There are no historical data on phosphorus concentrations in the Colorado River, and it is unknown whether loading for 1977-78 reflects average annual loading in the post-Lake Powell period. However, it seems likely that loading was higher during years when Lake Powell was being filled. Suspended sediments were transported through Lake Powell and discharged from Glen Canyon Dam during the mid-1960's (Paulson and Baker 1981). This would have resulted in higher phosphorus loading to Lake Mead than what we measured in 1977-1978. Moreover, it is probable that a greater percentage of the phosphorus inputs was retained in Lake Mead during years when nitrate loading from the Colorado River was high (Fig. 13). Phytoplankton can only use phosphorus to the extent that nitrogen is supplied in proportion to their optimum requirements (ca.10N:1P) (Schindler 1978). Nitrogen became limiting in the Lower Basin after 1972 (Paulson and Baker 1981) when loading from the Colorado River decreased (Fig. 13). This, in turn, would have reduced phosphorus retention in the Lower Basin. The rates of phosphorus retention we measured in 1977-78 may not, therefore, reflect those that occurred when ample nitrogen was available to the Lower Basin. Higher phosphorus during the late 1960's and early 1970's when nitrogen loading from the Colorado River was higher appears to be the main reason why absolute phosphorus sedimentation exceeded apparent sedimentation during the post-Lake Powell period.

3.2.4. Effects on Organic Carbon Sedimentation and Phytoplankton Productivity

The historical changes in nutrient loading to Lake Mead have also been accompanied by marked changes in organic carbon sedimentation and phytoplankton productivity. Reservoir-wide autochthonous carbon sedimentation was low prior to 1954 but increased sharply during the period from 1955-1962, followed by an abrupt decrease in the post-Lake Powell period (Table 8). The same trends were also evident for allochthonous organic carbon sedimentation. Organic carbon sedimentation was consistently higher in the Upper Basin during the pre-Lake Powell period and accounted for over 60% of reservoir-wide organic carbon sedimentation. This pattern was reversed after 1963, and the Lower Basin now contributes over 50% of organic carbon sedimentation in Lake Mead. However, reservoir-wide sedimentation has still been reduced by 76.8% of that which occurred in the 1955-1962 period.

During the post-Lake Powell period, autochthonous organic carbon sedimentation in various locations of Lake Mead (Fig. 12) was closely related to recent phytoplankton productivity measurements made at these locations by Paulson et al. (1980). There was a good correlation (r=0.979) between annual autochthonous organic carbon sedimentation and annual phytoplankton productivity (1977-78) at the six sediment sampling stations (Fig. 15). Linear regression of organic carbon sedimentation against phytoplankton productivity (equation 10)

Table 8. Reservoir-wide and individual basin sedimentation of autochthonous and allochthonous organic carbon in Lake Mead (MT $yr.^{-1}$).

	Time Interval	Whole Reservoir	Lower Basin	Upper Basin	Lower and Upper Basins
AUTOCHTHONOUS ORGANIC C	$\leq$ 1954	7710	48	6150	6198
	1955-62	33400	2290	20300	22590
	$\geq$ 1963	7720	3830	2450	6280
ALLOCHTHONOUS ORGANIC C	$\leq$ 1954	18900	85	13800	13885
	1955-62	32500	1710	21700	23410
	$\geq$ 1963	3300	1200	1320	2520

provided a means of predicting historical productivity in the reservoir.

$$PPR = -7 + 19.7\ (AOC) \qquad (10)$$

where:

PPR = rate of phytoplankton productivity (g C $m^{-2} yr^{-1}$)

AOC = autochthonous organic carbon sedimentation (g C $m^{-2} yr^{-1}$)

Rates of phytoplankton productivity estimated for each station with equation 10 were extrapolated over larger areas of the reservoir to estimate reservoir-wide and individual basin total annual production (Table 9) and average daily productivity (Table 10). The spatial and historical trends in total production (Table 9) necessarily follow those for autochthonous organic carbon sedimentation (Table 8) and thus do not provide much additional information. However, historical rates of productivity when compared to those in recent years (1977-78) enable us to better reconstruct the trophic history of Lake Mead.

Daily phytoplankton productivity averaged 1558 mg C $m^{-2} da^{-1}$ in the Lower Basin, 518 mg C $m^{-2} da^{-1}$ in the Upper Basin and 810 mg C m^{-2} da^{-1} reservoir-wide during 1977-1978 (Table 10). Using Likens' (1977) trophic lake and reservoir classification, Paulson et al. (1980) concluded that the Upper Basin was oligotrophic-mesotrophic and the Lower Basin mesotrophic-slightly eutrophic at these rates of phytoplankton productivity. The Upper Basin, therefore, would have been mesotrophic-eutrophic and the Lower Basin oligotrophic during the period prior to 1954 (Table 10). Productivity in Lake Mead rose sharply in the period from 1955-1962 (Table 10). The Upper

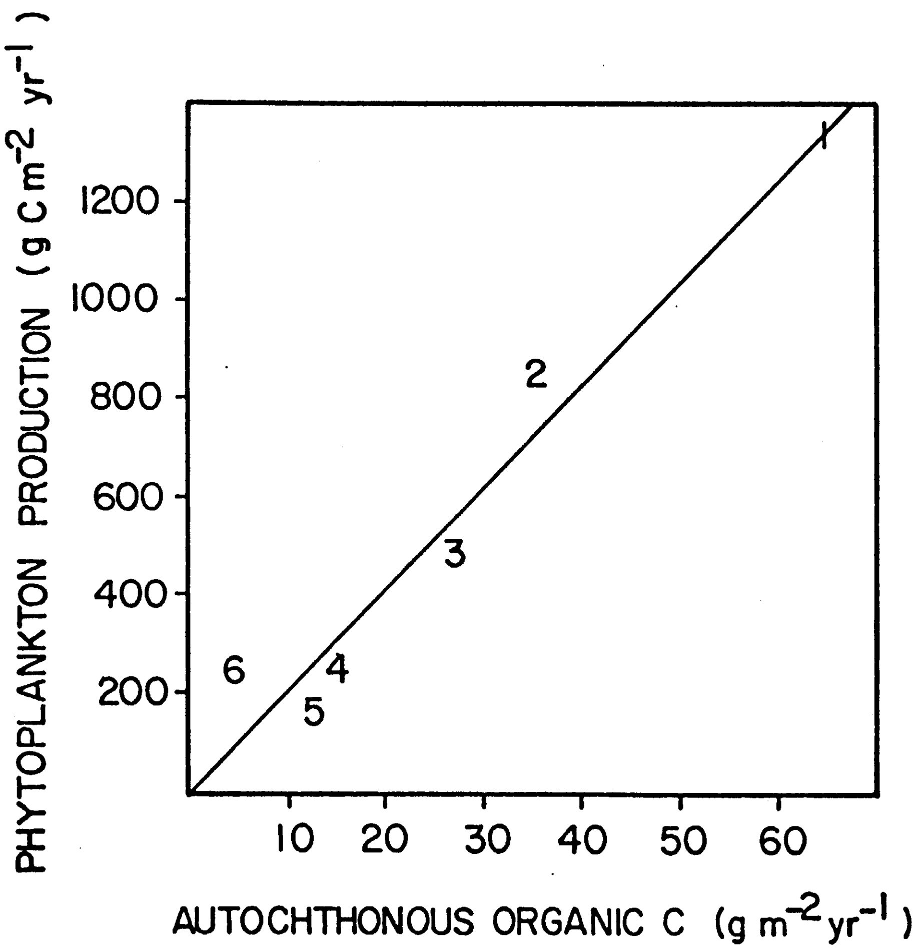

Figure 15. Relationship of recent estimates of phytoplankton productivity in Lake Mead (Paulson et al. 1980) to autochthonous organic carbon sedimentation in the post-Lake Powell period.

Table 9. Reservoir-wide and individual basin estimates of historical annual rates of phytoplankton production (MT $yr.^{-1}$ x 10^3).

Interval	Whole Lake	Lower Basin	Upper Basin	Lower and Upper Basins
≤ 1954	146	0.6	117	118
1955-62	651	43	395	438
≥ 1963	144	73	44	117

Table 10. Reservoir-wide and individual basin estimates of historical daily rates of phytoplankton productivity (mg C m^{-2} day^{-1}).

Internal	Whole Reservoir	Lower Basin	Upper Basin	Lower and Upper Basin
≤ 1954	895	133	1428	929
1955-62	3836	937	4612	3331
≥ 1963	831	1582	503	877
1977-78*	810	1558	518	876

* Area-weighted averages from Paulson et al. (1980)

Basin was eutrophic and the Lower Basin was mesotrophic during this period. Rates of phytoplankton productivity in the Upper Basin (4612 mg C $m^{-2}da^{-1}$) exceeded those that we recently measured in the inner Las Vegas Bay (3444 mg C $m^{-2}da^{-1}$ in 1977-1978), the most productive region in Lake Mead (Paulson et al. 1980). However, the trophic state of Lake Mead decreased after Lake Powell was formed and productivity has remained low ever since.

3.2.5. Spatial and Historical Patterns in Calcium Carbonate Precipitation

Historical patterns of calcium carbonate precipitation in Lake Mead have generally followed those observed for autochthonous and allochthonous organic carbon sedimentation. In the pre-1954 period, most of the calcium carbonate precipitation was allochthonous and this occurred primarily in the Upper Basin (Table 11). Allochthonous and autochthonous calcium carbonate precipitation then increased significantly during the period from 1955-1962. Reservoir-wide calcium carbonate precipitation increased to 397 x 10^3 MT yr^{-1}, and over 60% of this occurred in the Upper Basin. Autochthonous and allochthonous calcium carbonate precipitation decreased considerably in the Upper Basin but increased slightly in the Lower Basin during the post-Lake Powell period. However, reservoir-wide autochthonous carbonate precipitation was still reduced by 45% of that which occurred in the previous period. Allochthonous calcium carbonate precipitation followed a similar pattern.

The historical changes in autochthonous calcium carbonate

Table 11. Reservoir-wide and individual basin precipitation of calcium carbonate (MT $yr.^{-1} \times 10^3$).

Parameter	Interval	Whole Lake	Lower Basin	Upper Basin	Lower and Upper Basins
	$\leq$ 1954	72.70	4.95	61.50	66.45
AUTOCHTHONOUS	1955-62	397.00	108.00	240.00	348.00
$CaCO_3$	$\geq$ 1963	179.60	139.74	28.32	168.07
	$\leq$ 1954	523.00	3.47	395.00	398.47
ALLOCHTHONOUS	1955-62	1020.00	65.50	684.00	749.50
$CaCO_3$	$\geq$ 1963	132.00	62.10	44.10	106.20

precipitation in Lake Mead generally followed patterns similar to those observed for autochthonous organic carbon sedimentation (Table 8). This was especially evident in the Lower Basin where ratios of autochthonous organic carbon sedimentation: autochthonous calcium carbonate precipitation were similar at each station in the period after 1955 (Table 12). However, these ratios were much higher and more variable in the Upper Basin which indicates that there is inhibition of calcium carbonate precipitation, despite periods of high productivity and autochthonous organic carbon sedimentation.

Reynolds (1978) demonstrated that polyphenols in the Colorado River inflow to Lake Powell effectively inhibit calcite precipitation in the upper end of the reservoir. The polyphenols are derived from forested regions of the upper Colorado River drainage basin, and concentrations vary directly with seasonal patterns of runoff (Gloss et al. 1981). During spring, when the river forms an overflow in Lake Powell, polyphenol concentrations are high enough to inhibit calcite precipitation in the upper one-third of the reservoir. Calcite precipitation only occurs in the epilimnion down reservoir where dilution reduces polyphenol concentrations (Gloss et al. 1981).

It appears that a similar process was, and still is, operating to limit calcite precipitation in the Upper Basin of Lake Mead. Autochthonous organic carbon:calcium carbonate ratios have always been higher in the Upper Basin. The formation of Lake Powell did not have any appreciable influence on these ratios indicating that polyphenols are still being supplied to

Table 12. Ratios of autochthonous organic C to autochthonous $CaCO_3$-C in Lake Mead.

Interval	STATION 1	2	3	4	5	6
$\leq$ 1954	----	0.09	----	0.50	2.03	0.69
1955-62	----	0.16	0.20	0.50	1.86	0.37
$\geq$ 1963	0.20*	0.21	0.23	0.48	1.04	0.49

*$\geq$5/1969

Lake Mead either via export from Lake Powell or possibly from inputs in the Grand Canyon. Whatever the origin, it is clear that polyphenols have a significant effect in reducing calcium carbonate precipitation in Lake Mead. It is possible to obtain a quantitative estimate of this inhibition by extrapolation from the autochthonous organic carbon:calcium carbonate ratios in the Lower Basin where inhibition does not occur.

Our data indicate that sedimentation of 1 mole of organic carbon is accompanied by precipitation of 5.5 moles of calcium carbonate in the Lower Basin. Using this ratio and the rate of autochthonous organic carbon sedimentation in the Upper Basin, potential lakewide calcium carbonate precipitation would have been 3.5×10^5 MT yr^{-1} prior to 1954, 15×10^5 MT yr^{-1} during 1955-1962 and 3.5×10^5 MT yr^{-1} after 1963. Measured calcium carbonate precipitation in Lake Mead was 21% lower than this in the period prior to 1954, 26% lower during 1955-1962 and 51% lower after 1963.

3.2.6. Impacts of Changing Fertility on the Largemouth Bass Fishery

Largemouth bass were first introduced into Lake Mead in 1935 and annual plantings were made through 1942 (NDFG 1977). The largemouth bass fishery was reported to be fair to excellent in the late 1930's when the reservoir was filling. However, around 1940, fishermen complained that the bass were in poor condition and had lost their "gameness" (Hoffman and Jonez 1973). Studies conducted by Moffet (1943) revealed that there was a "lack of aquatic vegetation" and the "plankton was none to plentiful". The fishery recovered in 1941 when water levels in Lake Mead increased with high runoff from the Colorado River. The fishery then underwent another decline in the late 1940's which led to another investigation (Jonez and Sumner 1954) aimed at developing methods of enhancing the bass fishery. Jonez and Sumner (1954) concluded that stabilization of water levels, introductions of forage fish and fertilization could all have a beneficial impact on the largemouth bass population.

Threadfish shad (Dorosoma petenense) were introduced into Lake Mead in 1953 and 1954 and quickly became established in the reservoir. This caused a significant increase in growth rates of bass (Minckley 1972) but did not result in an appreciable increase in their abundance. Creel census data collected in Lake Mead since 1953 by the Nevada Department of Fish and Game (NDFG 1977) showed that the bass harvest only increased slightly after shad were introduced and the catch per angler day decreased during the period from 1953-1962 (Fig. 16). The fishery improved significantly in 1963 but has since undergone a progressive decline.

The decline in the largemouth bass fishery has been the subject of much local concern and investigation. The Arizona and Nevada Departments of Fish and Game are currently investigating the causes for the decline, and suspect it is related most to water level fluctuations during the spawning season. Moffet (1943), Jonez and Sumner (1954), Hoffman and Jonez (1973), and Allan and Romero (1975) have all noted an apparent correlation between water levels and success of the bass fishery in Lake

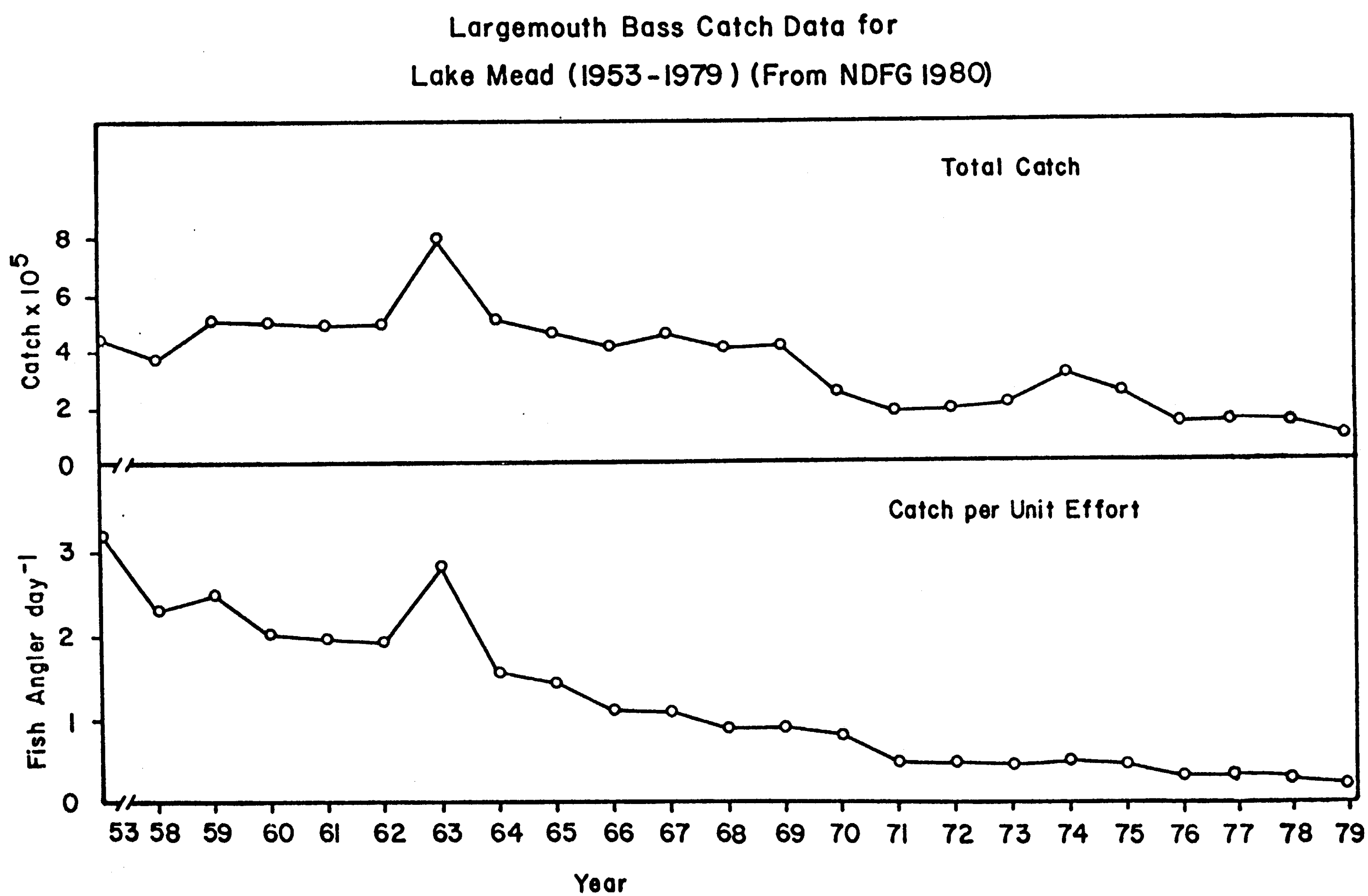

Figure 16. Largemouth bass total catch and catch per angler day during 1953-1979 (From NDFG 1980 and Allan and Roden 1978).

Mead. The high survival of bass observed in 1941 (Moffet 1943) and 1952 (Jonez and Sumner 1954) was associated with higher than normal runoff from the Colorado River and high water levels in Lake Mead. Hoffman and Jonez (1973) also observed that the bass catch improved following years of high runoff in 1957 and 1958. This was also evident in the catch for 1963 (Fig. 16) which followed a 10 m increase in water level during the spring of 1962 (Fig. 17).

Largemouth bass in Lake Mead prefer to nest and spawn at depths of 2-3 m (Allen and Romero 1975). The increased cover provided by submerged terrestial and aquatic vegetation is thought to enhance bass spawning and survival in years when water levels are high and stable (Allan and Romero 1975). Receding water levels, however, act in reverse, exposing the nests to greater wave action and can even cause the adult fish to abandon their nests (Deacon, Minckley and Paulson 1971).

Annual water levels in Lake Mead were maintained fairly constant and spring levels generally increased during the late 1950's and early 1960's (Fig. 17). Water levels decreased sharply in the period from 1963-1965. This was accompanied by a corresponding decrease in the bass harvest and angler success rate (Fig. 16). The fishery, however, continued to decline through 1971, despite steady increases in water levels and minimal fluctuations during the spring. There was only a slight increase in the bass harvest and the catch per angler day remained constant in 1973 and 1974, even though water levels increased by nearly 4 m during the spring of 1973 and the annual

Lake Mead Water Level Changes During Bass Spawning Season
(February – May) (USGS Data)

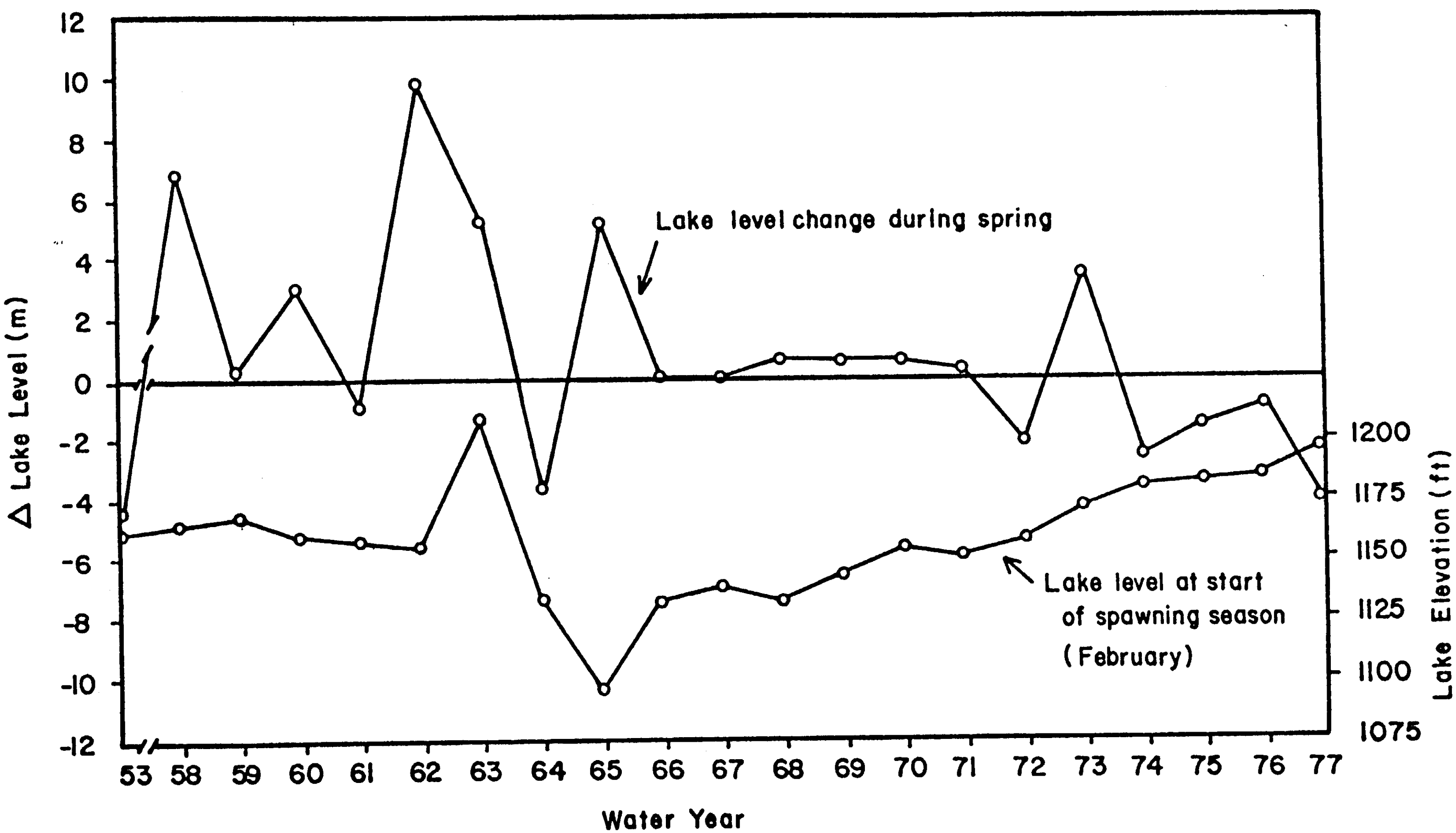

Figure 17. Annual lake elevations and water level fluctuations in Lake Mead during the spring largemouth bass spawning season (February-May). Data are end of the month values reported for the Hoover Dam intake towers (USGS 1953-1977).

levels were higher than those in the late 1950's and early 1960's. The correlation between lake levels and success of the bass fishery is therefore less evident in the post-Lake Powell period suggesting that perhaps factors other than cover and bass spawning success are involved in their decline.

The historical nutrient data on the Colorado River and chemical analyses of Lake Mead sediments clearly show that nutrient loading has varied in relation to runoff during the pre-Lake Powell period. Moreover, higher nutrient loading during the period from 1955-1962 caused a marked increase in reservoir-wide phytoplankton productivity. Productivity averaged 651 MT yr^{-1} or 3836 mg C $m^{-2}da^{-1}$ during this period reflecting the highly productive condition of the reservoir. However, nutrient loading to Lake Mead was drastically reduced during the post-Lake Powell period. Moreover, reductions in spring runoff have reduced the magnitude of the spring overflow that once transported nutrients across surface waters of the Upper Basin. The combination of decreased nutrient loading and availability resulted in marked declines in phytoplankton productivity during the post-Lake Powell period. Reservoir-wide productivity decreased to 144 MT yr^{-1}, or 831 mg C m^{-2} day^{-1}. Reductions in productivity were especially severe in the Upper Basin, which comprises two-thirds of the reservoir area. The Lower Basin would have been equally affected were it not for increased nutrient loading from Las Vegas Wash.

Benthic food resources in Lake Mead are depauperate (Jonez and Sumner 1954; Melancon 1976), and the fish populations are therefore almost wholly dependent on limnetic (open water) phytoplankton productivity, via transfers through zooplankton and shad, as their principal source of energy. Zooplankton abundance in Lake Mead is presently closely related to chlorophyll-a concentrations and phytoplankton productivity (Paulson et al. 1980) and a similar relationship has probably existed in the past. Comparisons of zooplankton data collected in 1971 (Everett 1972) with those collected in 1975 (Burke 1976), 1977-78 (Paulson et al. 1980) and 1980 (Paulson unpubl. data) reveal that zooplankton abundance has decreased by ten-fold over this period (Wilde 1981) (Fig. 18). This decline closely parallels reductions in nitrate loading from the Colorado River after 1970 (Fig. 13) as well as reductions in chlorophyll-a concentrations in Las Vegas Bay since 1972 (Deacon and Tew 1973; Deacon 1975, 1976, 1977). The decrease in chlorophyll-a concentrations in Las Vegas Bay has resulted primarily from reductions in the early spring pulse in productivity (Paulson 1981). The absence of a well-defined spring bloom and the historical decline in productivity in Lake Mead are the principal reasons for the decrease in zooplankton abundance (Wilde 1981).

Zooplankton have repeatedly been found to be the principal food resource for largemouth bass fry (Baker and Burke 1976; Keenan and Baker 1978; Greger and Baker 1980; Wilde and Baker 1981). Allan and Romero (1975) suggested that poor survival of bass fry in 1974 could have been due to low densities of zooplankton in Lake Mead. Ongoing investigations of bass reproduction have repeatedly shown that survival of bass fry and

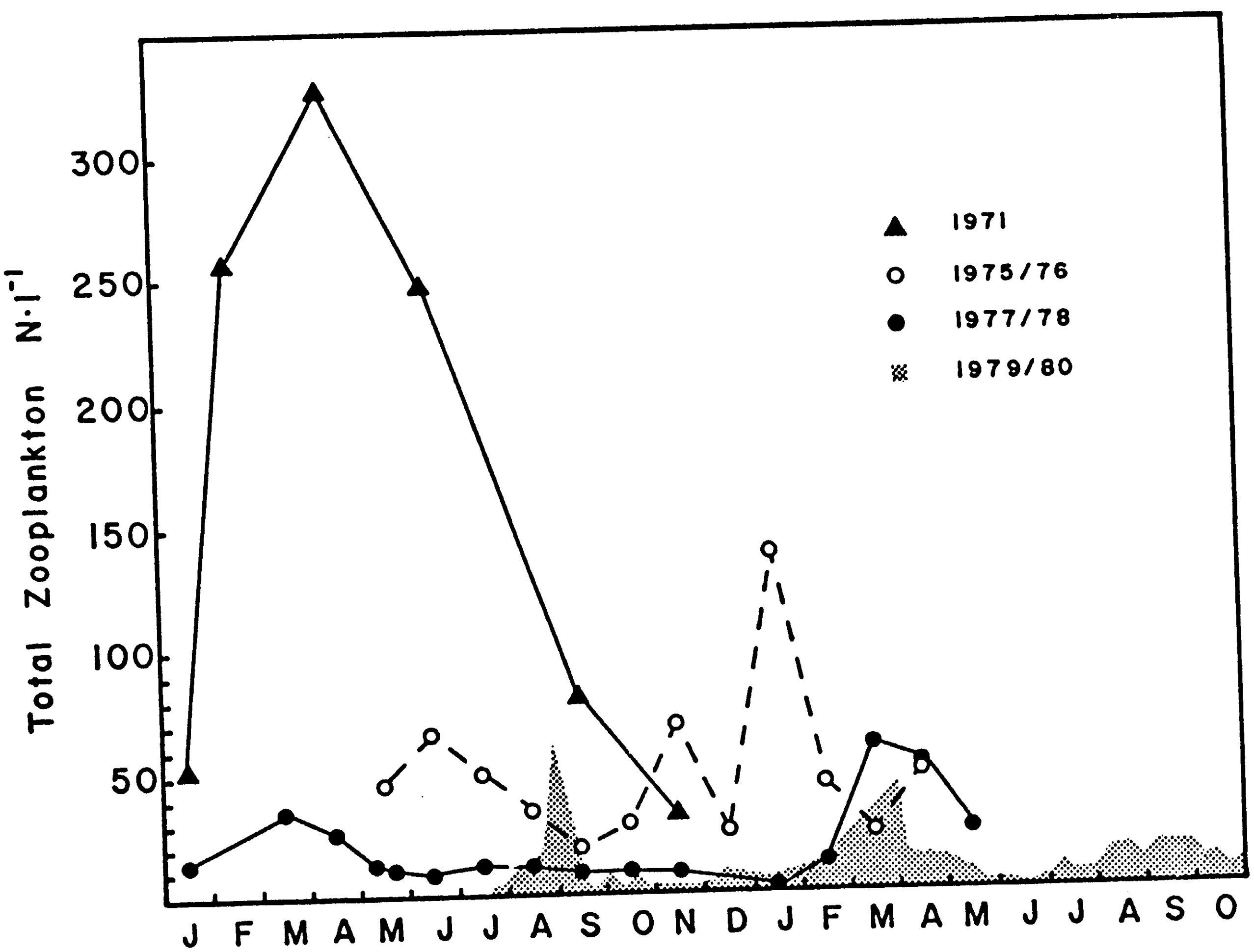

Figure 18. Zooplankton abundance in Boulder Basin, Lake Mead during 1971 (Everett 1972), 1975-76 (Burke 1976), 1977-78 (Paulson et al. 1980) and 1979-80 (Paulson unpubl. data). Graph was compiled by Wilde (1981).

recruitment into the catchable population are low, despite relatively good nesting and hatching success (Arizona and Nevada Departments of Wildlife, unpubl. data). Although there was a substantial decrease in limnetic zooplankton densities between 1971 and 1975 (Fig. 18), there was very little change in the catch of largemouth bass (Fig. 16). This suggests that either zooplankton are not limiting bass recruitment at all, or that even the higher 1971 zooplankton densities were limiting at that time. Other factors such as competition between bass fry and threadfin shad may be responsible for the poor recruitment.

The availability of zooplankton for bass fry may be reduced through zooplankton predation by threadfin shad. Shad are efficient planktivores, and they rely heavily on cladoceran zooplankton species in Lake Mead (Deacon et al. 1971). Shad, in turn, provide the principal food source for adult largemouth bass (Deacon et al. 1971). The adult bass (>1 year age) in Lake Mead responded with an increase in growth rates subsequent to the introduction of threadfin shad in 1954 (Minckley 1972). However, there was no appreciable increase in bass abundance perhaps reflecting greater competition between threadfin shad and bass fry. Peak spawning of shad occurs in May (Deacon et al. 1971) which overlaps with the bass spawning season and emergence of fry. In years when productivity and zooplankton densities were higher, competition for food was probably not sufficent to cause a decrease in bass survival but it may have prevented an increase that otherwise might have occurred. However, when productivity decreased after the formation of Lake Powell, it seems probable that threadfin shad competition for zooplankton contributed to the decrease in their abundance and ultimately to the decline of the largemouth bass population.

The threadfin shad population in Lake Mead, however, has also undergone a recent decline (Baker and Paulson 1981). Routine echo-sounding surveys conducted in the Lower Basin and periodically in the Upper Basin (Deacon and Tew 1973; Deacon 1975) have shown that shad were relatively abundant in the Lower Basin during the period from 1972 to 1975. Echo-sounding surveys made in 1979-80 demonstrated that the shad population has undergone a significant decline since 1975 (Baker and Paulson 1981). Limnetic areas of the Upper Basin and Boulder Basin are now characterized by an almost complete absence of shad. Las Vegas Bay and the upper Overton Arm are the only areas of the reservoir where shad are still found in fairly high abundance (Baker and Paulson 1981). These are also areas where fertility is higher (Paulson et al. 1980) indicating that the shad, like zooplankton, respond to changes in reservoir productivity. There may, therefore, have been an overall decrease in the shad population with the decline in reservoir-wide productivity since 1963, but it seems that the abrupt decrease between 1975 and 1980 was caused by other factors.

The recent decreases in the shad population are inversely related to the rapid increases in the striped bass (*Morone saxatilis*) population in Lake Mead. Striped bass were first introduced into Lake Mead in 1969 and annual plantings were made through 1972 (Allan and Roden 1978). Successful striped bass reproduction was first noted in 1973, and the population grew rapidly in the mid-1970's (Allan and Roden 1978). Threadfin shad and rainbow trout (*Salmo gairdneri*) comprised the principal diet of striped bass prior to 1976 (Allan and Roden 1978). However, rainbow trout almost disappeared from the catch in 1976, and this appeared to be due to predation by striped bass (Allan and Roden 1978). Threadfin shad have since become the principal food for striped bass, and their population apparently cannot withstand such intense predation, especially in light of the low fertility of Lake Mead. The striped bass and threadfin shad populations are currently in a state of flux, and it is difficult to predict whether the shad population will recover in the future. However, if not, this could have a positive influence on the largemouth bass population by reducing competition that seems to exist between bass fry and threadfin shad. The zooplankton, shad, largemouth bass, and striped bass populations should be closely monitored over the next several years to assess the consequences of these recent changes in the Lake Mead fishery.

3.3 Summary of the Effects of Glen Canyon Dam Operations on the Fertility, Productivity and Fishery of Lake Mead.

The construction of Glen Canyon Dam and formation of Lake Powell in 1963 has clearly had a significant impact on the fertility and productivity of Lake Mead. Reductions in spring discharge peaks combined with colder river temperatures, which cause the Colorado River inflow to flow deeper in Lake Mead, have virtually eliminated the overflow that once transported silt-laden, nutrient-rich river water across the surface of the Upper Basin (Paulson and Baker 1981). Retention of suspended sediments and dissolved phosphorus in Lake Powell have reduced phosphorus loading to Lake Mead by 80-90%. Nitrogen loading decreased initially, then increased again through 1970, but has since decreased to a lower steady state. The Upper Basin became severely phosphorus deficient and phytoplankton productivity decreased from 395 MT yr^{-1} during 1955-1962 to 44 MT yr^{-1} after 1963. Relatively high nitrogen loading from the Colorado River during 1965-1970 and increased phosphorous loading from Las Vegas Wash combined to elevate productivity in the Lower Basin over this period. However, development of nitrogen limitation in Las Vegas Bay and parts of Boulder Basin after 1972 (Paulson and Baker 1981) have since kept productivity in the Lower Basin far below that which occurred in the Upper Basin during the 1955-1962 period. Reservoir-wide productivity has therefore undergone a significant decrease in the post-Lake Powell period and the Upper Basin is now oligotrophic, Boulder Basin is mesotrophic and Las Vegas Bay ranges from mesotrophic to eutrophic (Paulson et al. 1980).

The decline in the largemouth bass fishery in Lake Mead is closely related to the historic changes in nutrient loading and productivity. Zooplankton populations in Boulder Basin have decreased in abundance since the first measurements were made in 1971 (Wilde 1981), and it is likely that an even more severe, reservoir-wide decline has occurred since 1963. In the face of declining zooplankton abundance, it appears that largemouth bass fry survival has undergone a corresponding decrease which has resulted in lower recruitment and ultimately contributed to the decline in the fishery. Threadfin shad predation on zooplankton may have further reduced zooplankton abundance thus compounding the effects created by declining fertility and productivity. Recent declines in the shad population could reduce food competition and perhaps enhance largemouth bass survival. However, it is unlikely that the largemouth bass fishery can be restored to pre-Lake Powell status unless methods can be implemented to increase the fertility of Lake Mead.

3.4 Methods for Enhancing the Fertility of Lake Mead

In a recent report, Paulson (1981) described how the operation of Hoover Dam has contributed to declines in fertility and productivity of Lake Mead. Hoover Dam is operated from a deep discharge (100 m) and nutrient losses in the discharge are high due to accumulation of nutrients in the hypolimnion during thermal stratification (Paulson et al. 1980; Paulson 1981) (Table 13). Prior to construction of Glen Canyon Dam, flooding and high runoff from the Colorado River periodically replenished nutrient concentrations in Lake Mead and fertility was sustained, despite high loss rates from Hoover Dam (Paulson 1981). However, once loading from the Colorado River was cut in 1963, the deep-water discharge at Hoover Dam rapidly stripped nutrients from Lake Mead and accelerated the decline in reservoir fertility and productivity (Paulson et al. 1979; Paulson 1981). Nutrient loss rates from Lake Mead would decrease considerably if Hoover Dam were operated from a surface, rather than deep-water discharge (Paulson et al. 1979; Paulson et al.

Table 13. Nutrient losses from Hoover Dam for an epilimnion and hypolimnion discharge during July, 1979 to July, 1980 (from Paulson, 1981).

Discharge Depth	Nutrient Loss (kg x 10^3) Inorganic P	Organic P	Total P	Inorganic N	Organic N	Total N
Epilimnion	30	71	101	1310	2809	4119
Hypolimnion	101	68	169	3845	2428	6273
Difference (Hypolimnion-Epilimnion)	71	-3	68	2535	-381	2154

1980; Paulson and Baker 1981; Paulson 1981) (Table 13). Greater retention of nitrogen and phosphorous in Lake Mead would increase productivity that, in turn, should enhance zooplankton abundance and perhaps survival of largemouth bass fry. Investigations are currently being conducted to better quantify the trophic relationships, but it seems that altering the discharge depth in Hoover Dam could represent an effective method of increasing reservoir fertility and productivity to improve the quality of the largemouth bass fishery.

It might also be possible to operate offline, pump-storage systems in a manner that would improve fertility in some parts of Lake Mead. Pump-storage hydroelectric units have been proposed for installation in the Spring Canyon, Pinto Valley and Rifle Range areas of Lake Mead. The Water and Power Resources Service is currently conducting pump-storage feasibility studies, but the design features and operating criteria of these systems have not yet been defined. Nonetheless, we have identified some possibilities whereby pump-storage systems can be used as nutrient recycling mechanisms (Paulson, Deacon, and Baker 1978) (Fig. 19).

Phytoplankton deplete nutrients from epilimnetic waters of the Lower Basin and to a lesser degree the Upper Basin of Lake Mead during the summer (Paulson et al. 1980; Paulson and Baker 1981; Paulson 1981). However, nutrients accumulate in the metalimnion and hypolimnion due to sinking and remineralization of autochthonous organic matter and periodic underflows of the Las Vegas Wash and Colorado River density currents. When the

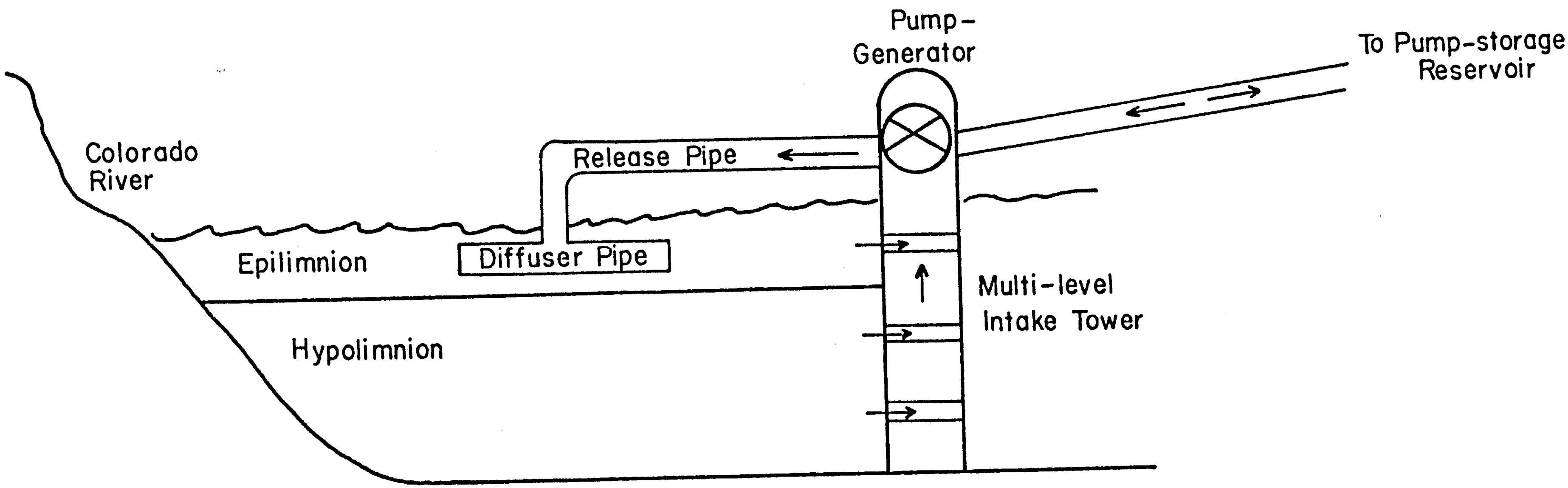

Figure 19. A pump-storage hydroelectric unit designed to recirculate nutrients in Lake Mead.

reservoir is thermally-stratified (June-October), mixing of nutrient-rich waters from the metalimnion and hypolimnion into the epilimnion is minimal. Such mixing, however, could be achieved if pump-storage systems were operated in a manner similar to that shown in Fig. 19. Water could be withdrawn from the hypolimnion and pumped into the storage reservoir, where it could be held for a brief period to increase the temperature. Water could then be released back through the generators and returned to the epilimnion of Lake Mead via a diffuser. Recycling nutrients in this manner would greatly enhance availability of nitrogen and phosphorus for phytoplankton growth in the local vicinity of the pump-storage units. The Lower Basin would exhibit a greater response than the Upper Basin because of additional phosphorus inputs from Las Vegas Wash. Although there may be possible engineering problems associated with such a pump-storage system, it clearly represents another mechanism for enhancing the productivity of Lake Mead.

The final mechanism we have identified for enhancing fertility of at least the Lower Basin of Lake Mead is to continue allowing nutrients to enter from Las Vegas Wash. This inflow supplies about 60% of the annual phosphorous input to the reservoir (Baker and Paulson 1981) and nitrogen loading has been increasing since 1979 (Fig. 14). In 1973, the Nevada State Environmental Commission adopted a 0.5 mg l^{-1} phosphorus standard on sewage effluents discharged into Lake Mead. An advanced wastewater treatment plant is currently being constructed in Las Vegas to reduce effluent phosphorus concentrations to this level, if present studies (Las Vegas

Valley Water Quality Program) demonstrate that this is necessary to protect water quality in Lake Mead. Paulson et al. (1980) cautioned that severe reductions in phosphorus loading would be accompained by decreased fertility and productivity in most of the Lower Basin of Lake Mead. Morever, Las Vegas Wash, via discharges from Hoover Dam, supplies the principle phosphorus source to Lake Mohave, and similar reductions in fertility could be expected in this, and perhaps other, downstream reservoirs. Lake Mohave currently supports an excellent largemouth bass fishery and a major reason for this is the relatively high productivity which is sustained by discharges of phosphorus-rich waters from Hoover Dam. The potential that extreme phosphorus removal will cause further declines in the Lake Mead fishery and perhaps initiate a similar decline in Lake Mohave clearly exists, and should be carefully considered in current efforts to establish water quality standards for Las Vegas Wash to protect beneficial uses of Lake Mead. If alternatives can be developed to avoid "point source" water quality problems in the inner Las Vegas Bay (e.g. diffusers), it seems that increased nutrient loading from Las Vegas Wash could be used to enhance the fishery of Lake Mead.

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5.0 GLOSSARY OF TERMS

allochthonous - produced within the catchment basin of a lake and brought to the lake in various organic forms

autochthonous - produced within the lake, used to describe the origin of organic matter

bottomset delta - that part of the delta from the foot of the foreset delta to the dam having a slope of 4-9 feet per mile in Lake Mead

calcareous sediments - sediments characterized by appreciable calcium carbonate content

carbonate precipitation (calcite formation) - the precipitation of calcium and bicarbonate, usually occurring in alkaline hardwater lakes, often in response to elevated pH brought about by photosynthetic removal of CO_2

catch per angler day - total annual fish harvest divided by total number of angler efforts (in days)

chlorophyll-a - photosynthetic plant pigment often used as a biomass indicator for phytoplankton

cladoceran zooplankton - free-floating animals of the sub-class Cladocera, e.g. Daphnia and Bosmina

denitrification - the biochemical reduction of oxidized nitrogen anions, nitrite and nitrate, to elemental nitrogen (N_2) gas

density current - an inflow of water having a density different than that of the receiving water due to differences in temperature and/or dissolved salts concentration

echo sounding surveys - use of sound-waves in detecting bottom definition and fish distribution in lakes

epilimnion - the upper region of a thermally stratified lake lying above the thermocline (region of maximum rate of temperature change with depth), characterized by warm, circulating, and fairly turbulent water

eutrophic - describing a body of water characterized by appreciable organic material and nutrients, and in which hypolimnetic oxygen declines are present during some time of the year

foreset delta - the delta front between the topset and bottomset delta having a very steep slope, ranging from 300 ft. per mile at the top to 25 ft. per mile at the foot in Lake Mead hypolimnion - the region of a thermally stratified lake lying below the thermocline (see epilimnion), characterized by cold, relatively non-disturbed or non-turbulent water

inorganic phosphorus - compounds such as orthophosphate, calcium phosphates and polyphosphates which do not contain organic carbon

limnetic - describing the open-water or pelagic region of lakes

marbling - visually apparent discontinuities in sediment cores

metric tons (MT) - 1000 kg

mesotrophic - describing lakes which fall between oligotrophic and eutrophic conditions, characterized by moderate amounts of organic material and nutrients; hypolimnetic oxygen decreases occur, but are not common

morphometry - collection of measurements of physical characteristics of lakes (morphology), such as maximum depth, length, shoreline development, area, volume, etc.

NaOH-extractable phosphorus - orthophosphate and non-occluded inorganic phosphorus loosely bound to aluminum or iron compounds; used to indicate the amount of phosphorus readily available for biological growth

nitrification - biological conversion of organic and inorganic nitrogen compounds from a reduced state to a more oxidized state (e.g. ammonia (NH_3) to nitrate (NO_3)).

oligotrophic - describing a body of water generally deficient in organic material and nutrients and in which hypolimnetic oxygen decreases are usually absent

organic phosphorus - phosphorus compounds containing organic compounds derived from some biologically-mediated process

oxidized sediment zones - regions of the sediments characterized by a relatively high redox potential (see redox depth) and relatively oxidized chemical compounds

planktivores - organisms which consume plankton (free-floating animals and plants which depend on water current for locomotion)

polyphenols - organic compounds which adsorb to the surface of calcium carbonate precipitates, thereby reducing the surface area of the solid in contact with water and consequently slowing or eliminating further precipitation

pore water - water contained within the spaces between sediment particles (interstitial water) post-depositional nutrient transformations - conversions of nutrients to different forms, occurring after they are deposited in the sediment

productivity - rate of new organic carbon accumulation per unit volume per unit time

pump-storage units - hydroelectric facilities used to produce peaking power through the use of reversible turbines

recruitment - addition of individuals to a population through reproduction or immigration

redox depth - the depth of sediment at which the boundary between a reducing and oxidizing environment occurs. Redox is the oxidizing ability of the sediments, measured in volts.

reduced sediment zones - region of the sediment characterized by a relatively low redox potential (see redox depth) and reduced chemical compounds

remineralization - the biologically-mediated conversion of organic matter to carbon dioxide and inorganic compounds

sediment bulk density - grams of dry sediment (125°C) per unit volume (cm^3)

sediment inorganic carbon content - amount of inorganic carbon compounds such as $MgCO_3$, $CaCO_3$, dolomite, aragonite contained per gram of sediment, dried at 125°C; determined by difference in weight loss between samples combusted at 550°C and 950°C

sediment organic matter content - amount (by weight) of organic compounds per gram dry weight of sediment (125°C) determined by loss in weight between samples dried at 125°C and combusted at 550°C. Combustion at 550°C converts organic compounds to CO_2 which is then lost as a gas.

sediment organic nitrogen content - amount of organic nitrogen compounds (by weight) per gram sediment dry weight (125°C), determined by combustion in a carbon, hydrogen, nitrogen (CHN) elemental analyzer

sediment-water interface - region lying between the uppermost surface of the sediments and the water overlying the sediments

sulfate reduction - the bacteria-mediated conversion of sulfate ($SO_4^{=}$) to sulfide ($S^{=}$); the oxygen derived from the conversion is then used to oxidize organic matter or molecular hydrogen surficial sediments - most recently deposited sedimentary minerial lying in the uppermost layer of the sediment of a lake

thalweg - the longitudinal profile of a river valley or submarine canyon

thermal stratification - conditions occurring in a lake as a result of solar radiation and consequent heating which produces waters of different temperatures and hence densities (see epi-, hypo-, and metalimnion)

topset delta - the uppermost part of the delta at the river inflow having an average slope of 1.2-1.3 feet per mile in Lake Mead

trophic state - referring to the rate per unit time at which organic matter is supplied to or produced within a lake

wet sediment volume - grams of wet sediment per unit volume (cm^3)

zooplankton - animals whose movements are partly, if not wholly, controlled by water currents