INTERRELATIONSHIPS AMONG NUTRIENTS, PLANKTON AND STRIPED BASS IN LAKE MEAD

By

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Technical Report No. 10

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Final Report to the Nevada Department of Wildlife, Striped Bass Investigations

June, 1983

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ACKNOWLEDGEMENTS

We wish to thank Nevada Department of Wildlife personnel, especially Cal Allan and Bob Sumner, for their assistance and cooperation in the study. Special thanks also go to: Mick Reese for supervising the field sampling; Sherrell Paulson and Renee Hughes for the nutrient analyses; Patrick Sollberger for the chlorophyll-*a* analyses; Ed Albert for the ^{14}C counting, Gene Wilde for the zooplankton counting and Jim Williams and Jamie Meyer for the computer programming. We are also indebted to Laurie Vincent for typing the manuscript.

1.0 INTRODUCTION

The striped bass (Morone saxatilis) fishery in Lake Mead has experienced numerous problems in recent years. Fishermen complained that the incidence of large striped bass in the catch decreased during 1980. They also noted that a large percentage of the fish were emaciated and in poor condition. These observations were substantiated by creel census data (NDW 1980) which showed that angler success and condition factors of striped bass decreased in 1980 (Baker and Paulson 1983). Nutritional problems were identified as the most likely cause for their poor condition (Sakanari 1981).

Threadfin shad (Dorosoma petenense) comprise the principal forage base for striped bass in Lake Mead (Allan and Roden 1978, Albert and Baker 1983). Echo sounding surveys have shown that shad were very abundant in limnetic areas of the reservoir during 1972-1975 (Baker and Paulson 1983). Limnetic areas in the upper basin and Boulder Basin were nearly devoid of shad in 1980 (Baker and Paulson 1983). It appears that predation by striped bass was the major cause for the decline in shad abundance. However, this was probably compounded by the low fertility and productivity in the reservoir.

Chlorophyll-a concentrations averaged only 1.3 μg/l in the upper basin and 3.0 μg/l in the Boulder Basin during 1977-78 (Paulson et al. 1980). Chlorophyll-a averaged 7 μg/l and ranged as high as 23 μg/l in Las Vegas Bay due to inflows of secondary-treated sewage effluents from Las Vegas Wash. Numerous investigators have found that fish production is closely related to levels of phytoplankton productivity (Melack 1976, Oglesby 1977, Jones and Hoyer 1981). Rinne et al. (1981) also noted that the abundance of threadfin shad was closely related to chlorophyll-a concentrations in the Salt River Reservoirs, Arizona. Shad are still fairly abundant in the Las Vegas Bay area suggesting that a similar relationship exists in Lake Mead.

This relationship most likely reflects the effects of higher productivity on densities of zooplankton. Zooplankton comprise an important component in diets of threadfin shad in Lake Mead (Deacon et al. 1972). Previous studies have shown that zooplankton standing crops in the reservoir were generally related to chlorophyll-a concentrations (Paulson et al. 1980, Wilde 1981). However, there was considerable seasonal variation in the relationship and some differences in the response of various zooplankton groups to chlorophyll-a gradients in the reservoir. The Nevada Department of Wildlife (NDW) initiated this investigation to further evaluate the relationship between zooplankton densities and various limnological factors in Lake Mead. The project was part of a larger investigation being conducted by NDW to evaluate the factors regulating the striped bass population in Lake Mead.

2.0 DESCRIPTION OF THE STUDY AREA

2.1 Lake Mead

Lake Mead is a large interstate impoundment located 15 km northeast of Las Vegas, Nevada in the Mojave Desert of southeastern Nevada and northwestern Arizona. The reservoir was formed in 1935 by construction of Hoover Dam and is the second in a series of reservoirs on the Colorado River that include Lake Powell, Lake Mead, Lake Mohave, and Lake Havasu. Lake Mead extends 183 km from the mouth of the Grand Canyon (Pierce Ferry) to Black Canyon, the site of Hoover Dam. The reservoir is 28 km wide between Bonelli Bay and Overton, the northwest arm of the reservoir (Fig. 2.1.1). Lake Mead is comprised of four large basins: Boulder, Virgin, Temple and Gregg Basin, interspersed with four narrow canyons: Black, Boulder, Virgin and Iceberg Canyon. The reservoir is bordered by the Muddy and Frenchman Mountains on the north and the Virgin and Black Mountains on the south. In this report, we refer to the area from Virgin Basin to Pierce Ferry as the Upper Arm; the area above Boulder Canyon as the Upper Basin, and the area below Boulder Canyon as the Lower Basin.

In terms of volume, Lake Mead is the largest reservoir in the country, and second only to Lake Powell in surface area (Table 2.1.1). The shoreline is extremely irregular (SLD = 9.7) and includes several large bays (Las Vegas and Bonelli) and numerous coves. The reservoir has a short hydraulic retention time (3-4 yrs.) due to the great inflow from the Colorado River. The discharge from Hoover Dam is in the hypolimnion at 83 m depth (at operating level of 364 m). Other pertinent morphometric characteristics for Lake Mead are summarized in Table 2.1.1.

The principal water inflow to Lake Mead is derived from the Colorado River, but the Virgin and Muddy Rivers, which discharge into the Overton Arm, and Las Vegas Wash, which discharges into Las Vegas Bay, also contribute year-round inflows. There is only one principal water diversion from Lake Mead. This is located at the Southern Nevada Water Project near Saddle Island, where municipal, irrigation and industrial waters are diverted to the Las Vegas Metropolitan Area.

The predominate geological feature of the Lake Mead floor and surrounding area is the sedimentary deposits of the Muddy Creek formation that were formed during the Paleozoic and Mesozoic eras

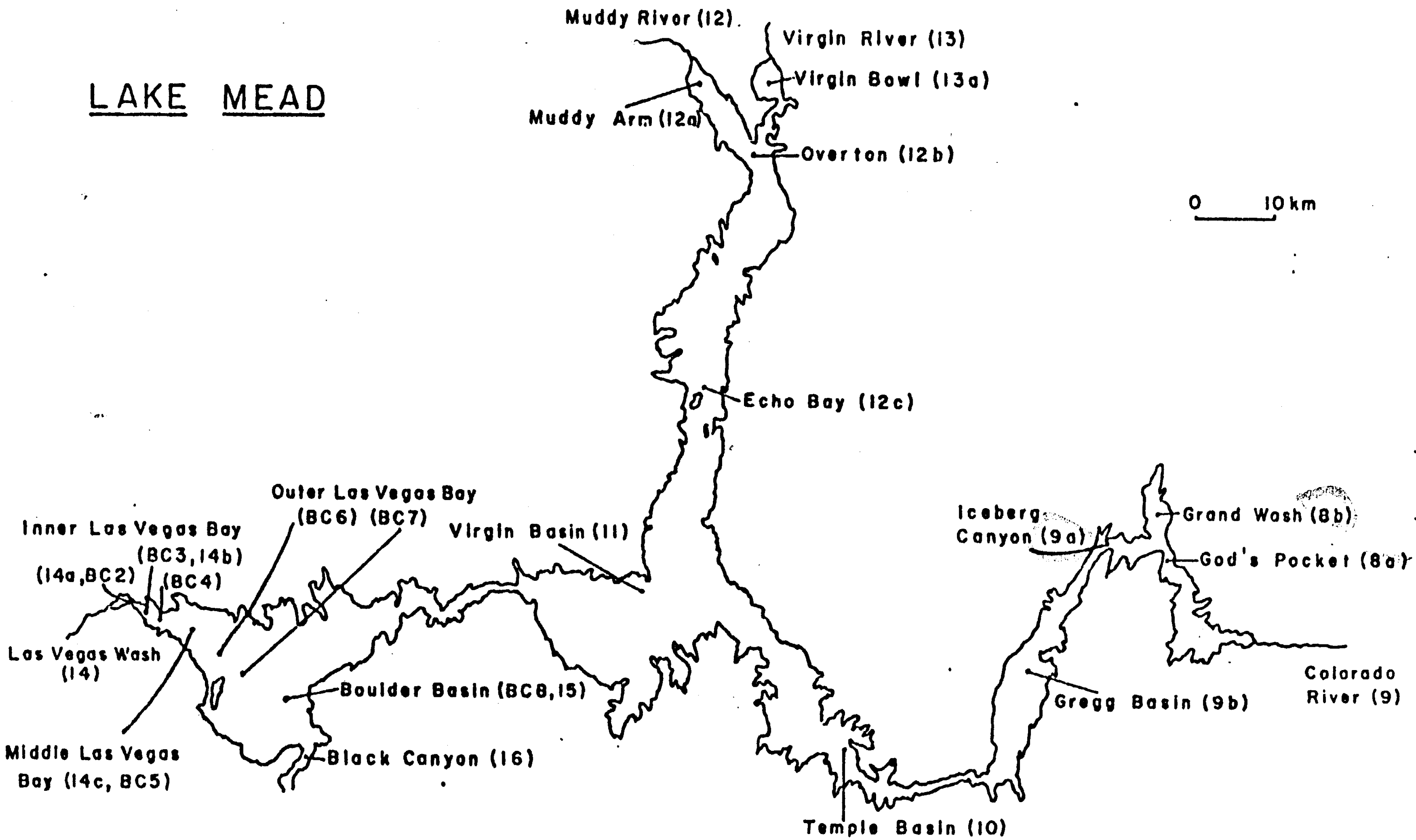

Figure 2.3 Map of Lake Mead showing locations of sampling stations.

Table 2.1.1. Morphometric characteristics of Lake Mead (Paulson et. al. 1980)

Parameter	Lake Mead
Maximum operating level (m)	374.0
Maximum depth (m)	180.0
Mean depth (m)	55.0
Surface area (km^2)	660.0
Volume ($m^3 \times 10^9$)	36.0
Maximum length (km)	183.0
Maximum width (km)	28.0
Shoreline development*	9.7
Discharge depth (m)	83.0
Annual discharge (1977)($m^3 \times 10^9$)	9.3
Replacement time at maximum operating level (years)	3.9

* Unitless parameter to measure regularity of shoreline, value of 1 is equivalent to a lake shaped in a perfect circle.

(Longwell 1936). These deposits consist of moderately consolidated sand, silt and clay. There are also layers of shale, sandstone and limestone interspersed with beds of gypsum, anhydrite and rock salt (Longwell 1936). Deposition of fine silt material since formation of the reservoir has altered the original floor of Lake Mead. Up to 25 m of silt was deposited in the upper reaches of the reservoir before Lake Powell was formed in 1963 (Lara and Sanders 1970).

The vegetation surrounding Lake Mead is comprised primarily of salt cedar (Tamarix gallica) and creosote bush (Larrea tridentata). Emergent macrophytes are rare, but some coves contain a few isolated stands of cattails (Typa sp.) and sedges (Scirpus sp.). Submergent macrophytes are also rare, but Potomogeton pectinatus and Najas sp. occur sporadically in shallow coves.

The water quality of the Colorado River and Lake Mead is alkaline (pH 7.6 - 8.3), and the TDS averages about 700 mg/l. The princpal constituents of TDS are the anions sulfate > carbonate > chloride and cations sodium > calcium > magnesium > potassium. Nitrogen concentrations are moderate (ca. < 0.2 - .5 mg/l) but phosphorus is extremely low (ca. .010 mg/l) throughout the river. Silica is present in very high quantities (ca. 7-8 mg/l).

The climate is arid with annual precipitation averaging about 8 cm. Mean annual temperature is about 19°C with a range from 45°C in the summer down to -1°C in the winter. Winds are highly variable, but generally, southerly winds prevail in the summer compared to north-easterly winds in the winter.

3.0 METHODS

3.1 Sampling Locations

The location of sampling stations in Lake Mead are depicted in Fig. 2.3 The stations are labeled by name and number for easy reference in subsequent sections of this report.

3.2 Phytoplankton Productivity

Phytoplankton productivity was measured monthly, *in situ*, with the ^{14}C-method (Steeman-Nielsen 1952, Goldman 1963). Bi-weekly measurements were also made at the Lower Basin stations during summer (July-September). Water samples were collected from 0, 1, 3, 5, 7, 10, 15, 20, and 25 m, or to the bottom at shallow stations. Samples were collected with a 3-liter Van Dorn sampler and transferred to 125-ml glass-stoppered reagent bottles. Two light bottles and an opaque bottle from each depth were inoculated with 1 ml of a 1.0 µCi/ml $NaH^{14}CO_3$ solution. The bottles were resuspended at the depth of collection and incubated for a 3-4 hour period during mid-day. Since several stations had to be sampled each day, synoptic incubations were used for stations where light transmittance was similar. Stations 14a, 14b and 15 in the Lower Basin, 12a, 12b and 13a in the Overton Arm and 8b, 9a, and 9b in the Upper Arm were incubated on location. Station 11 (Virgin Basin) was incubated at station 12c (Echo Bay) and station 10 (Temple Bar) was incubated at station 9b (Gregg Basin). After the incubation period, the bottles were stored in light-proof ice chests and transported to the laboratory for processing.

The entire contents of each bottle were filtered through .45 µ membrane filters (47 mm dia.) at 100 mm Hg. The filters were rinsed with

.005 N HCl to dissolve any carbonate residue embedded in the filters. Each filter was transferred to a 22 ml scintillation vial, allowed to dry, and then filled with 20 ml of scintillation cocktail (2 parts PCS:1 part Xylene). Radioactivity was measured with a Beckman LS-100 Scintillation Counter, calibrated with a certified standard $NaH^{14}CO_3$ solution.

In order to determine inorganic carbon (^{12}C), total alkalinity was determined on a water sample collected at the same depth as phytoplankton productivity. Temperature and pH were first measured, and a 50 ml sample was then titrated with .02 N HCl to pH 4.8 (APHA 1975). Inorganic carbon was calculated from conversion tables of Saunders et al. (1962).

A pyroheliometer (Weather Master), placed in the vicinity of the sampling stations was used to record solar radiation during the incubation period. Incident solar radiation was determined by planimetry of the recording. Estimates of total daily solar radiation were obtained from the University of Nevada, Las Vegas Biological Sciences Department or the Las Vegas Airport. Daily phytoplankton productivity was computed by extrapolation from the ratio of solar radiation during the day to solar radiation during the incubation period. Integral (areal) phytoplankton productivity (mg C/m^2/day) was computed by trapezoidal integration of discrete depth interval measurements.

3.3 Chlorophyll-a

Chlorophyll-a concentrations were measured monthly at each sampling location. Weekly or bi-weekly measurements were also made at the Lower Basin stations during summer (July-September). One-liter water samples were collected from a 0-2.5 m integrated sample at station 14a and a 0-5 m integrated sample at the other stations. The samples were stored in the dark in an ice chest and immediately transported to the laboratory. A 500 1000 ml subsample, depending upon phytoplankton densities, was treated with magnesium carbonate and filtered through glass fiber filters (GFC) at 100 mm Hg. The filters were then ground in 3-5 ml of 90% acetone, and the final volume brought to 10 ml. This was followed by a three-hour extraction period in the dark (Golterman 1969). The sample was then centrifuged, and the supernatant decanted into 1 cm cuvettes. Absorbance readings were made at 750, 663, 645, 630, 510, 480 nm on a Perkin Elmer Model 552 Spectrophotometer. Chlorophyll-a concentrations were calculated according to the equations of Strickland and Parsons (1972).

3.4 Nutrient Analyses

3.4.1 Sample Collection and Preservation

Nutrient concentrations were measured monthly at each sampling location. Weekly or bi-weekly measurements were also made at the Lower Basin stations during summer (July-September). Water samples for nutrient analyses were collected from a 0-2.5 m integrated sample at station 14a and 0-5 m integrated sample at the other reservoir stations. At deeper stations, samples were also collected at 10 m, 25 m and 70 m with a Van Dorn sampler. Samples were also collected at 50 m and 90 m at Hoover Dam (station 16). Composite samples were collected at the inflow stations at a mid-depth in the water column with a 3-liter Van Dorn sampler. Water samples for soluble nutrient analyses (ammonia, nitrate + nitrite and ortho-phosphorus) were filtered through glass fiber filters (GFC). All samples were frozen and analyzed within 1-2 weeks after collection.

3.4.2 Ammonia

A 50 ml filtered subsample, or a suitable aliquot diluted to the range of sensitivity, was analyzed for ammonia with the phenol hypochlorite method according to the procedures of Solorzano (1969) as modified by Liddicoat et al. (1975). Absorbance readings were made at 640 nm in a 10-cm curvette with a Perkin Elmer Model 552 Spectrophotometer.

3.4.3 Nitrate + Nitrite

A 50 ml filtered subsample, or a suitable aliquot diluted to the range of sensitivity, was analyzed by the hydrazine reduction method first described by Mullin and Riley (1955) and later updated by Kamphake et al. (1967). Absorbance readings were made at 543 nm in a 5-cm cuvette with a Perkin Elmer Model 552 Spectrophotometer.

3.4.4 Total Nitrogen

A 50 ml unfiltered subsample, or suitable aliquot diluted to the range of sensitivity, was analyzed for total nitrogen according to the methods of D'Elia et al. (1977). Absorbance readings were made at 543 nm in a 1 cm curvette with a Perkin Elmer Model 552 Spectrophotometer.

3.4.5 Orthophosphorus and Total Phosphorus

Orthophosphorus and total phosphorus were determined using the ascorbic acid method described by Strickland and Parsons (1972) and APHA (1975). For total phosphorus, a 50 ml, unfiltered sample was treated with an ammonia persulfate solution to release phosphorus from particulate and dissolved organic matter. For orthophosphorus, a 50 ml sample was filtered through glass-fiber filters, prior to addition of other reagents. Absorbance readings were made at 645 nm in a 10-cm cuvette with a Perkin Elmer Model 552 Spectrophotometer. A more detailed description of our methods of nutrient analyses are presented in Kellar et al. (1981).

3.5 Nutrient Loading

Total and inorganic nitrogen and phosphorus loads were determined for the principal inflows to Lake Mead and the discharge from Hoover Dam. Nutrient concentrations were measured monthly in the Colorado River, Virgin River, Muddy River, Las Vegas Wash and Hoover Dam. Weekly or bi-weekly measurements were also made in Las Vegas Wash during summer (July-September). Discharge data were derived from the U.S. Geological Survey Water Resources Data for Nevada annual reports.

Nutrient loads were computed monthly by equation (1).

$$Q_i = C_i \times V_i \times k_i\text{---}k_n \qquad (1)$$

where:

Q = nutrient loads (kg/month)

C = monthly or average monthly nutrient concentrations (mg/l)

V = average discharge rate (m^3/sec)

k = unit conversion factors

i = time interval (months)

Average annual flow weighted concentrations ($\bar{C}$) were determined by equation (2).

$$\bar{C} = \Sigma \frac{Q_i}{V_i} \text{ ---} k_i \text{-} k_n \tag{2}$$

Annual nutrient loads were then computed by multiplying $\bar{C}$ by annual discharge rates.

Evans and Paulson (1983) have shown that a large percentage (10-39%) of the total phosphorus in the Colorado River and tributaries is bound to suspended sediments and unavailable for biological uptake. Based on results of that study, biologically available phosphorus (BAP) was estimated by equation (3).

$$BAP = [TP - OP \times 0.1] + OP \tag{3}$$

where:

BAP = biologically available phosphorus (mg/l)

TP = total phosphorus (mg/l)

OP = orthophosphorus (mg/l)

3.6 Physical Measurements

Temperature, oxygen, pH and conductivity were measured monthly at each station with a Hydrolab Model IIA or Model 8000 Water Quality Analyzer. Weekly or bi-weekly measurement were also made at the Lower Basin stations during summer (July-September). Underwater light transmittance was measured with a Li-Cor Model L-192 Underwater Quantum Sensor.

3.7 Zooplankton Sampling and Analyses

3.7.1 Zooplankton Collection and Enumeration

Zooplankton samples were collected monthly at each station with a Wisconsin plankton net (80 µm mesh) in a vertical haul from 70 m at deep stations or from the bottom at shallower stations. Weekly or bi-weekly collections were also made at the Lower Basin stations during summer (July-September). The samples were preserved with a 5% formalin/sucrose solution and stored at room temperatures in polyethylene vials. Zooplankton identifications and counts were determined on three replicate subsamples in a Sedgewick-Rafter counting chamber. Zooplankton densities per unit area (number/m^2) were estimated by extrapolation from the actual area sampled by the Wisconsin net. Zooplankton densities per unit volume (number/m^3) were calculated by dividing the number/m^2 by the depth of the tow. Although tows were made from 70 m at the deep stations, these were standardized to 40 m to allow for comparisons with historical data.

3.7.2 Zooplankton Feeding Experiments

Feeding experiments were conducted during July 23-12 August, 1981 in order to evaluate the growth and reproduction of Daphnia pulex under different natural food regimes. D. pulex were collected from Boulder Basin and cultured in the laboratory on a Chlamydomonas reinhardi food supply. Newly hatched D. pulex neonates from the culture were transferred to 125 ml glass jars (one neonate/jar) containing water from Lake Mead. Lake water was collected from the inner Las Vegas Bay (14a), middle Las Vegas Bay (14c) and Boulder Basin (15) and used as different food treatments. The lake water was prefiltered to remove zooplankton.

The jars containing lake water and D. pulex neonates were then placed in an outdoor pool at water temperatures ranging from 20-22°C. Five replicates were used for each food treatment. The water was changed daily with lake water collected from the stations in Lake Mead. Fresh lake water was collected every 3-5 days.

Food concentrations were determined by chlorophyll-a concentrations in lake water collected from each station. Zooplankton feed on a variety of suspended material in the size range from 4-30 µm (Haney 1973). Chlorophyll-a was therefore not a direct measure of grazable food. However, it did provide an index of relative food availability because the phytoplankton species composition in the inner Las Vegas Bay, middle Las Vegas Bay and Boulder Basin is similar (Brown and Caldwell 1981).

D. pulex growth was determined by total length measurements on each animal at the start and end of the experiment. Reproduction was determined by counting the number of neonates hatched in each jar. These were removed from the jars when the water was replaced each day.

3.7.3 Zooplankton Statistical Analyses

A non parametric (Spearman Rank) correlation analysis was used to evaluate the relationship among densities of dominant zooplankton species and various limnological and biological factors. The zooplankton data were entered in the correlations as the number of organisms/m^3 over 40 m standardized tow depths at deep stations or to the bottom at shallow stations. Physical factors (temperature, oxygen, pH, and conductivity) were entered as depth-integrated averages to 40 m at deep stations or to the bottom at shallow stations. Integral phytoplankton productivity (mg C/m^2/day) and 0-2.5 m or 0-5 m depth integrated chlorophyll-a were used in the correlation analyses. Total fish abundance was entered as a relative value ranging from 0-5.

3.8 Fish Echo Sounding Surveys

Echo sounding surveys were conducted at each station to determine the relative abundance of fish. A Furuno Model FM 22-D echo sounder was used in the surveys. This instrument sounds at a frequency of 50 KHZ, and the transducer has a beam angle of 28°. Echo sounding transects were run at an approximate speed of 5 mph for a distance of about 1000 m in the immediate vicinity of each station. The echo sounding traces were visually inspected for fish targets and assigned a relative abundance value based on the following criteria: An abundance value of one was assigned to traces with no targets; few targets were assigned a value of two and several targets a value of three. A value of four was given to traces where numerous targets were present, and a value of five was assigned to traces where dense numbers of individuals or schools of fish were present.

4.0 RESULTS

4.1 Temperature Structure and Stratification

Water temperatures in the four major basins were isothermal or near isothermal at 11-12°C from December through February (Fig. 4.1.1-4.1.4). Surface temperatures began to increase in March, and by June, a distinct thermocline had developed. The thermocline was located at approximately 10 m in June and declined to a depth of 15-18 m by September as surface temperatures cooled. By December, the lake was generally completely mixed.

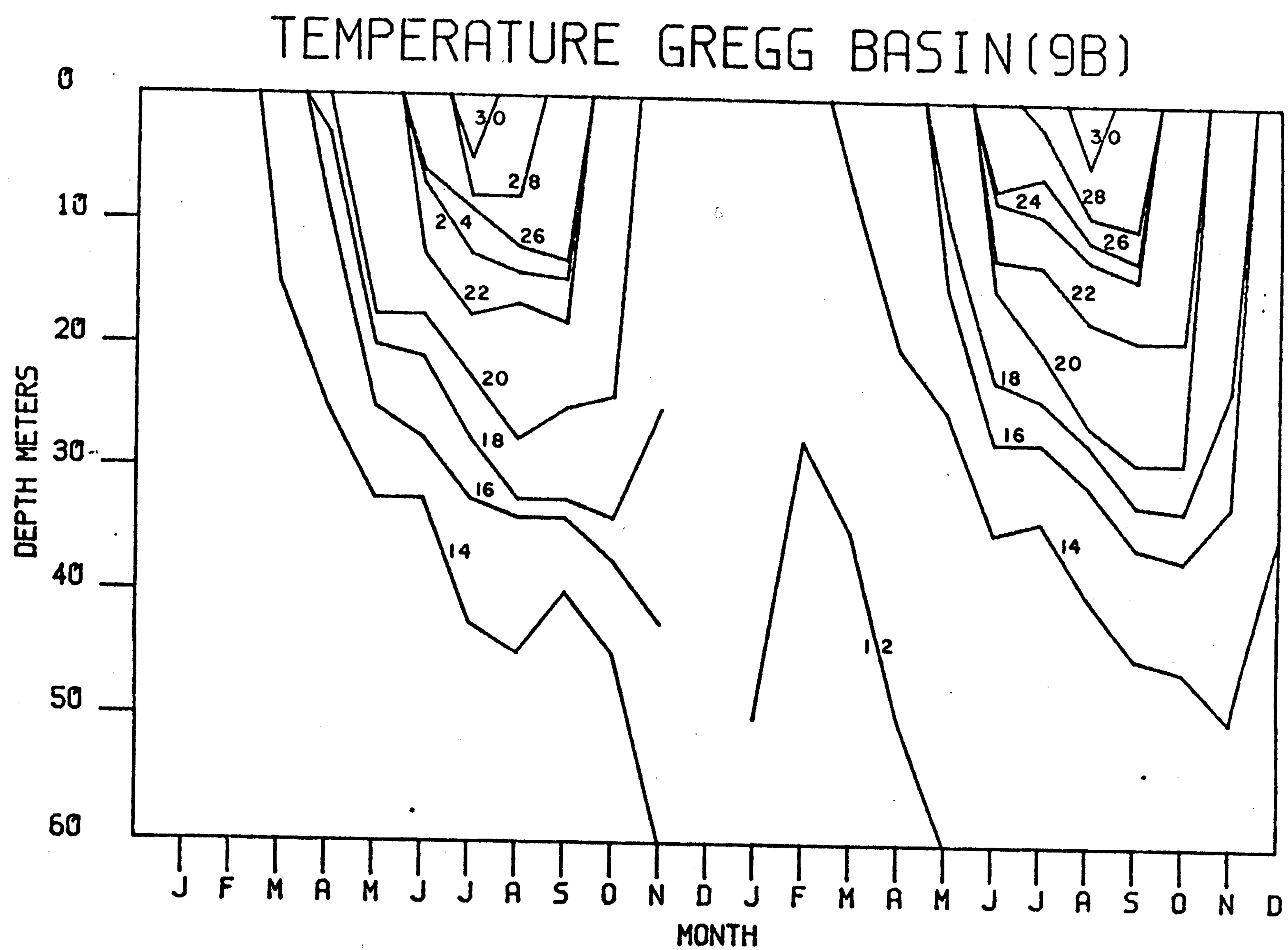

Figure 4.1.1. Temperature isotherms for Gregg Basin (9b) during 1981 and 1982.

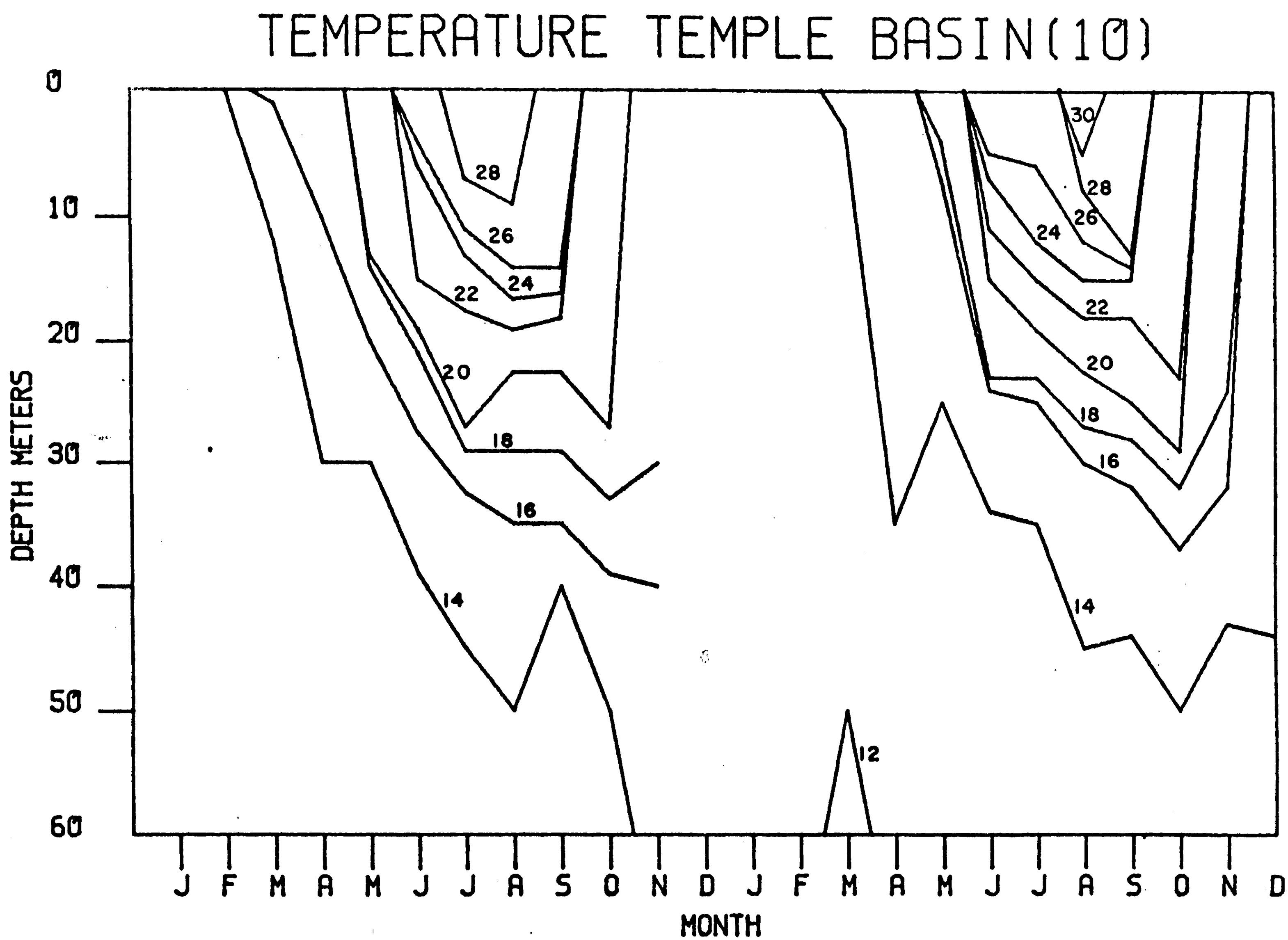

Figure 4.1.2. Temperature isotherms for Temple Basin during 1981 and 1982.

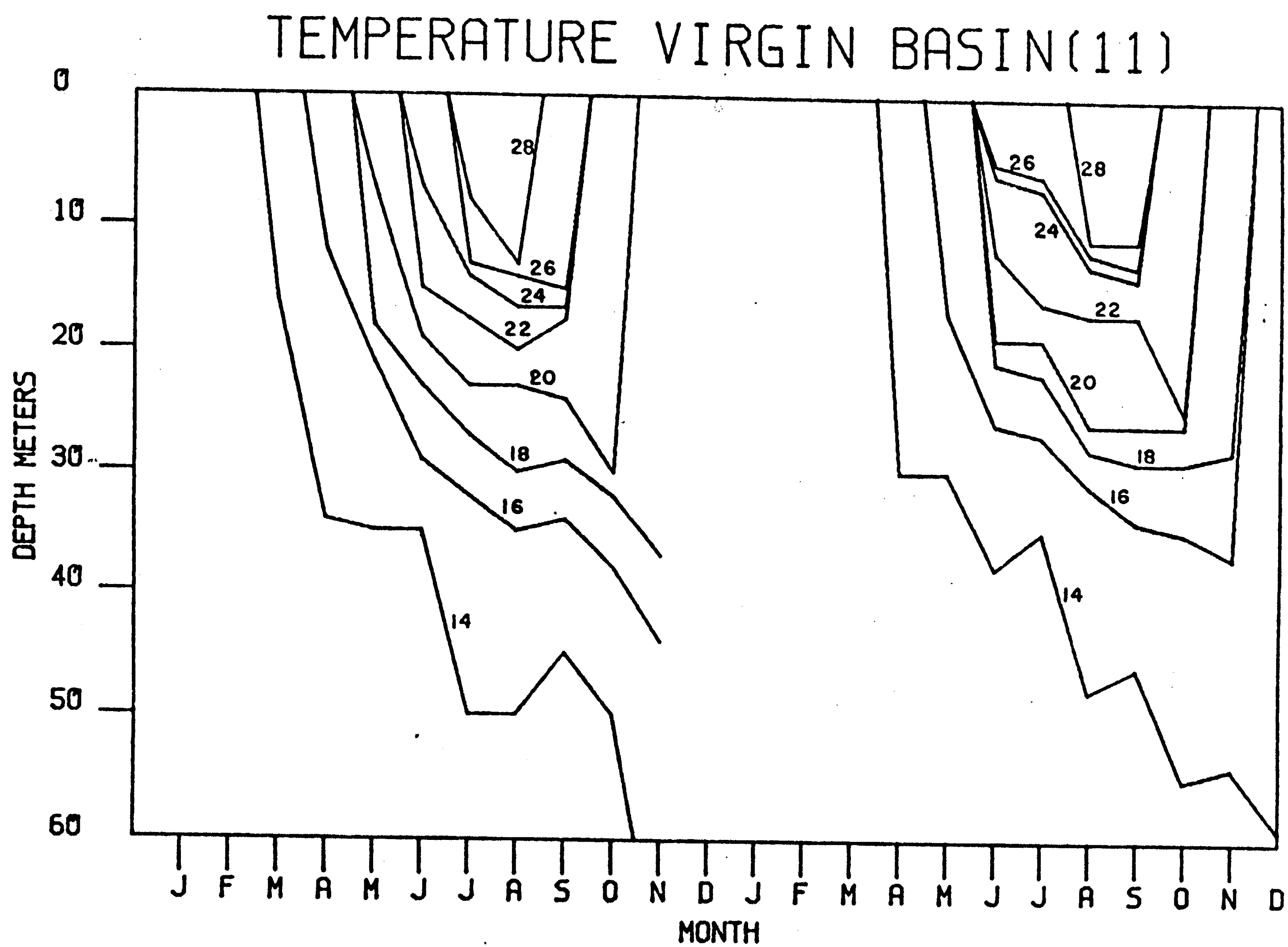

Figure 4.1.3. Temperature isotherms for Virgin Basin (11) during 1981 and 1982.

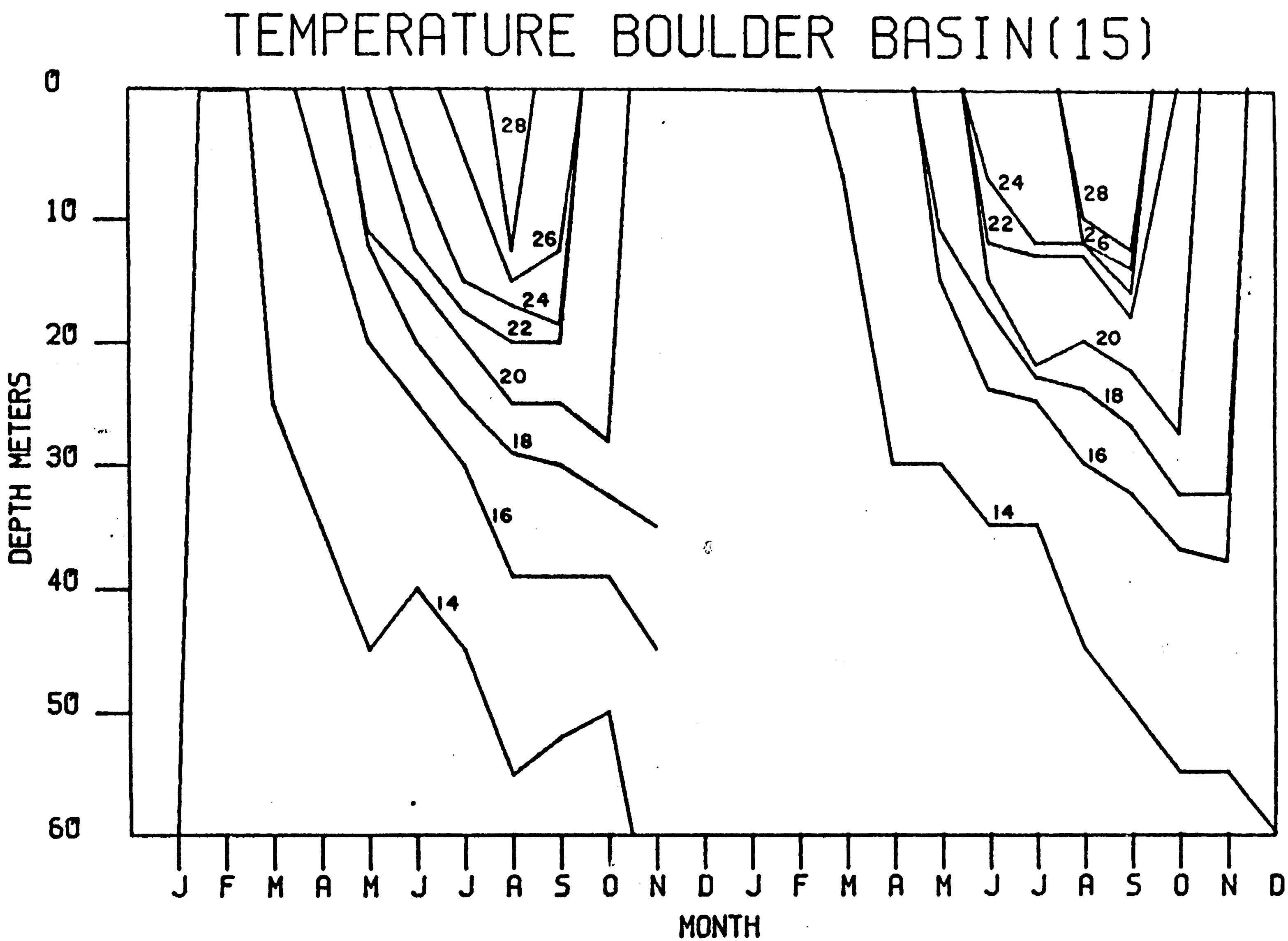

Figure 4.1.4. Temperature isotherms for Boulder Basin (15) during 1981 and 1982.

There were some differences in thermal structure between the major basins with Gregg and Temple Basins being similar and Virgin and Boulder Basins being similar. Maximum water temperatures in Gregg and Temple Basins were approximately 2° warmer than those found in Virgin and Boulder Basins. Gregg and Temple Basins also had cooler hypolimnetic temperatures resulting in stronger thermal stratification. The cooler hypolimnetic temperatures in these basins were the result of cold-water inflows from the Colorado River during summer.

Thermal structure at the shallow inflow stations was somewhat different than that in their respective basins (Figs. 4.1.5 - 4.1.7). Summer surface temperatures at Iceberg Canyon (9b) were very similar to those found in Gregg Basin, but the depth of the thermocline was much shallower, and winter and bottom temperatures were much cooler. This again was due to the Colorado River inflow. Temperatures in the Overton Arm (12b) and in the inner Las Vegas Bay (14b) were warmer than those at their respective basin stations, and the depth of the thermocline was generally deeper. Thermal stratification did not develop at stations with depths less than 15 m.

There were also some differences in thermal structure between years (1981-1982) at all stations. Spring temperatures (April-May) were generally 1-2° warmer in 1981, however, late summer temperatures (Aug.-Sept.) were generally 2° warmer in 1982. Thermal stratification was stronger, and a shallower thermocline existed with the warm, late-summer temperatures in 1982.

4.2 Oxygen Concentrations

Oxygen concentrations (December-February) were at or near

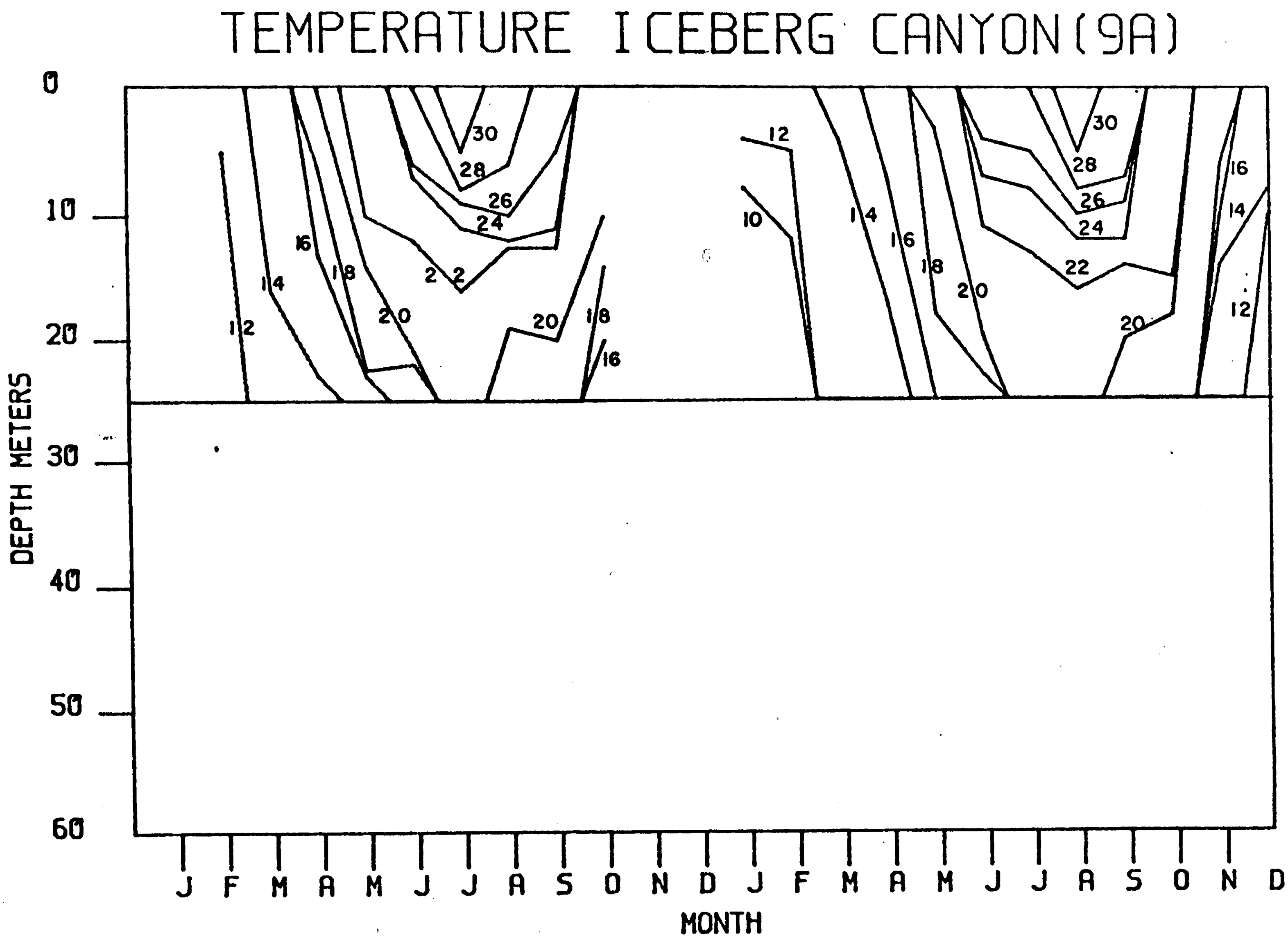

Figure 4.1.5. Temperature isotherms (°C) for Iceberg Canyon (9a) during 1981 and 1982.

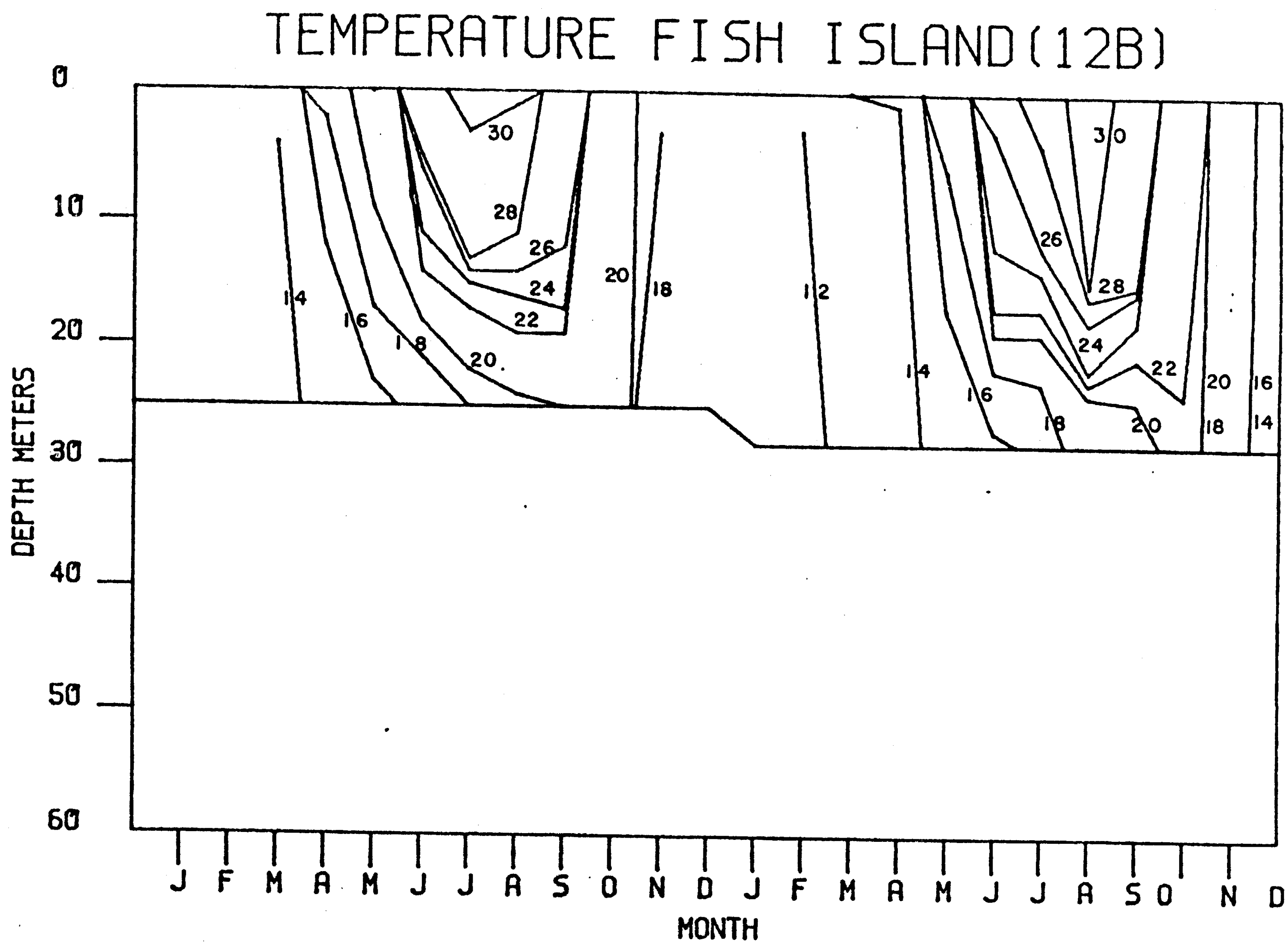

Figure 4.1.6. Temperature isotherms (°C) for Overton (Fish Island) (12b) during 1981 and 1982.

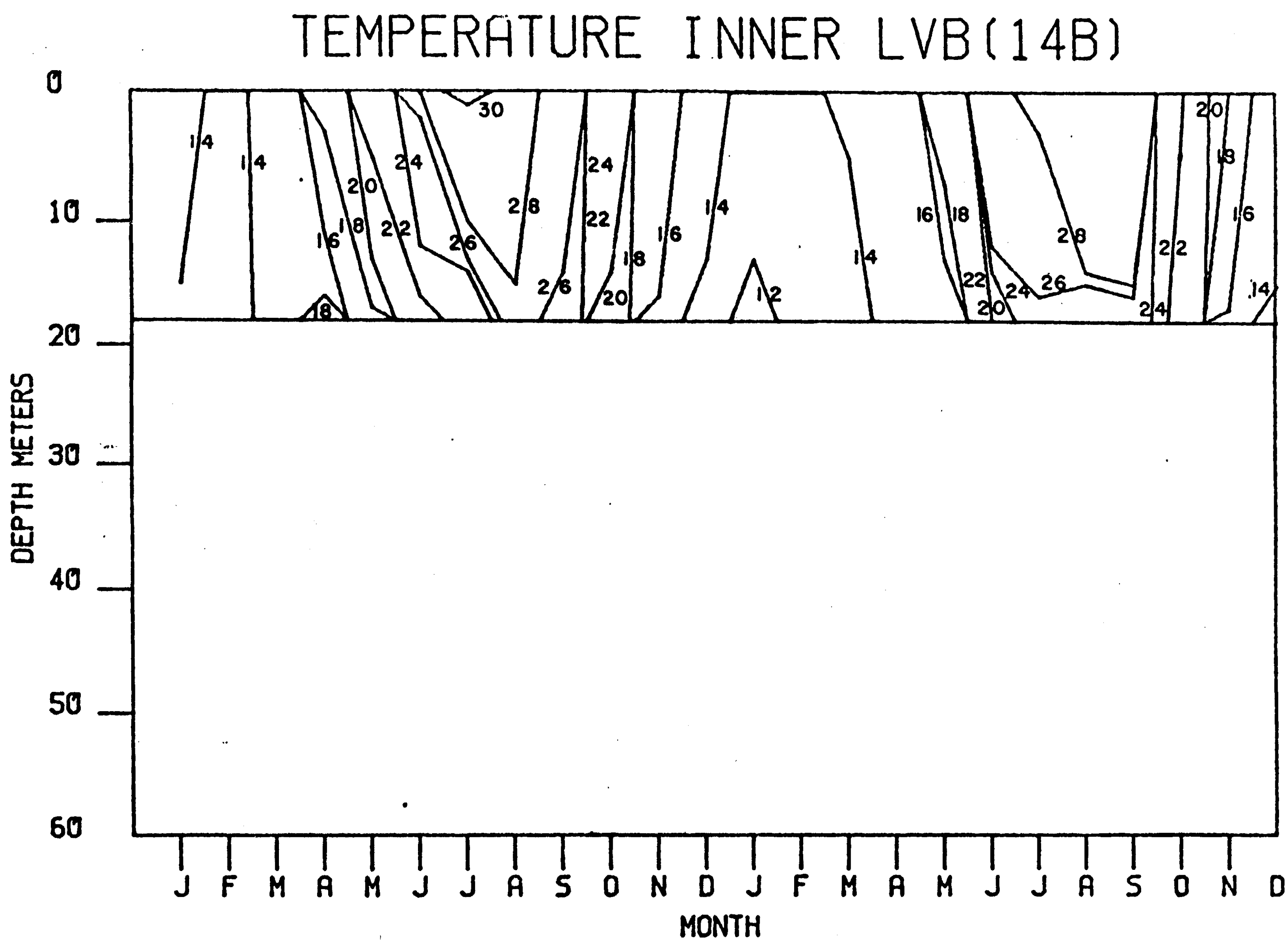

Figure 4.1.7. Temperature isotherms (°C) for the inner Las Vegas Bay (14b) during 1981 and 1982.

saturation and uniform down the water column (orthhograde) during the isothermal periods in winter. With the development of thermal stratification in June and July, oxygen concentrations in the metalimnion were typically lower than those found in either the epilimnion or hypolimnion (Fig. 4.2.1). This resulted in a negative heterograde oxygen profile during summer. There was a progressive decline in epilimnetic oxygen concentrations throughout the stratified period and minimums were lowest in the fall (Sept.-Nov.) just prior to mixing. Oxygen depletion also occurred at the bottom and in areas of the lake where the depth was less than 100 m. In shallow areas of the lake (< 15m), oxygen concentrations usually remained high because thermal stratification did not develop and mixing was sufficient to maintain high oxygen concentrations throughout the water column.

Mid-water oxygen minimums have occurred in Lake Mead ever since the reservoir was formed (Paulson et al. 1980). In the four major basins, oxygen depletion was most severe in Gregg Basin followed by Temple and Boulder Basins with Virgin Basin having the highest oxygen concentrations (Fig. 4.2.1). Gregg Basin, because of its relatively shallow depth, had low oxygen concentrations in both the metalimnion and hypolimnion resulting in clinograde conditions. This was also found in Temple Basin in 1981. Low oxygen concentrations were found in the metalimnion and at the bottom in Boulder and Virgin Basins. The magnitude of depletion was greater in Boulder Basin apparently because nutrient inputs from Las Vegas Wash elevated phytoplankton production which in turn increases oxygen demands in the metalimnion (Brown and Caldwell 1981).

The magnitude of oxygen depletion throughout the lake was greater

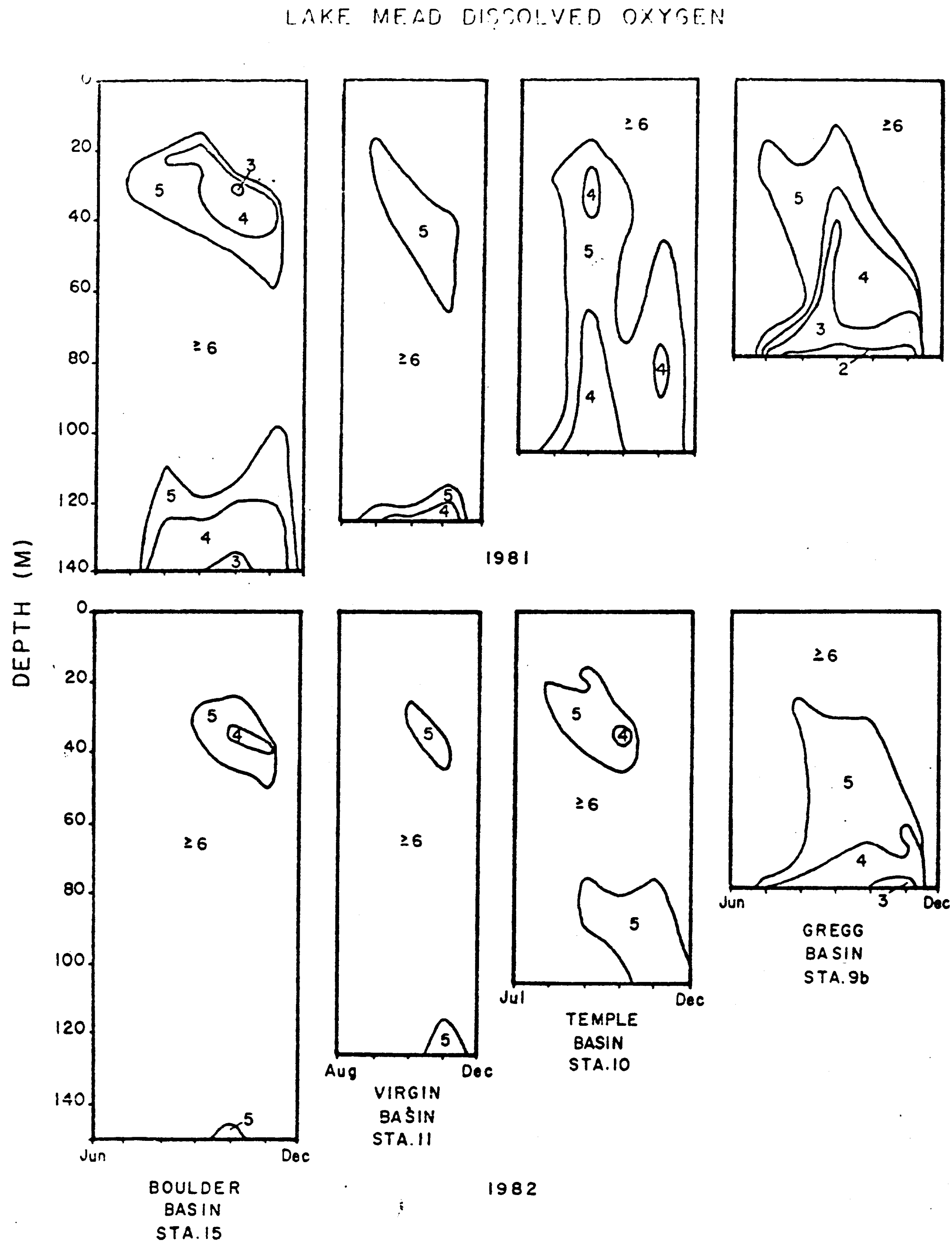

Figure 4.2.1. Dissolved oxygen isopleths (mg/l) during mid summer, fall and winter in the main basin areas during 1981 and 1982.

in 1981 than in 1982. Phytoplankton productivity measurements in the Upper Arm and Overton Arm were discontinued in 1982, and therefore, we could not determine if this was due to an overall decrease in productivity. There was a decrease in productivity in Boulder Basin that was related to decreased phosphorus loading from Las Vegas Wash in 1982 (see section 5.1.1). This could not have influenced conditions in the upper basins based on known circulation patterns (Paulson et al. 1980). Improved oxygen conditions in Boulder Basin were probably due in part to decreased phosphorus loading, but this also had to be influenced by some other factor operating throughout the lake. Changes in circulation patterns and mixing of the Colorado River inflow are suspected as the primary cause for increased oxygen concentrations in 1982.

4.3 Nutrient Loading

The Colorado River was the principal nutrient source for Lake Mead due to the large hydrologic input that it provides to the reservoir. The Colorado River contributed 63% of the total phosphorus (TP) inputs in 1981 and 84% in 1982 (Table 4.1.1). TP loads from the Virgin River were slightly higher than those from Las Vegas Wash. The Muddy River was an insignificant phosphorus input to Lake Mead.

A large percentage of the total phosphorus inputs from the Colorado River and Virgin River was bound to suspended sediments. Evans and Paulson (1983) estimated that 10-40% of the sediment bound phosphorus was biologically available. Bio-available phosphorus (BAP) loads from the Colorado River comprised 49% of the inputs in 1981 and 72% in 1982 (Table 4.1.1). Although TP loads from Las Vegas Wash were lower than the Colorado River and Virgin River, it was a significant source of BAP and OP. Las Vegas Wash provided 57% of the OP loads in 1981 and 45% in 1982.

Table 4.1.1. Nutrient loadings, loss rates and budgets for Lake Mead during 1981 and 1982.

		NUTRIENT (t/yr.)				
Location	Year	Total Phosphorus	Bio-available Phosphorus	Ortho Phosphorus	Total Nitrogen	Dissolved Inorganic Nitrogen
Grand Canyon	1981	636	117	59	7433	3728
Las Vegas Wash	1981	115	90	87	930	820
Virgin River	1981	255	30	5	267	99
Muddy River	1981	2	1	1	7	4
Total Input	1981	1008	238	152	8637	4651
Hoover Dam Output	1981	138	77	70	4978	3586
Retention (%)	1981	86	68	54	42	23
Grand Canyon	1982	1126	160	53	6858	3784
Las Vegas Wash	1982	98	50	44	754	727
Virgin River	1982	111	13	2	270	147
Muddy River	1982	1	1	1	5	3
Total Input	1982	1336	224	100	7887	4661
Hoover Dam Output	1982	89	46	41	4347	2852
Retention (%)	1982	93	79	59	45	39

The Colorado River was by far the largest input of total and inorganic nitrogen to Lake Mead. It contributed 86% of the total nitrogen (TN) and 80% of the inorganic nitrogen (IN) inputs during both years of the study (Table 4.1.1). Las Vegas Wash provided about 10% and the Virgin River 3-5% of the TN and IN unputs. The Muddy River was a minor nitrogen input to the reservoir.

There was considerable seasonal variability in nutrient loading from the Colorado River. TP loads were highest during the summer and early fall when discharges from Glenn Canyon Dam were elevated for power generation (Fig. 4.3.1). About 75-80% of the phosphorus inputs occurred during August-October of both years. TN and IN loads were less variable, but the highest loading also occurred during the summer and early fall periods (Fig. 4.3.1).

Nutrient loading from Las Vegas Wash showed less seasonal variability, but there were marked differences in loads between 1981 and 1982 (Fig. 4.3.2). Phosphorus loading decreased considerably after July 1981 when the City of Las Vegas and Clark County reduced their sewage effluent phosphorus concentrations to 1 mg/l. This resulted in a 50-60% decrease in TP, BAP and OP loads. Phosphorus loadings remained low and fairly constant during the rest of the study, except during the February, 1982 flood in Las Vegas Wash. TN and IN loads were also slightly lower in 1982 than in 1981.

Nutrient loss rates from Hoover Dam were high during both years of the study due to the large discharges (Table 4.1.1). However, significant amounts of nutrients were still retained in the reservoir. Total phosphorus retention was 86% in 1981 and 93% in 1982. BAP retention was 68% in 1981 and 80% in 1982. OP retention was about 55% in

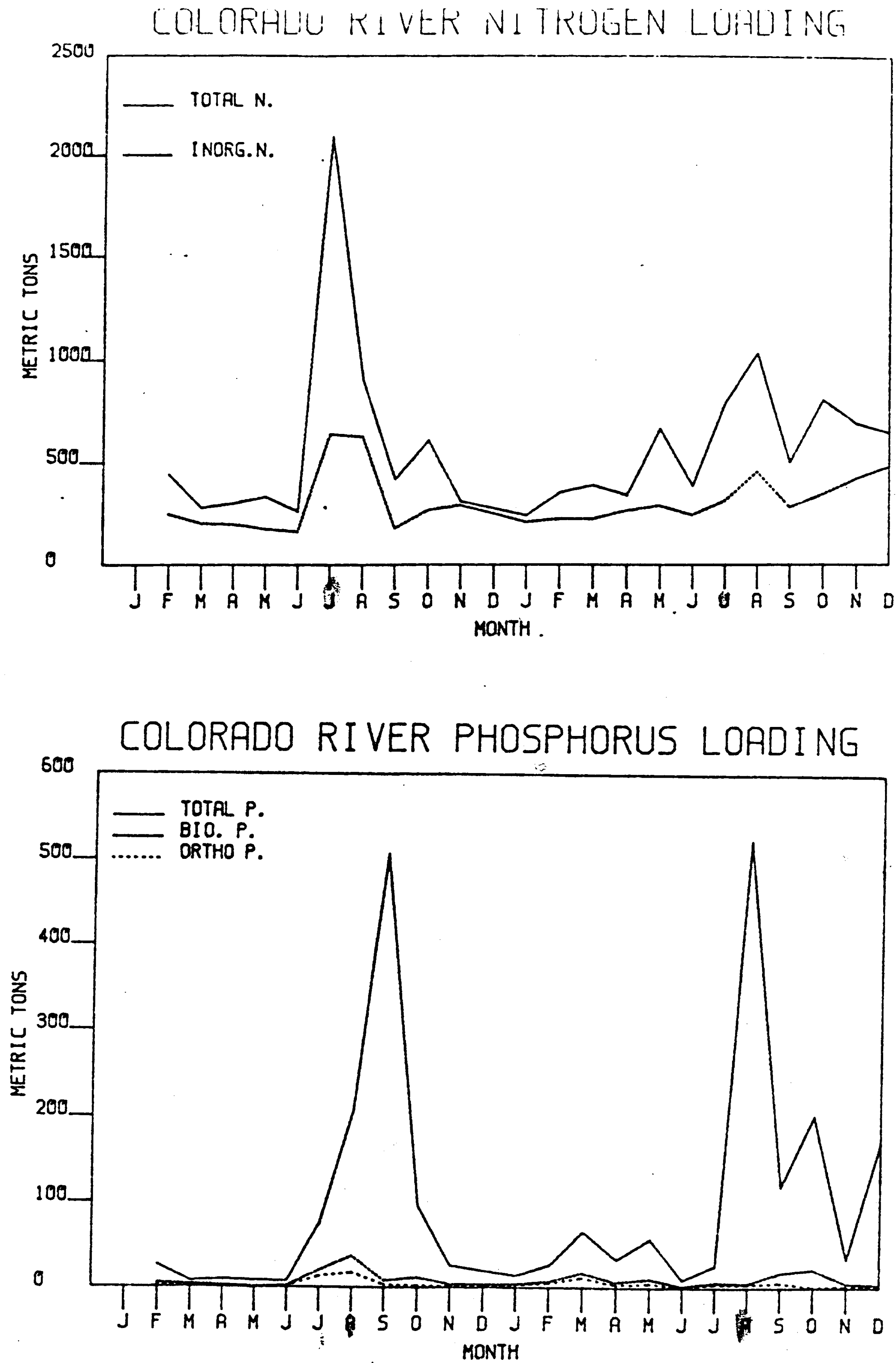

Figure 4.3.1. Nutrient loading patterns in the Colorado River inflow to Lake Mead during 1981 and 1982.

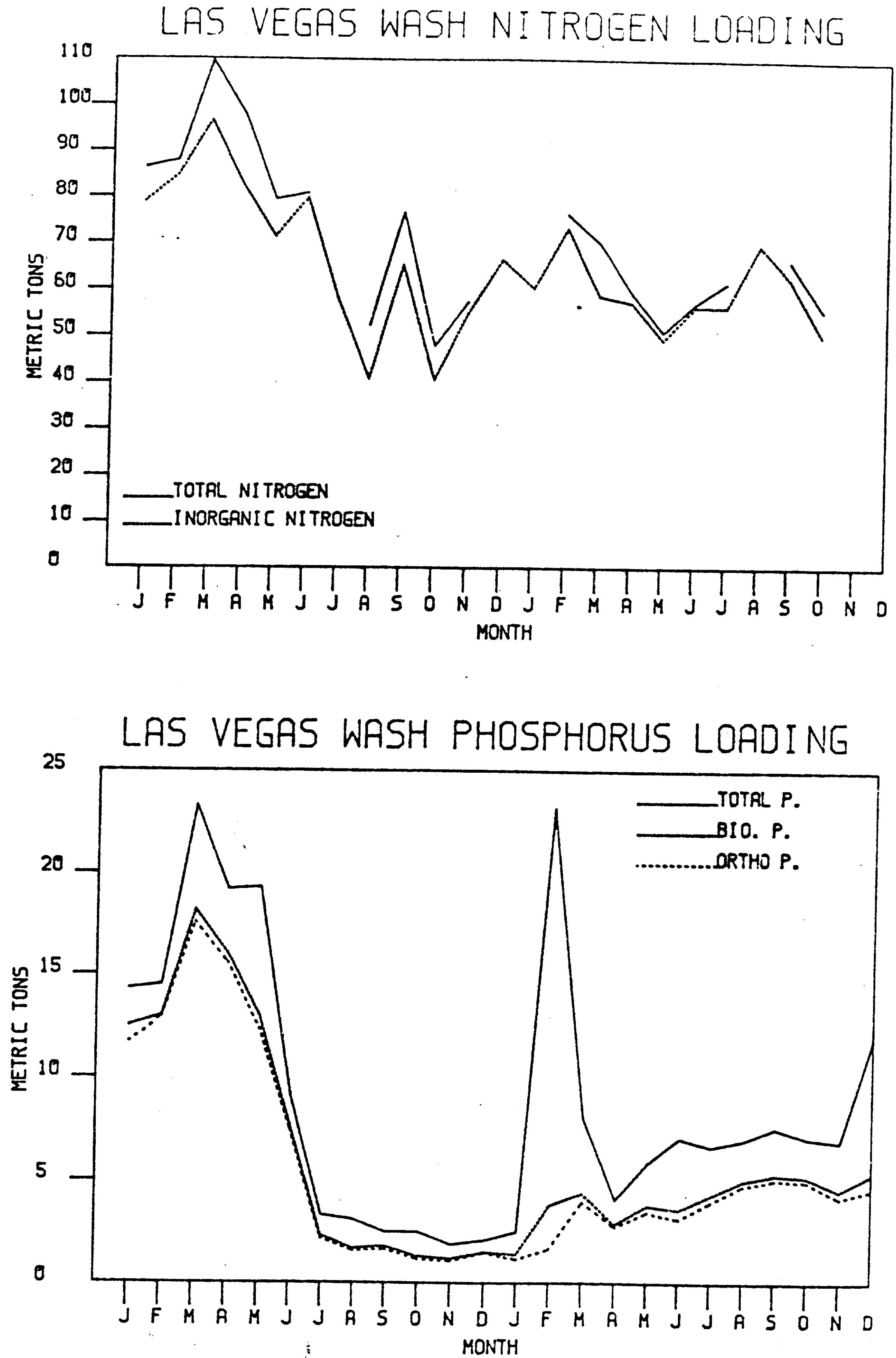

Figure 4.3.2. Nutrient loading patterns for the Las Vegas Wash inflow to Lake Mead during 1981 and 1982.

both years (Table 4.1.1). About 45% of the total nitrogen inputs were retained during both years. Inorganic nitrogen retention was 23% in 1981 and 39% in 1982.

4.4 Spatial, Seasonal and Annual Variations in Nutrient Concentrations

Total phosphorus (TP) concentrations in Lake Mead were generally very low, except near the inflow stations. The highest TP concentrations occurred in the inner Las Vegas Bay (14a) near the Las Vegas Wash inflow (Fig. 4.4.1). TP concentrations exceeded .200 mg/l in the inner bay during April-June 1981. TP concentrations decreased steadily during late summer and fall of 1981 and reached a minimum during the winter of 1981-82. There was an increase in TP concentrations in the inner Las Vegas Bay during spring and summer of 1982, but levels were not as high as in 1981. Orthophosphorus (OP) concentrations followed similar seasonal trends in the inner Las Vegas Bay (Fig. 4.4.1). However, OP concentrations decreased abruptly during July 1981. This coincided with the decrease in phosphorus loading that occurred in Las Vegas Wash when the City of Las Vegas and Clark County reduced phosphorus concentrations in their effluents to 1 mg/l. OP concentrations showed some increase during the spring and summer of 1982, but concentrations were much lower than in 1981.

TP concentrations decreased considerably between the inner Las Vegas Bay and the middle Las Vegas Bay (14c) (Fig. 4.4.1). Seasonal variations were also less evident in the middle Las Vegas Bay, although TP concentrations did increase somewhat during summer and fall periods. TP concentrations were lower during the summer of 1982 than in 1981. OP concentrations in the middle Las Vegas Bay were low throughout the study

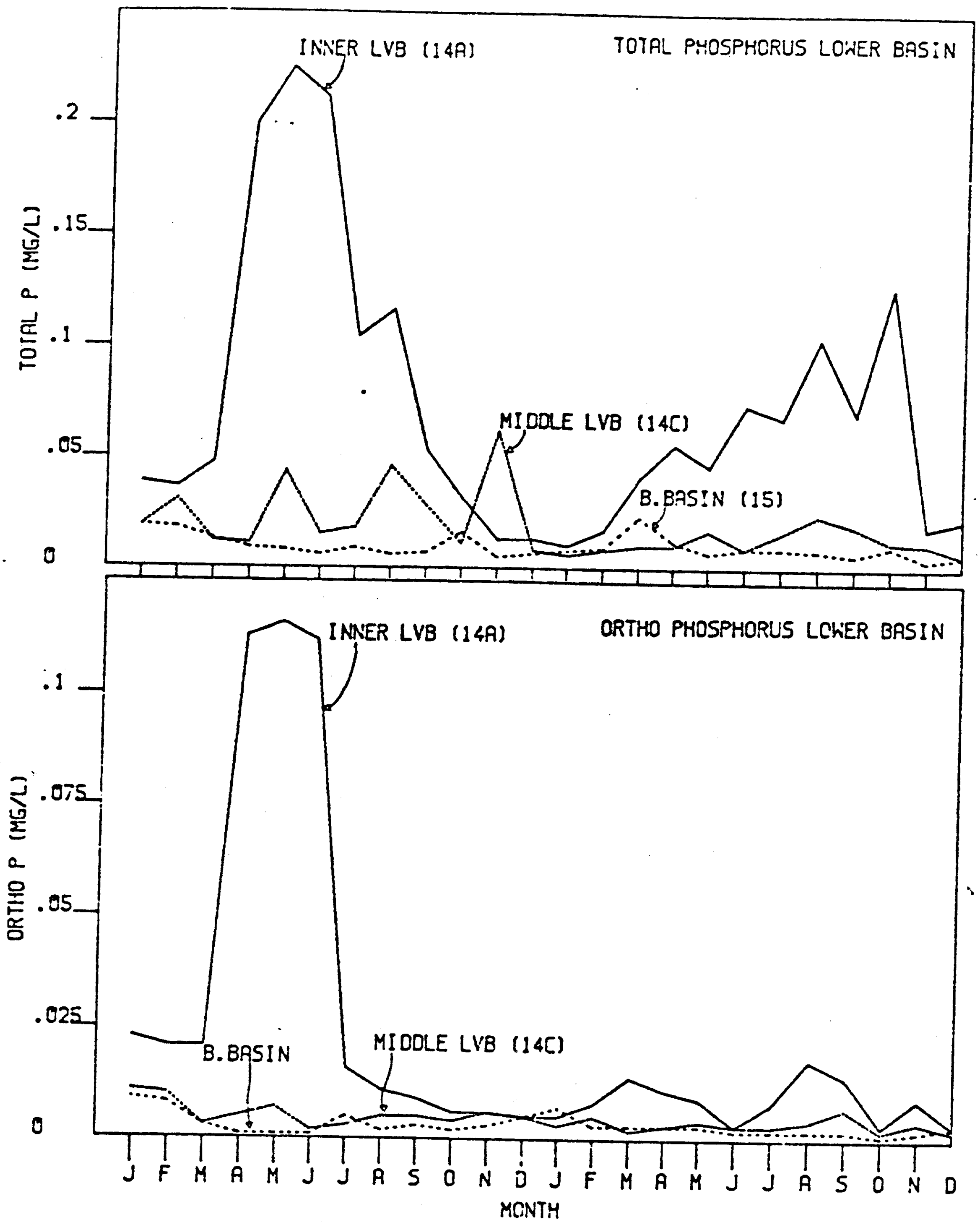

Figure 4.4.1. Total and orthophosphorus concentrations at select locations in the Lower Basin of Lake Mead during 1981 and 1982.

(Fig. 4.4.1).

TP concentrations in Boulder Basin (15) and other main basin stations were very low and averaged .005-.010 mg/l (Fig. 4.4.1, Fig. 4.4.2). TP concentrations occasionally exceeded .02 mg/l near the inflow stations in the Overton Arm and Muddy Arm (Fig. 4.4.2). Peaks in TP that occurred in the Virgin Bowl (13a) and Muddy Arm (12a) during July 1981 and at Gods Pocket (8a) and Iceberg Canyon (9a) during August, 1981 were associated with higher phosphorus loading from floods in the river inflows. Except for these events, TP concentrations generally remained low and did not show much seasonal or annual variation. OP concentrations were extremely low in the Overton Arm and Upper Arm during both years of the study (Fig. 4.4.3).

Total nitrogen (TN), nitrate + nitrite and ammonia concentrations were also highest in the inner Las Vegas Bay (14a) (Fig. 4.4.4). TN concentrations reached 2.2 mg/l at this station during June 1981. This was associated with peaks in nitrate + nitrite and ammonia (Fig. 4.4.4). TN concentrations in the inner Las Vegas Bay remained high through the summer and fall of 1981, but in winter, TN levels, as well as nitrate + nitrite and ammonia, were comparable to those in the middle Las Vegas Bay (14c) and Boulder Basin (15). TN, nitrate + nitrite and ammonia also increased in the inner Las Vegas Bay during the summer of 1982, but concentrations were lower than in 1981.

Nitrate + nitrite were the only nutrients that showed a definite seasonal pattern in Lake Mead. Nitrate + nitrite reached a maximum during the winter-spring months when concentrations averaged .25-.30 mg/l across the entire reservoir (Figs. 4.4.4 - 4.4.5). Nitrate + nitrite concentrations then decreased steadily during the early summer,

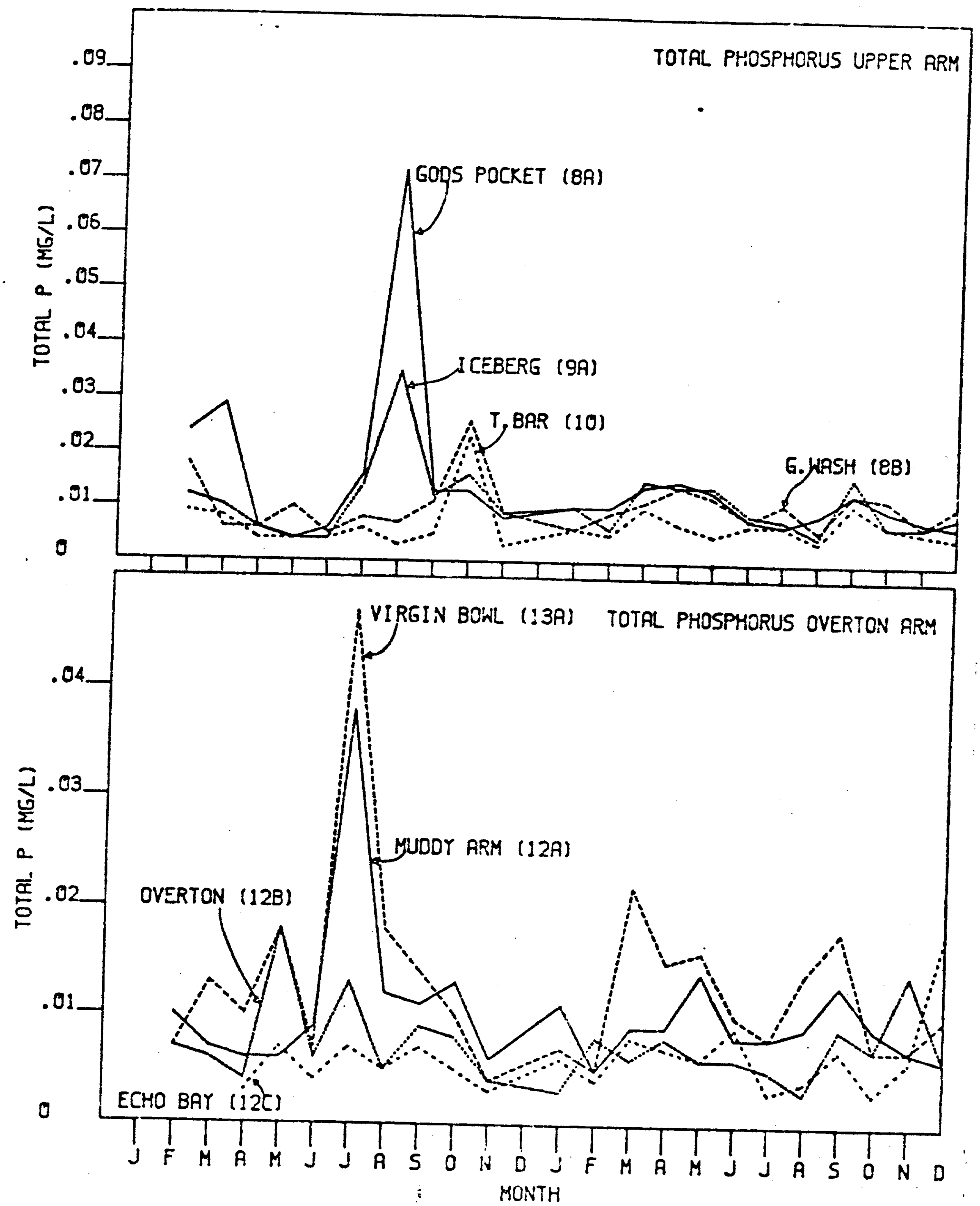

Figure 4.4.2. Total phosphorus concentrations (mg/l) at select locations in the Upper Arm and Overton Arm of Lake Mead during 1981 and 1982.

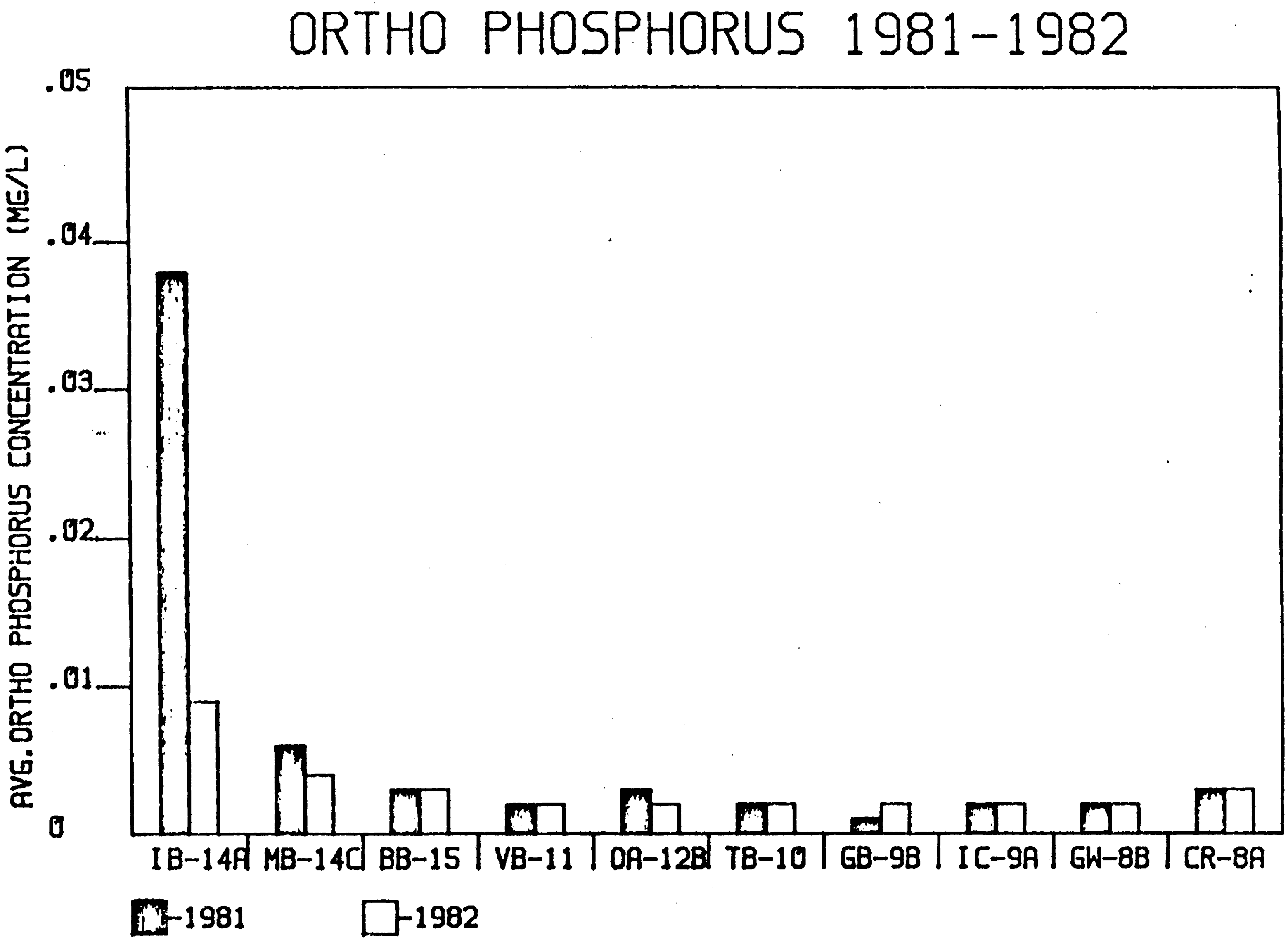

Figure 4.4.3. Annual average orthophosphorus concentrations (mg/l) at select locations in Lake Mead during 1981 and 1982.

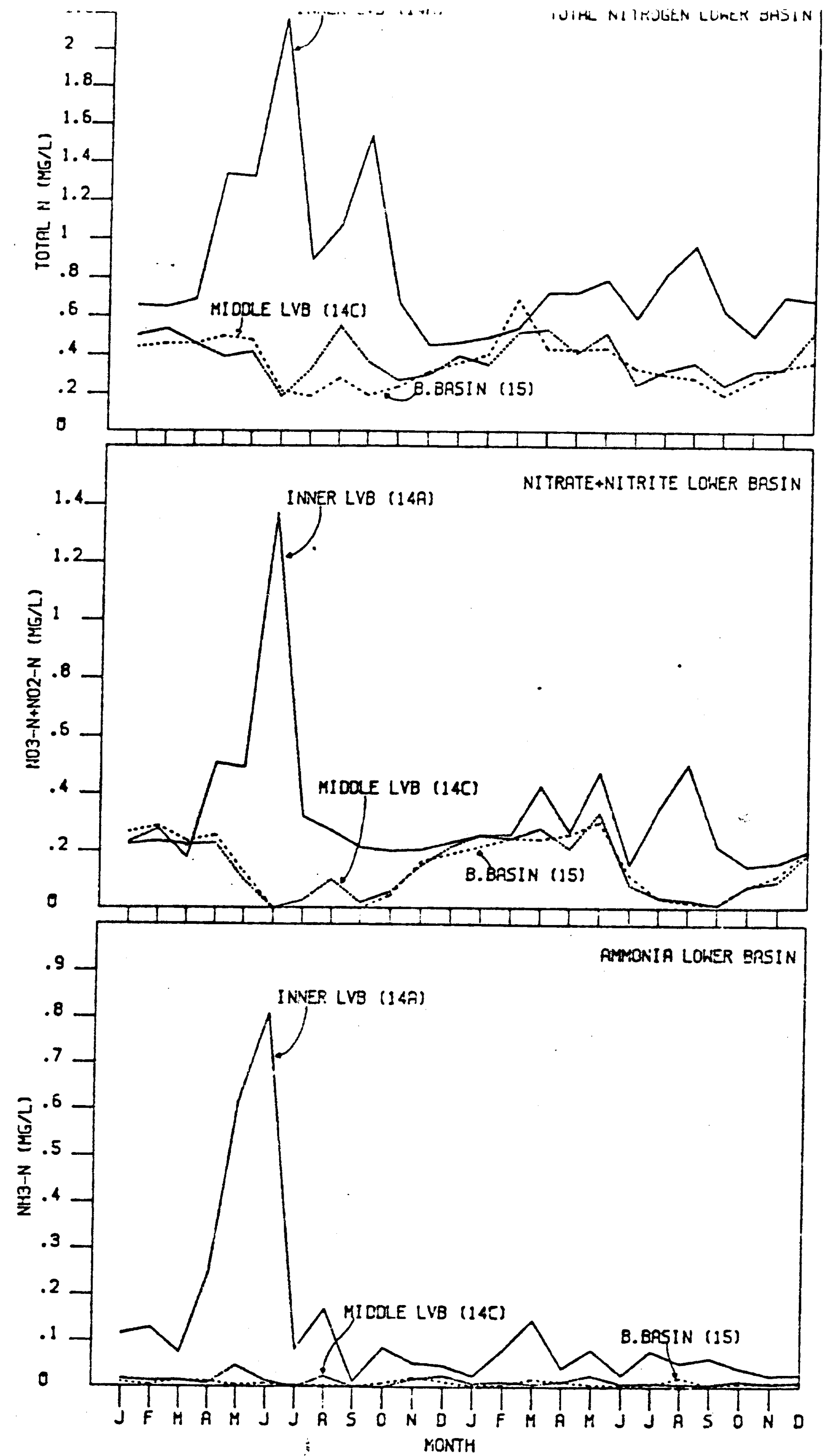

Figure 4.4.4. Total nitrogen, nitrate + nitrite and ammonia concentrations at select locations in the Lower Basin of Lake Mead during 1981 and 1982.

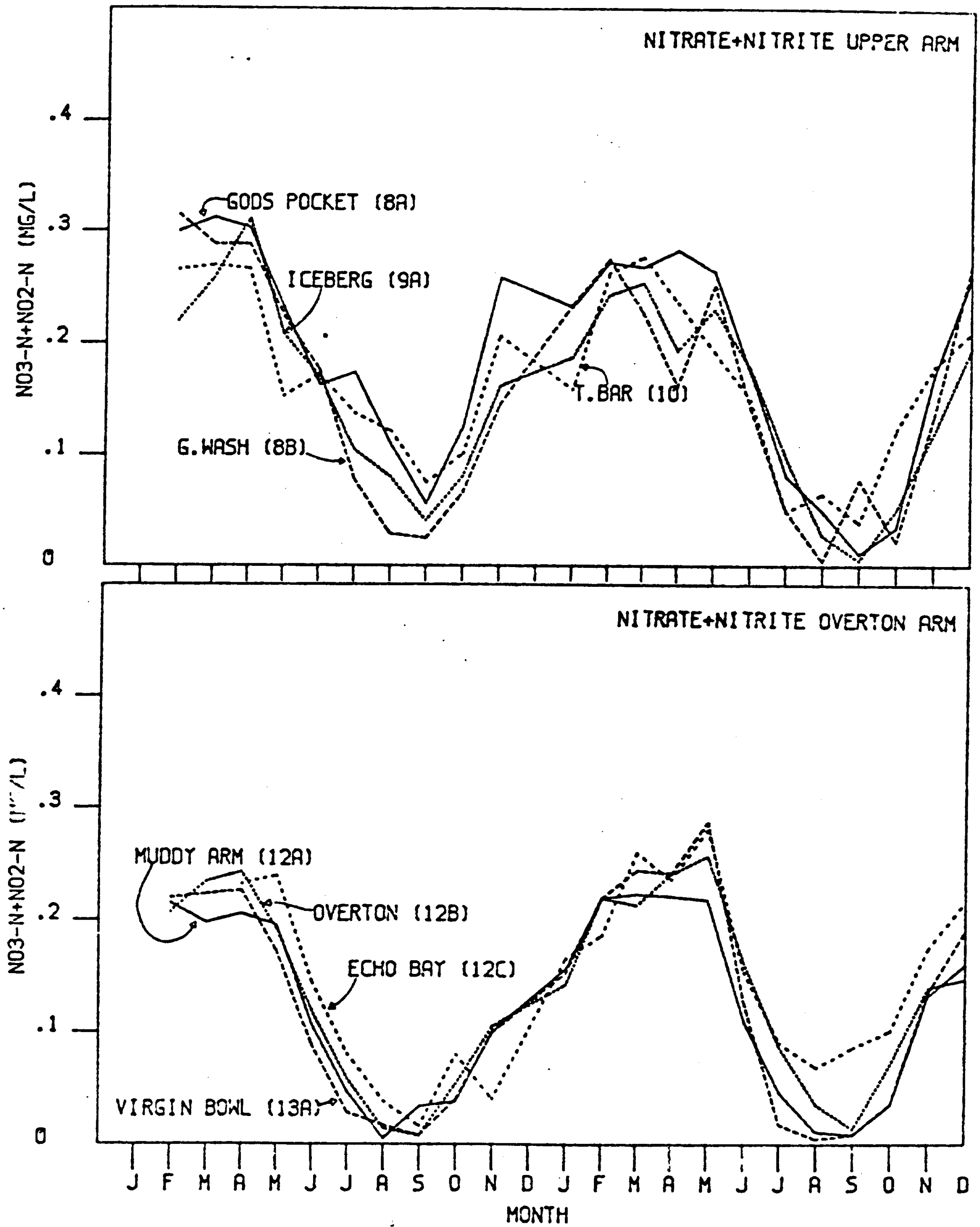

Figure 4.4.5. Nitrate + nitrite concentrations (mg/l) at select locations in Lake Mead during 1981 and 1982.

reached a minimum during August and September and increased again during fall (Figs. 4.4.4 - 4.4.5). These trends were evident throughout the reservoir during both 1981 and 1982.

There was little seasonal or spatial variation in ammonia concentrations outside the inner Las Vegas Bay (Fig. 4.4.6). Ammonia concentrations averaged < .010 mg/l in the middle Las Vegas Bay and Boulder Basin and were about .005 mg/l elsewhere in the reservoir (Fig. 4.4.6). There was some seasonal variation in TN concentrations as a result of seasonal changes in nitrate + nitrite (Figs. 4.4.4, 4.4.5), but spatial differences were minimal outside the inner Las Vegas Bay (Fig. 4.4.7).

4.5 Spatial, Seasonal and Annual Variations in Chlorophyll-a Concentrations and Phytoplankton Productivity

Nutrient inputs from Las Vegas Wash significantly elevated chlorophyll-*a* concentrations in the inner Las Vegas Bay (14a). Chlorophyll-*a* concentrations at this station exceeded 50 μg/l during the spring and summer of 1981 (Fig. 4.5.1). Chlorophyll-*a* was slightly lower during comparable periods in 1982, but concentrations were still high considering that phosphorus loading in Las Vegas Wash was reduced to 1 mg/l after July, 1981. Chlorophyll-*a* concentrations in the inner Las Vegas Bay during winter months were similar to those in the middle Las Vegas Bay (14c) and Boulder Basin (15).

Chlorophyll-*a* in the middle Las Vegas Bay (14c) also showed an increase during the spring and summer months, but concentrations were much lower than the inner Las Vegas Bay. Chlorophyll-*a* concentrations in Boulder Basin and other main reservoir stations were extremely low, and

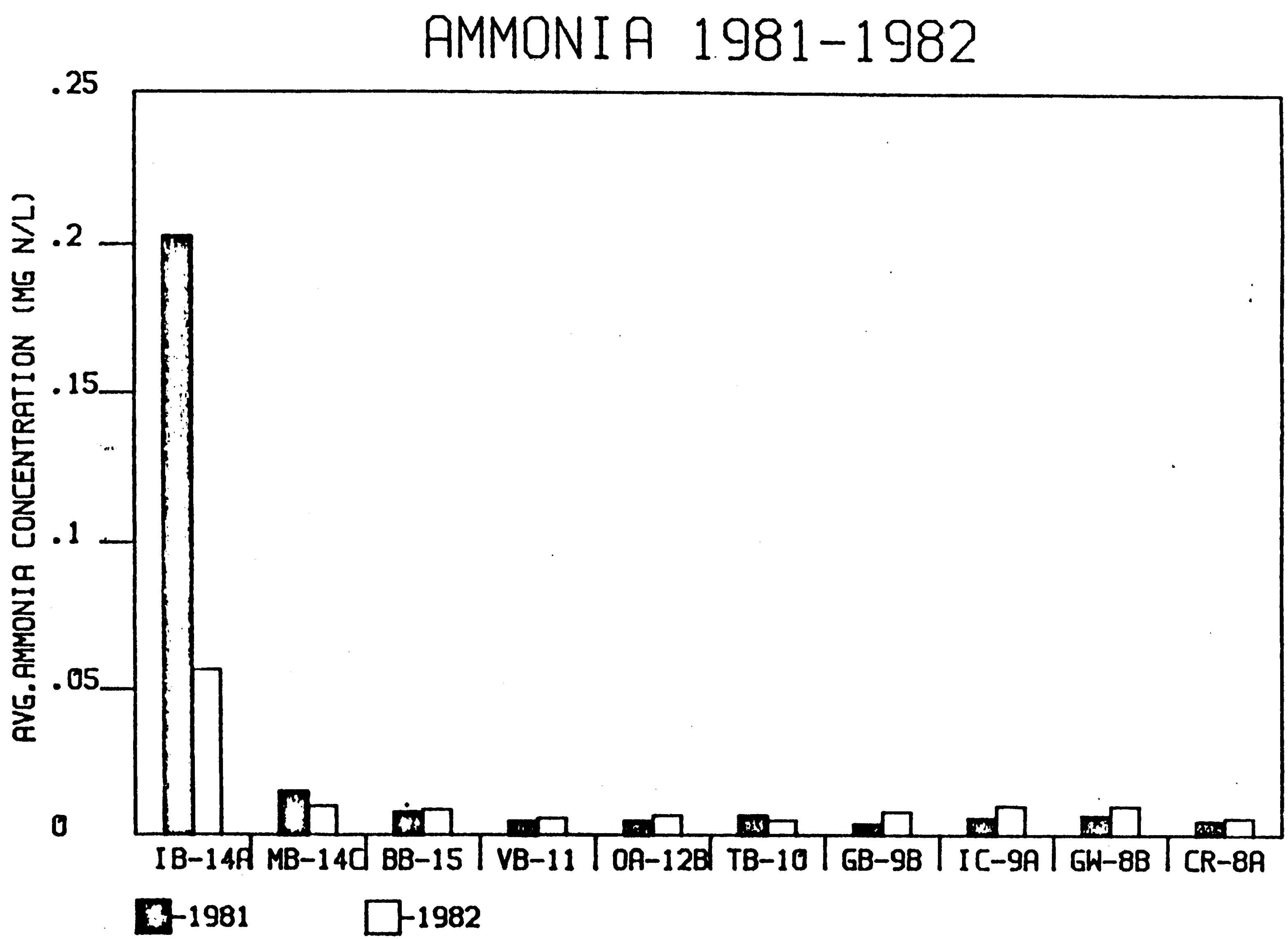

Figure 4.4.6. Annual average ammonia concentrations (mg/l) at select locations in Lake Mead during 1981 and 1982.

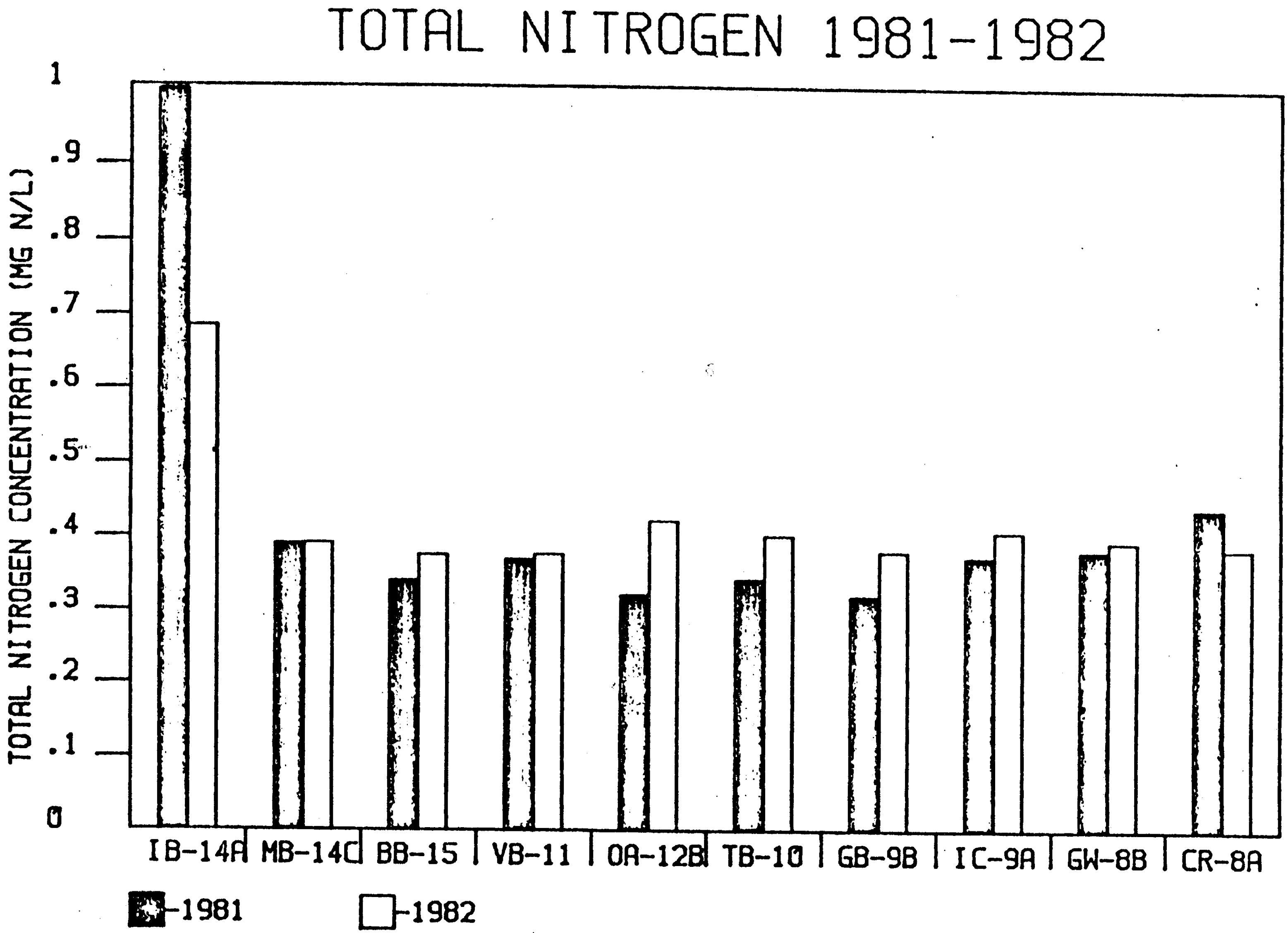

Figure 4.4.7. Annual average total nitrogen concentrations (mg/l) at select locations in Lake Mead during 1981 and 1982.

there was little seasonal variation (Fig. 4.5.1). Chlorophyll-a concentrations were, however, elevated somewhat near the inflow stations in the Overton Arm and Upper Arm (Fig. 4.5.1). Chlorophyll-a concentrations reached 3-5 μg/l in the Virgin Bowl (13a) and the Muddy Arm (12a) during the summers of 1981 and 1982 (Fig. 4.5.1). Chlorophyll-a concentrations also increased in Gods Pocket (8a), Grand Wash (8b) and Iceberg Canyon (9a) during the summer of 1981 (Fig. 4.5.1). The highest chlorophyll-a in the upper basin occurred in April, 1982 when concentrations in Grand Wash (8b) and Iceberg Canyon (9a) ranged from 7-9 μg/l (Fig. 4.5.1). Chlorophyll-a concentrations at these stations decreased during the summer, but then increased again during September, 1982. Chlorophyll-a concentrations during the winter months were generally similar at all stations in the upper basin.

Phytoplankton productivity measurements were made at select locations in the upper basin during January, 1981 - March, 1982 (Fig. 4.5.2) and at the lower basin stations during the whole study (Fig. 4.5.3). Phytoplankton productivity followed the same seasonal patterns in all areas of Lake Mead. Productivity was low during the winter months then increased to a maximum during spring and summer and decreased again in fall (Figs. 4.5.2 - 4.5.3). Spatial differences in productivity were minimal during the winter, and rates averaged about 150-300 mg C/m^2/day at all stations However, there were marked spatial differences in productivity during the spring and summer. Productivity was highest in the inner Las Vegas Bay (14a) where rates ranged from 3,000-4,000 mg C/m^2/day during most of the summer. Productivity exceeded 10,000 mg C/m^2/day in the inner Las Vegas Bay during June 1982. Phytoplankton productivity in the middle Las Vegas Bay ranged from 2,000-3,000 mg C/m^2/day during the spring and summer of 1981 but

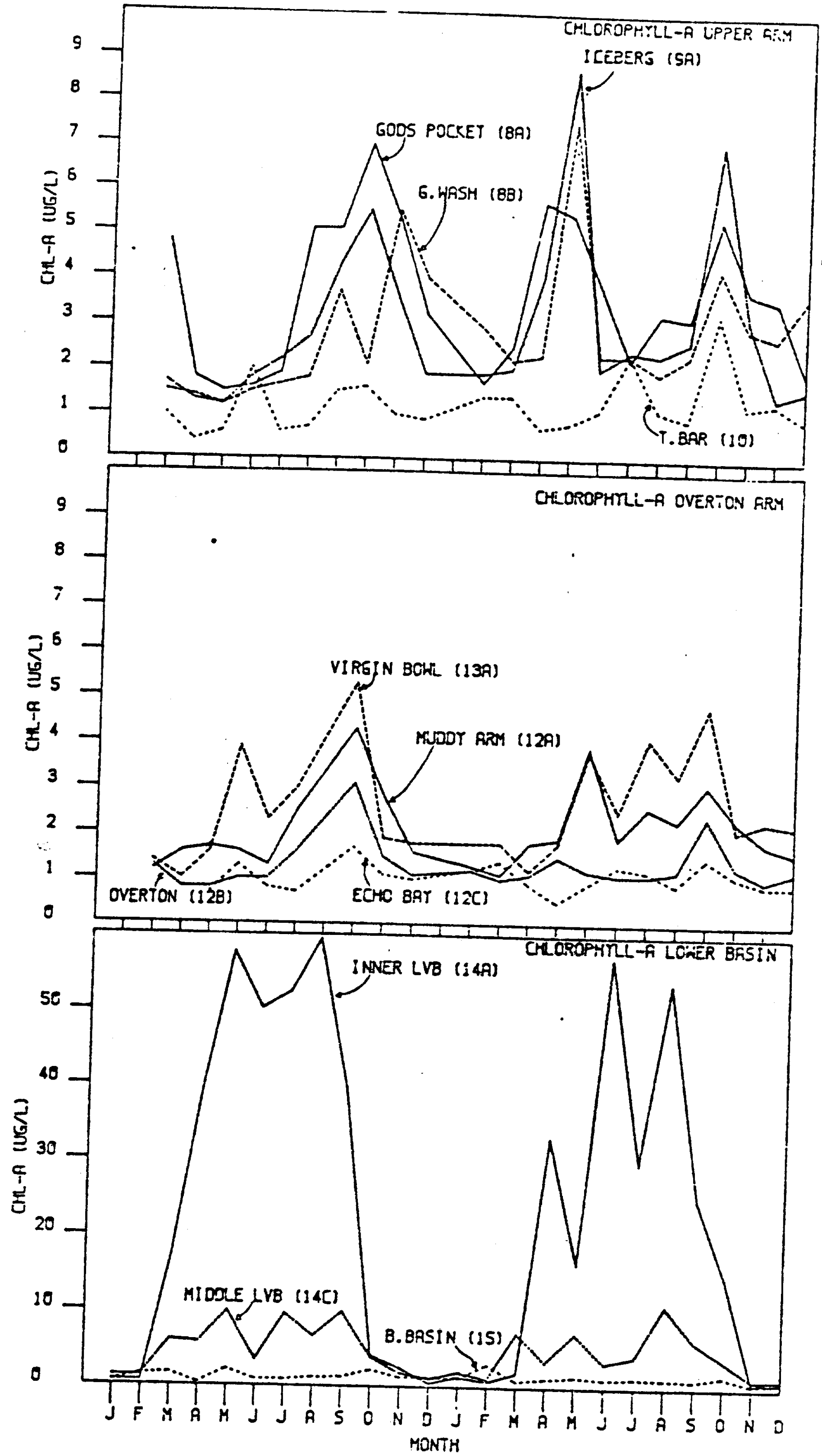

Figure 4.5.1. Chlorophyll-a concentrations in the Upper Arm, Overton Arm and Lower Basin of Lake Mead during 1981 and 1982.

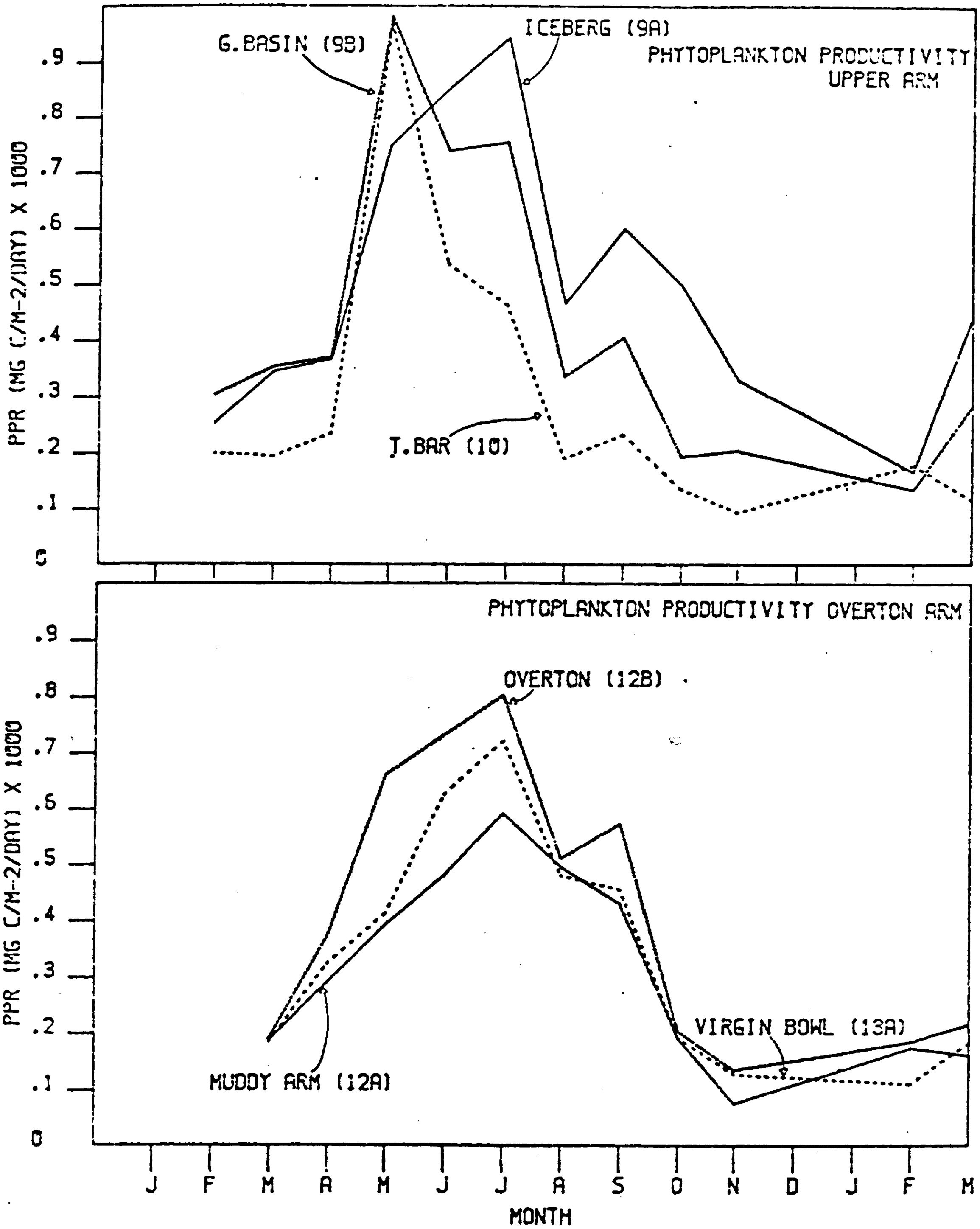

Figure 4 5.2. Phytoplankton productivity (mgC/m^2/day) at select locations in the Overton Arm and Upper Arm of Lake Mead during 1981 and 1982.

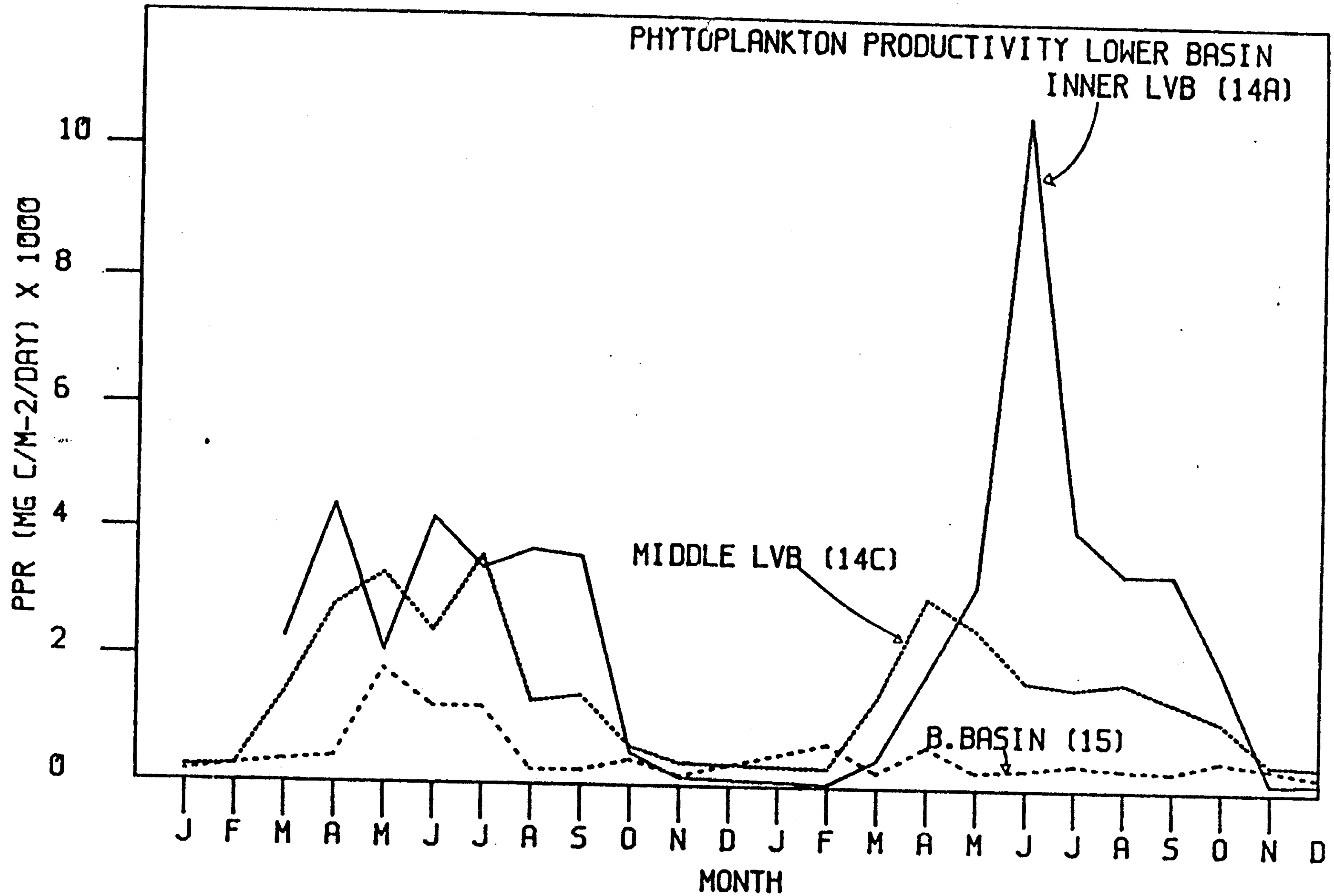

Figure 4.5.3. Phytoplankton productivity ($mgC/m^2/day$) at select locations in the Lower Basin of Lake Mead during 1981 and 1982.

decreased to about 1500 mg C/m^2/day during the summer of 1982. Productivity in Boulder Basin was considerably lower than the middle Las Vegas Bay, particularly during 1982.

Phytoplankton productivity in the upper basin never exceeded 1000 mg C/m^2/day during the period of measurement. Productivity was similar in the Upper Arm stations during early summer, but during late summer and fall, rates were higher at Iceberg Canyon (9a) than Gregg Basin (9b) or Temple Bar (10). Productivity in the Overton Arm was lower than the Upper Arm and Las Vegas Bay (Fig. 4.5.2). Productivity differences were minimal among stations in the Overton Arm, except for a brief period during May-June 1981. During this period, productivity was higher at Overton (12b) and the Virgin Bowl ((13a) than the Muddy Arm (12a).

4.6 Zooplankton Dynamics in Lake Mead

4.6.1 Zooplankton Species Composition

The zooplankton community in Lake Mead was comprised of numerous species of rotifers, cladocerans and copepods (Table 4.6.1). The rotifers were the most diverse group, but the abundances of most species were low. *Polyarthra* sp. and *Syncheata* sp. were the predominate rotifers in the reservoir. They occurred at most locations and were abundant near the inflow stations. *Asplanchna priodonta* and the species of *Keratella* were common during some periods (Table 4.6.1). The other rotifers were rare and occurred infrequently in the reservoir.

The cladocerans were the second-most diverse zooplankton group in Lake Mead (Table 4.6.1). *Daphnia pulex*, *D. galeata mendotae* and *Bosmina longirostris* were the most abundant cladocerans. *D. parvula* and

Table 4.6.1. Zooplankton species in Lake Mead.

Species	Relative Abundance
ROTIFERA	
Asplanchna priodonta (Gosse)	common
Brachionus calyciflorus (Pallas)	rare
B. patulus (Müller)	rare
B. quadridentatus (Herman)	rare
Collotheca sp.	rare
Conochilus unicornis (Rousselet)	rare
Dicrarophorus sp.	rare
Euchlanis sp.	rare
Filinia sp.	rare
Kellicottia longispina (Kellicott)	rare
Keratella cochlearis (Gosse)	common
K. earlinae (Ahlstrom)	common
K. gracilenta	common
K. quadrata (Müller)	rare
K. serrulata (Ahlstrom)	rare
Lecane (Lecans) Luna (Müller)	rare
L. (Monostyla) lunaris (Ehrbg)	rare
Lepadella sp.	rare
Ploeosoma sp.	rare
Polyarthra spp.	abundant
Syncheata sp.	abundant
Trichocerca spp.	common
CLADOCERA	
Alona guttata (Sais)	common
A. quadrangularis (Müller)	rare
Bosmina longirostris	abundant
Ceriodaphnia lacustris (Birge)	rare
C. quadrangula (Müller)	rare
Chydorus sphaericus (Müller)	rare
Daphnia galeata mendotae (Birge)	abundant
D. pulex (Leydig)	abundant
Diaphanosoma brachyurum (Lieven)	common
Leptodora kindti (Focke)	rare
Macrochaetus sp.	rare
Moina sp.	rare
Polyphemus pediculus (Linne)	rare

Table - continued

COPEPODA

Cyclops bicuspidatus thomasi (Forbes)	abundant
C. vernalis americanus (Fischer)	common
Diaptomus clavipes (Schacht)	common
D. reighardi (Marsh)	common
D. siciloides (Lilljeborg)	common
Eucyclops agilis (Kock)	rare
Macrocyclops albidus (Jurine)	rare
Mesocyclops edax (Forbes)	common

Diaphanosoma brachyurum were common during some periods of the study. The other cladocerans occurred sparodically in the reservoir and their abundances were usually low.

Cyclops bicuspidatus and Diaptomus siciloides were the predominate copepods in Lake Mead (Table 4.6.1). D. ashlandi, D. reighardi and D. clavipes were common during some periods near the inflow stations. Mesocylops edax was also common in some locations.

4.6.2 Seasonal Succession and Spatial Variations in Abundances of Predominate Zooplankton

The seasonal succession patterns of Daphnia pulex were similar throughout Lake Mead (Fig. 4.6.1). D. pulex abundances were low during summer, increased in fall, reached a maximum in winter and then decreased again during spring. During the winter periods, the highest abundance of D. pulex occurred in the inner Las Vegas Bay (14a), followed by the Virgin Bowl (13a) and Iceberg Canyon (9a). The abundances of D. pulex decreased considerably downlake from the inflow stations during winter periods. Their abundances were low throughout the reservoir during summer periods.

The succession patterns of Daphnia galeata differed among locations in the reservoir (Fig. 4.6.2). D. galeata reached maximum abundance during spring in the inner Las Vegas Bay (14a), which was slightly later than for D. pulex. D. galeata was also most abundant during spring in the middle Las Vegas Bay (14c) during 1981, but in 1982, their peak abundance occurred during fall (Fig. 4.6.2). D. galeata abundances were extremely low in Boulder Basin (15), but did increase somewhat during the summer (Fig. 4.6.2). This was also the case at the other main

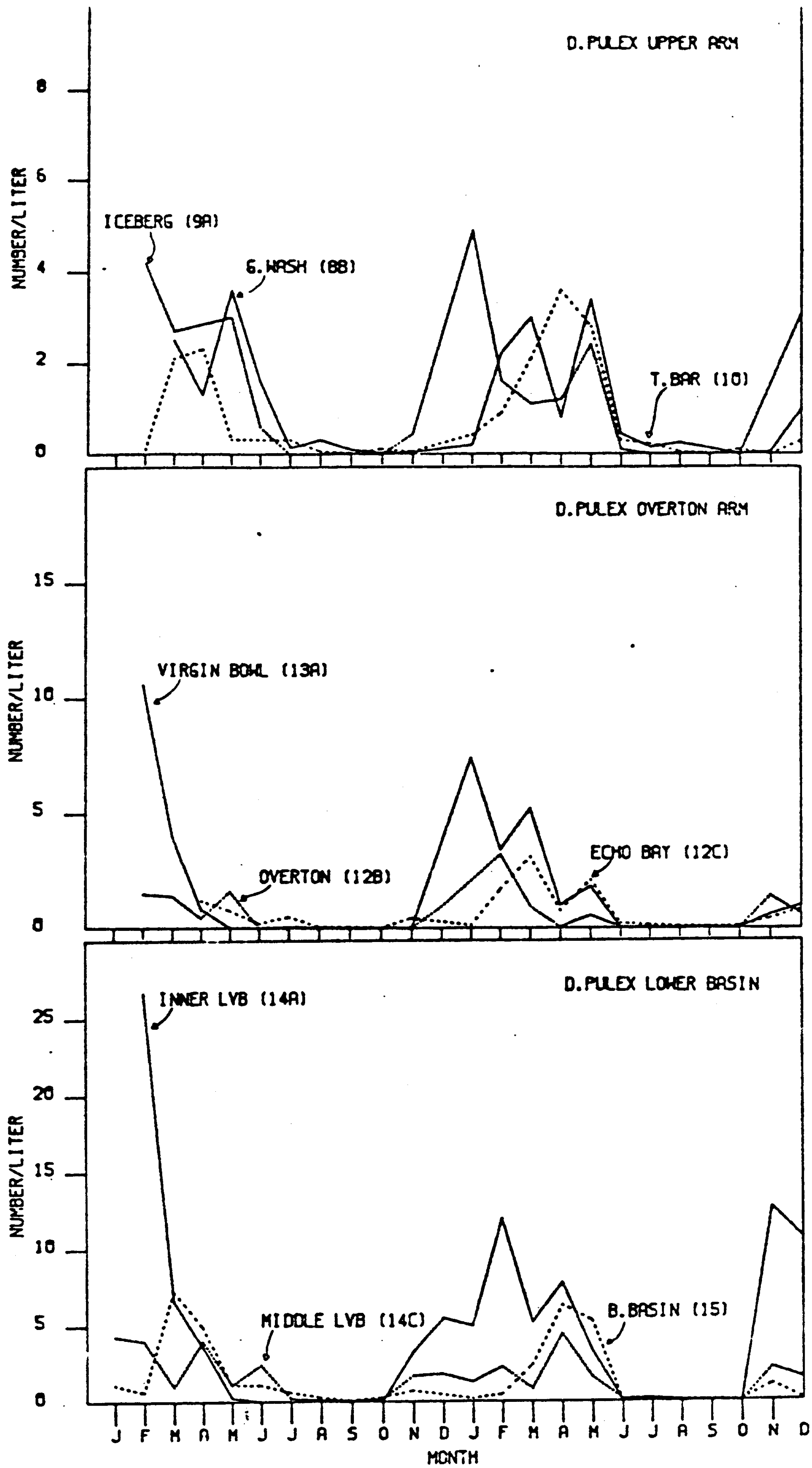

Figure 4.6.1. Seasonal succession patterns of Daphnia pulex in Lake Mead during 1981 and 1982.

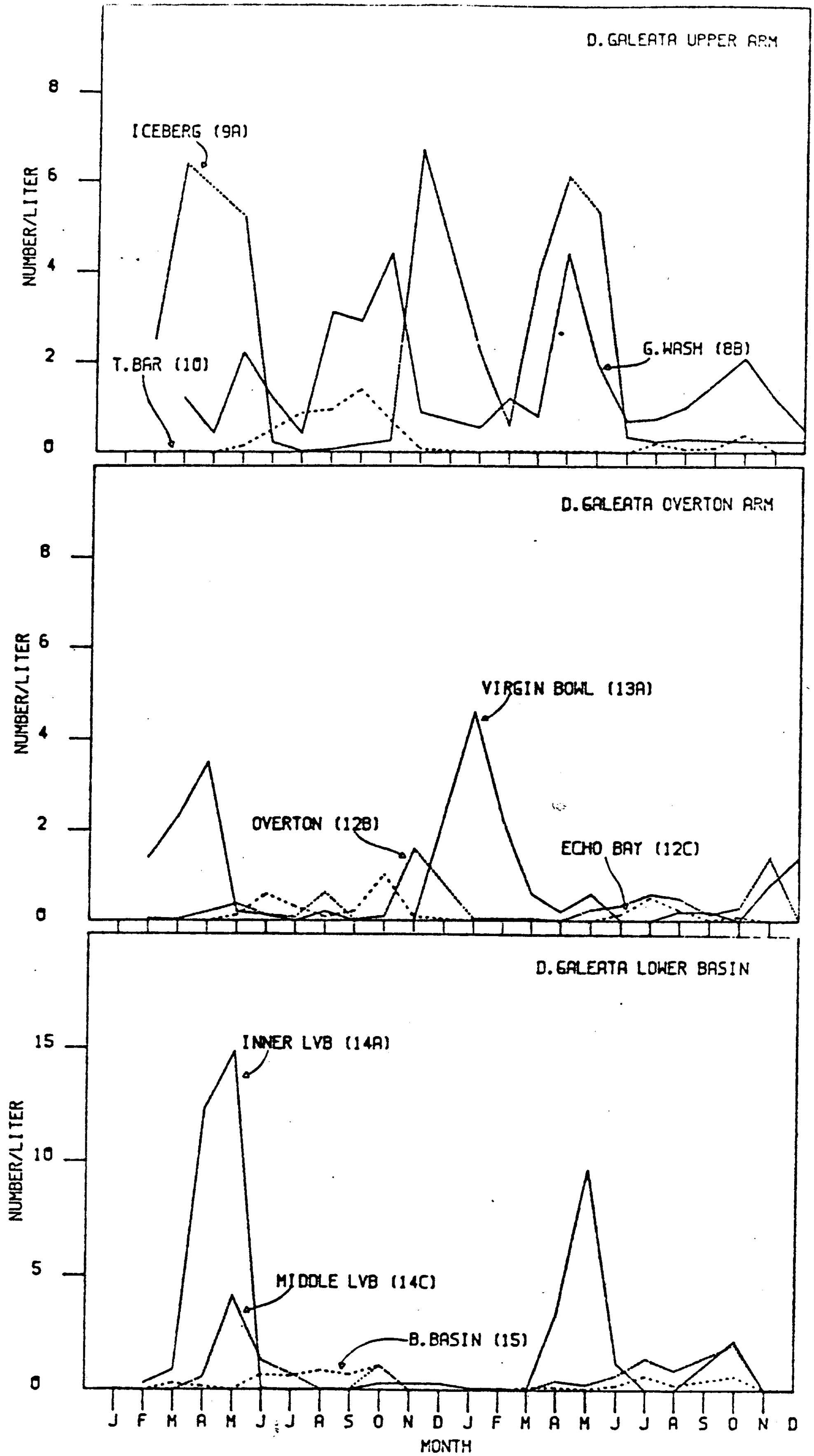

Figure 4.6.2. Seasonal succession patterns of Daphnia galeata mendotae in Lake Mead during 1981 and 1982.

reservoir stations in Echo Bay (12c) and Temple Bar (10). In the Virgin Bowl (13a), *D. galeata* reached maximum abundances during spring in 1981 and winter in 1982 (Fig. 4.6.2). The succession patterns of *D. galeata* were extremely erratic in the Upper Arm of Lake Mead. They reached maximum abundance during spring periods in Iceberg Canyon (9a) but also showed a secondary maximum during November 1981. In Grand Wash (8b), *D. galeata* abundance was highest during fall in 1981 and spring in 1982 (Fig. 4.6.2), but a secondary peak also occurred in October, 1982.

The succession patterns of *Bosmina longirostris* were also extremely variable (Fig. 4.6.3). There were two peaks of abundance in the inner Las Vegas Bay (14a) during 1981, one during May-June and another, larger peak during October. *B. longirostris* densities were lower at this station throughout 1982, but there was some increase in their abundance during the spring and summer. In the middle Las Vegas Bay (14c), *B. longirostris* reached maximum abundance during the summer of both years, but they were less numerous during 1982 (Fig. 4.6.3).

Similar succession patterns were also evident in Boulder Basin (15), Echo Bay (12c) Overton (12b) and Temple Bar (10), but densities were low (Fig. 4.6.3). *B. longirostris* was more abundant near the inflow stations in the upper basin. Their highest densities occurred during May of 1981 and 1982 in the Virgin Bowl (13a), Grand Wash (8b) and Iceberg Canyon (9c). Secondary maxima also occurred during fall and winter of 1981 at the Virgin Bowl (13a) and Grand Wash (8b). It is interesting to note that *B. longirostris* was the only cladoceran that reached densities in the upper basin inflow stations comparable to those in the inner Las Vegas Bay (14a).

The abundances of adult copepods in Lake Mead were extremely low,

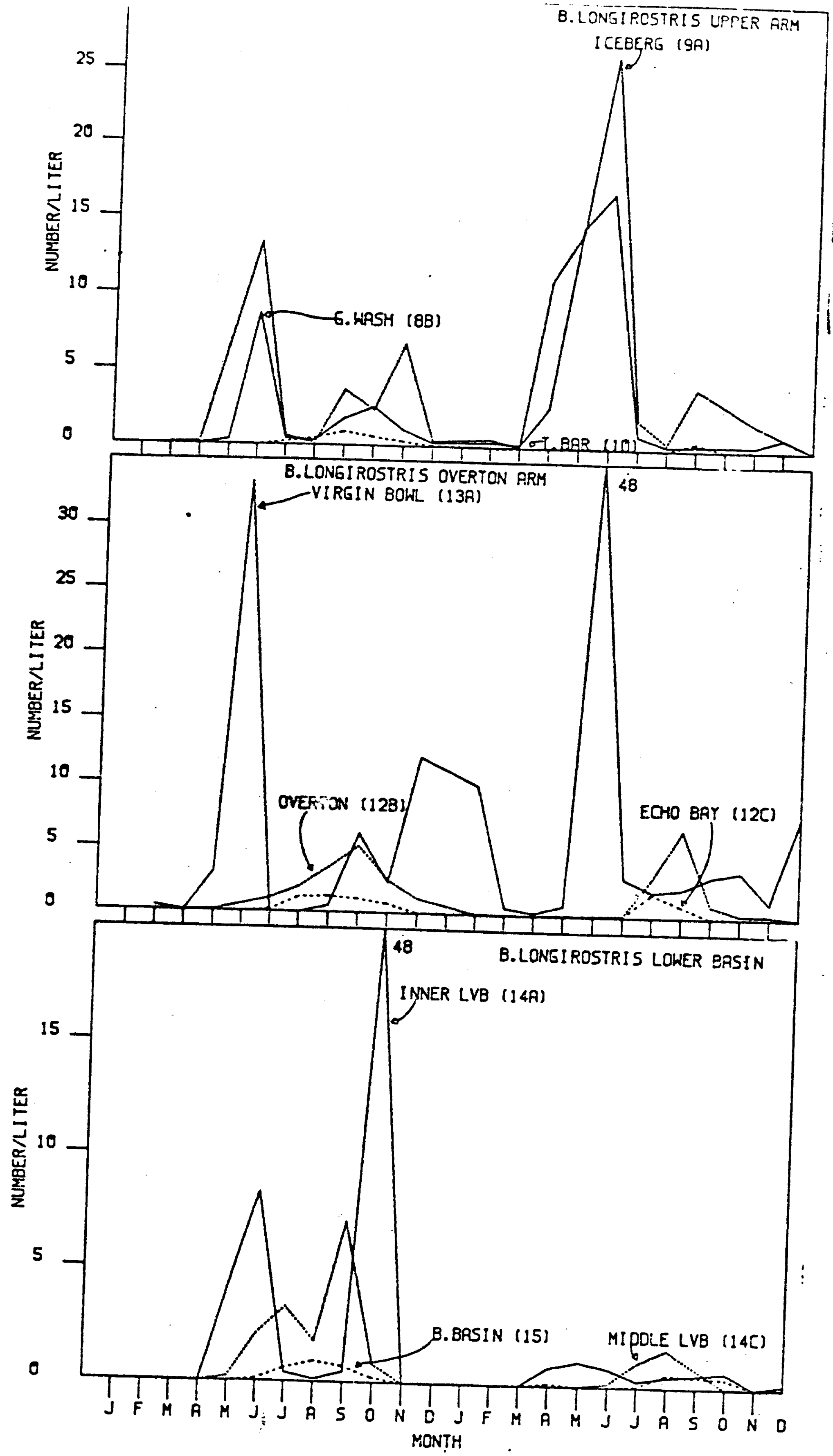

Figure 4.6.3. Seasonal succession patterns of <u>Bosmina longirostris</u> in Lake Mead during 1981 and 1982.

except for the inner Las Vegas Bay (14a) and the Virgin Bowl (13a). D. siciloides, the dominant calanoid copepod, reached maximum abundance during fall and early winter at these stations (Fig. 4.6.4). Densities in the inner Las Vegas Bay (14a) were, however, nearly five times greater than in the Virgin Bowl (13a). D. siciloides was present at the other stations during these periods, but their abundances were very low (Fig. 4.6.4).

Cyclops bicuspidatus, the principal cyclopoid copepod, was also abundant in the inner Las Vegas Bay (14a) during late winter and spring periods of both years (Fig. 4.6.5). The same seasonal succession patterns were evident in the middle Las Vegas Bay (14c) and Boulder Basin (15), but densities were much lower. C. bicuspidatus was most numerous during February, 1982 in the Virgin Bowl (13a) and Overton (12b) (Fig. 4.6.5). Seasonal variations in C. bicuspidatus abundances were minimal in Upper Arm stations, but some increases in abundances did occur during winter and spring months.

There were no consistent seasonal succession patterns evident for the predominate rotifers. The densities of Polyarthra sp. and Syncheata sp. were extremely variable near the inflow stations where they were most abundant (Figs. 4.6.6 - 4.6.7). However, densities in the inner Las Vegas Bay (14a) were usually higher than stations in the Overton Arm or Upper Arm. Rotifer densities were extremely low at the main reservoir stations.

4.7 Relative Abundances of Fish

It was not possible to quantify abundances of individual fish species from the echo soundings. However, these did provide a means to

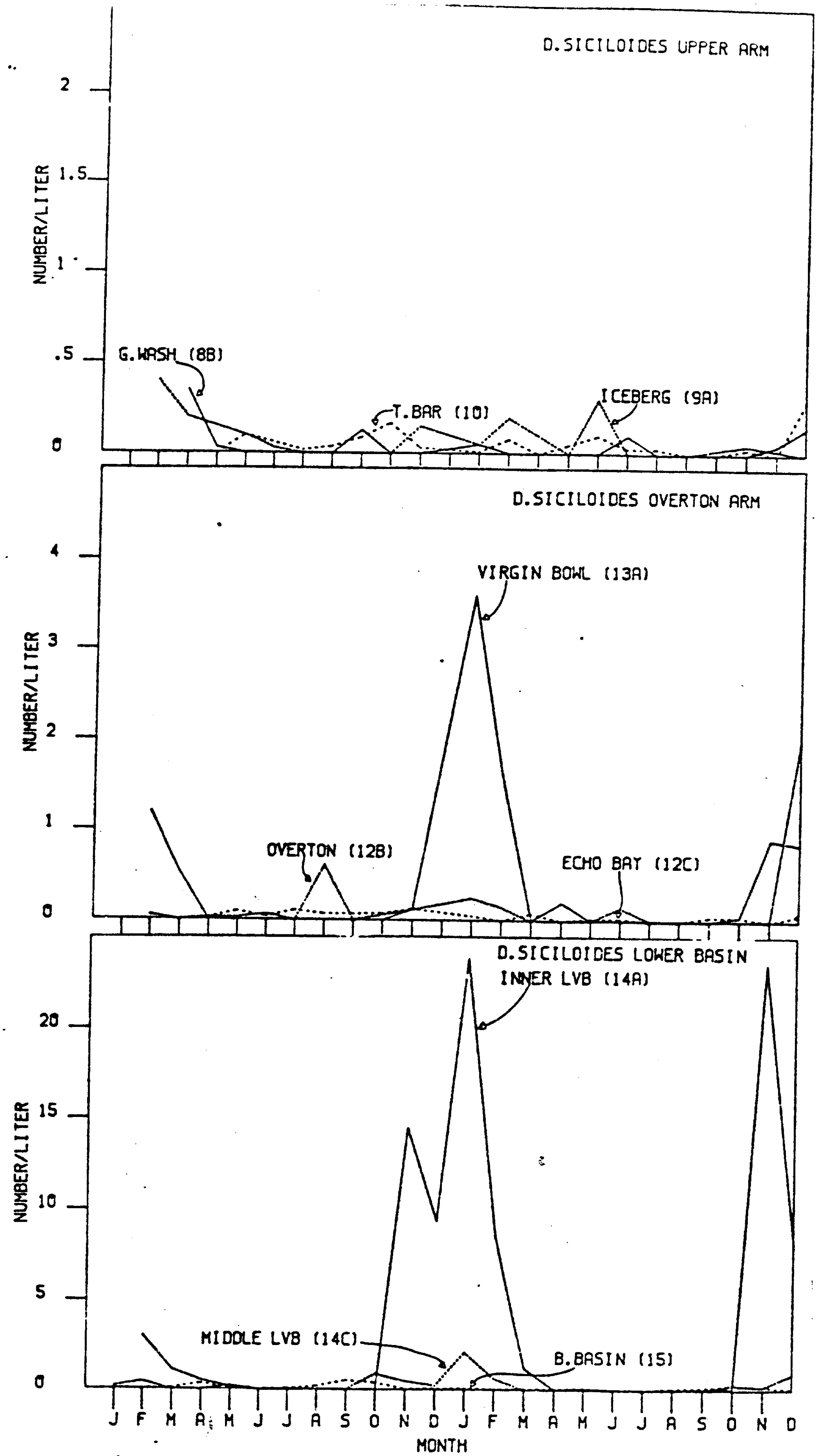

Figure 4.6.4. Seasonal succession patterns for Diaptomus siciloides in Lake Mead during 1981 and 1982.

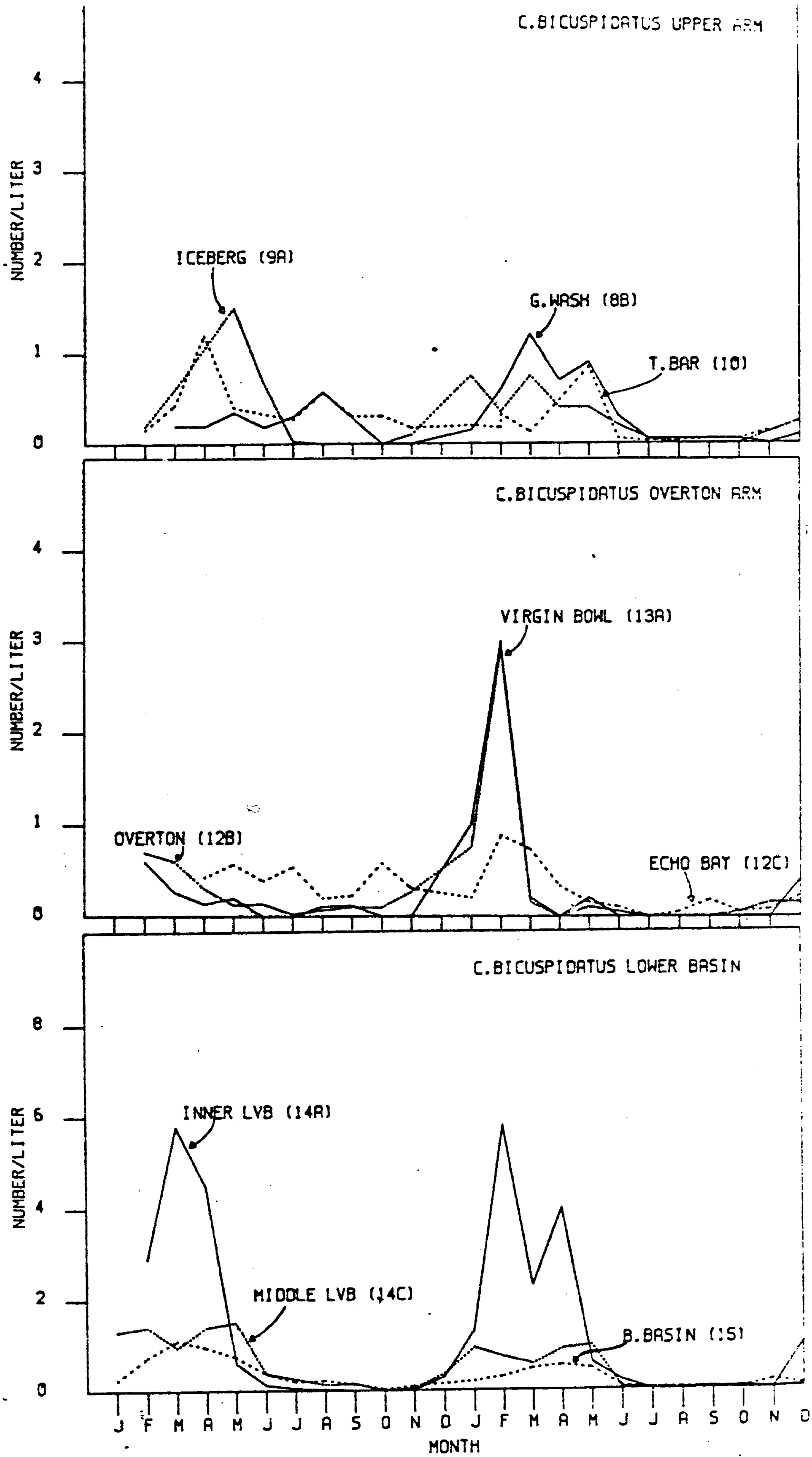

Figure 4.6.5. Seasonal succession patterns for Cyclops bicuspidatus in Lake Mead during 1981 and 1982.

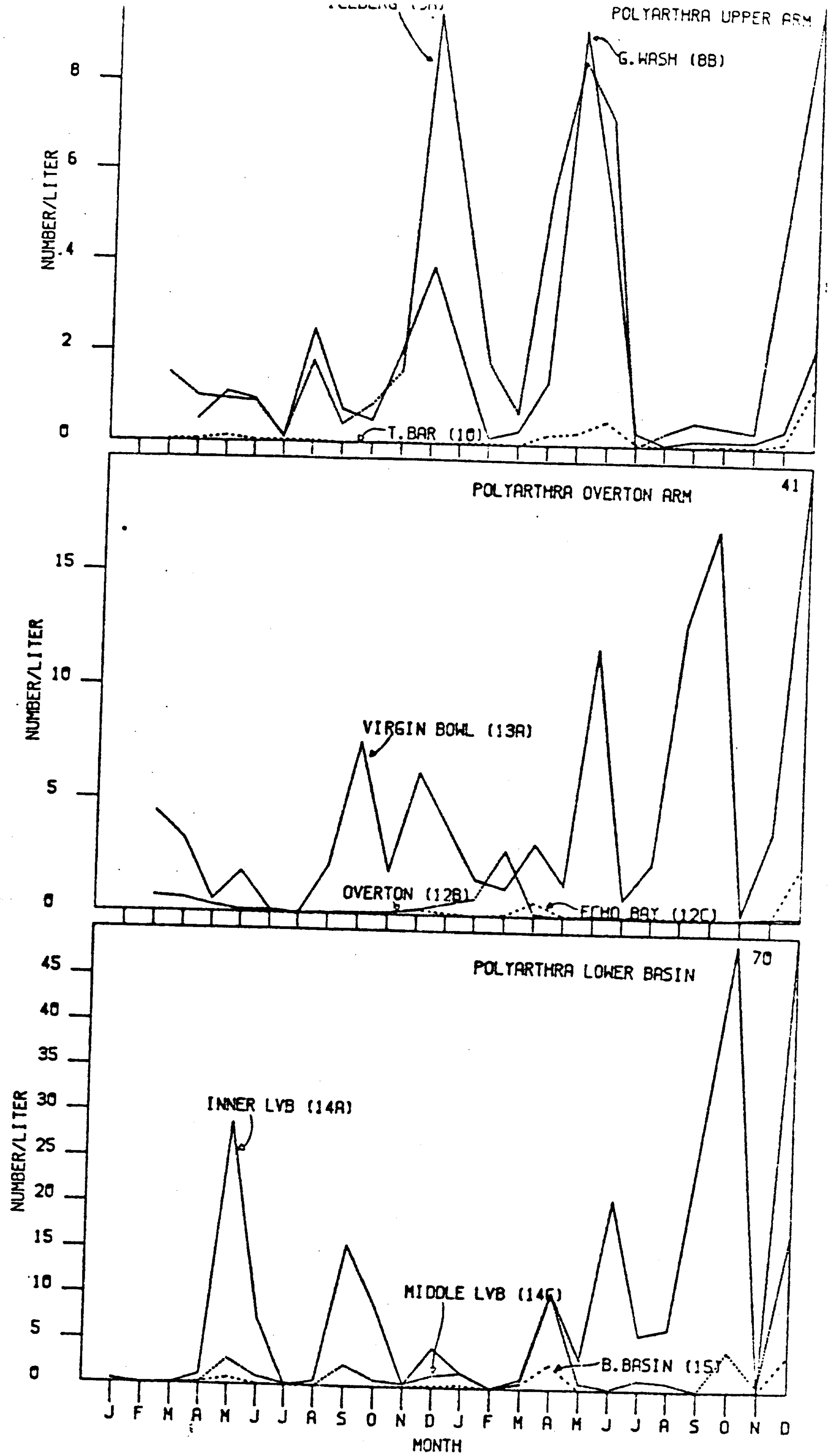

Figure 4.6.6. Seasonal succession patterns of Polyarthra sp. in Lake Mead during 1981 and 1982.

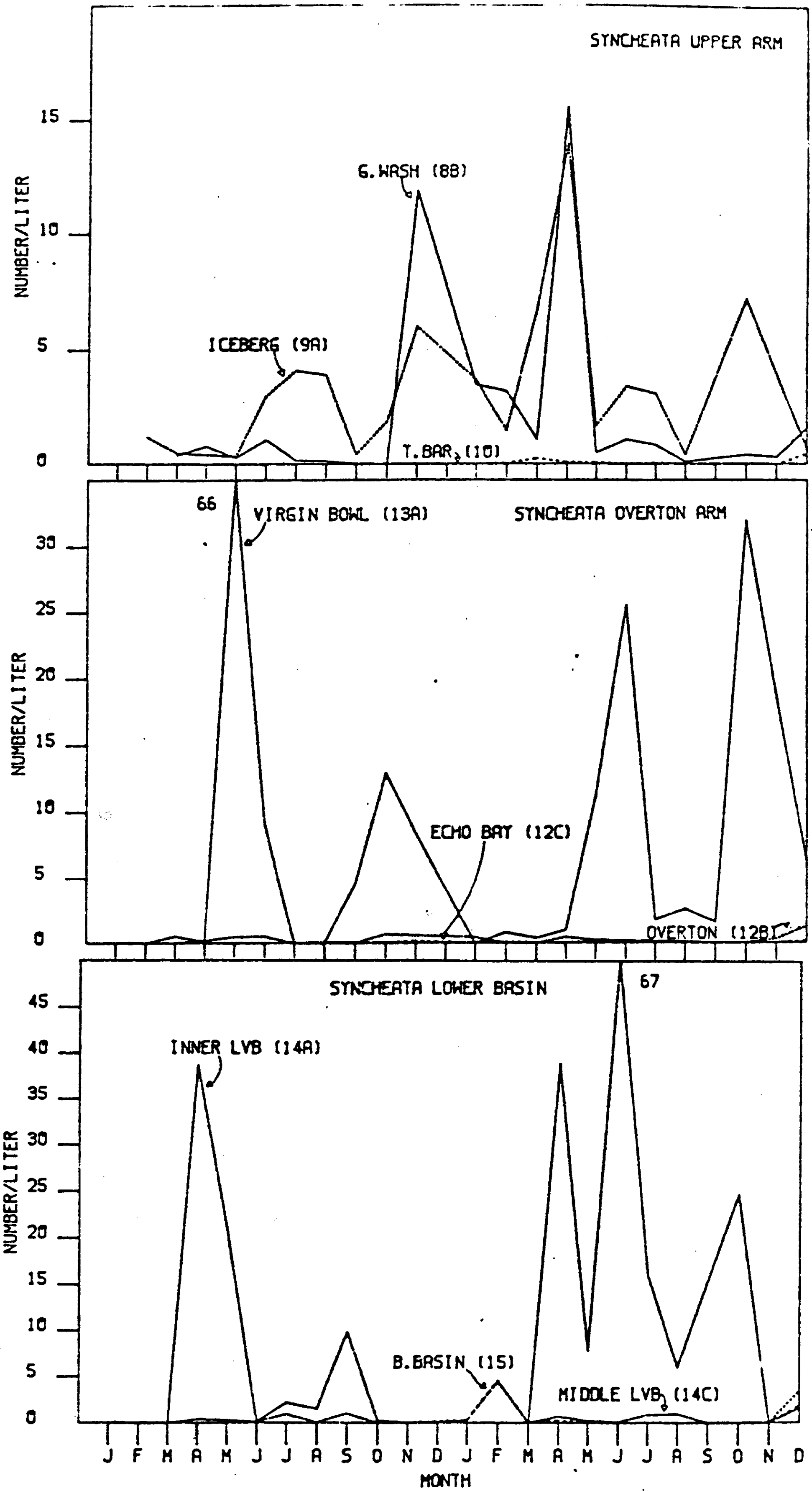

Figure 4.6.7. Seasonal succession patterns of Syncheata sp. in Lake Mead during 1981 and 1982.

estimate relative abundances of the total fish population. The echo sounding results indicate that fish were most abundant near the inflow stations (Fig. 4.7.1). The highest fish abundances occurred in the inner Las Vegas Bay (14a) and the Virgin Bowl (13a) (Fig. 1.7.1). Fish were also fairly numerous in the middle Las Vegas Bay (14c), Overton (12b), Muddy Arm (12a) and stations upstream of Iceberg Canyon (9a). Fish were extremely rare at the main reservoir stations (9b, 10, 11, 12c, 15) where the population consisted of a few scattered individuals. These patterns were consistent during both years of the study (Fig. 4.7.1).

There were some seasonal variations in fish abundances near the inflow stations (Fig. 4.7.2). Fish were generally most numerous during the spring and summer months, and lowest abundances occurred during the fall and winter (Fig. 4.7.2).

4.8 Statistical Analyses

4.8.1 Zooplankton

A non parametric correlation analysis was used to evaluate relationships among densities of major zooplankton taxa and various environmental factors. The correlation analysis was run for the combined inflow stations (8a, 8b, 9a, 12a, 12b, 13a, 14a, 14b, BC4 and 14c) and for the Las Vegas Bay stations (14a, 14b, BC4, and 14c) where spatial and seasonal variations in zooplankton abundances and environmental factors were most evident.

A number of statistically significant relationships were derived from the correlation analyses for both data sets. *Daphnia pulex*, *Diaptomus siciloides* and *Cyclops bicuspidatus* showed consistent negative relationships to temperature, chlorophyll-*a* and fish abundance (Tables

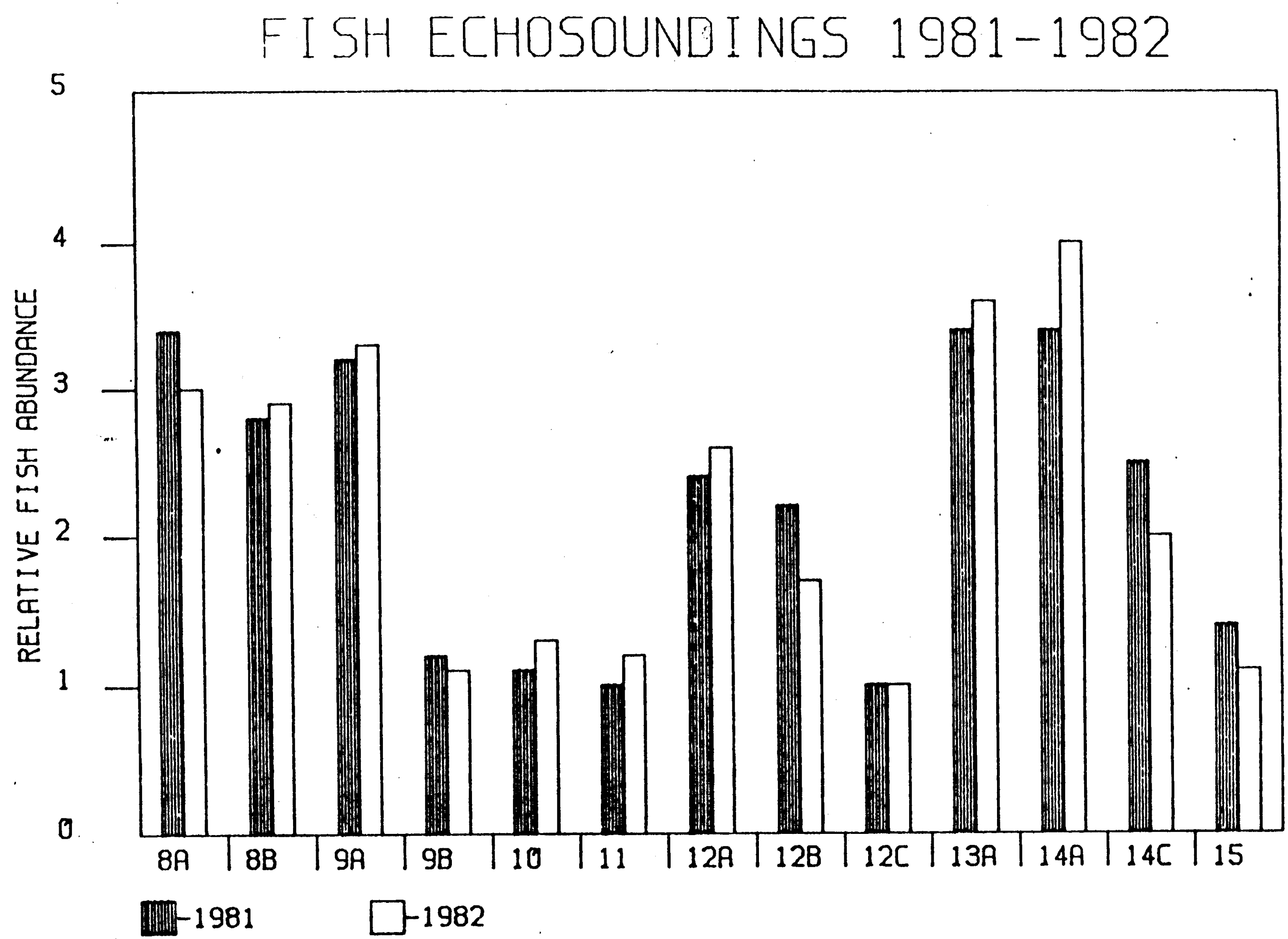

Figure 4.7.1. Average relative fish abundances at select locations in Lake Mead during 1981 and 1982 (see METHODS section for abundance criteria).

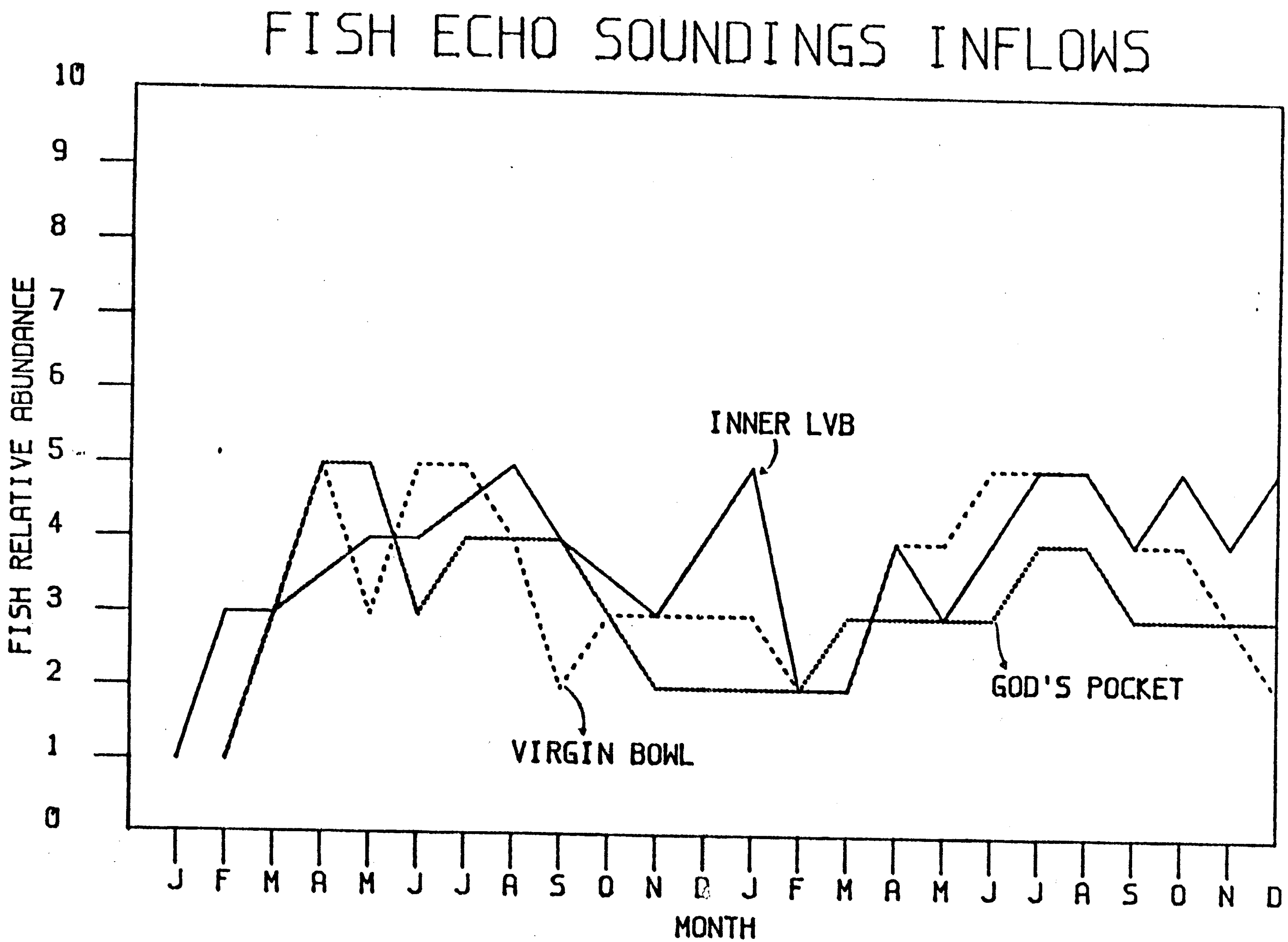

Figure 4.7.2. Monthly relative fish abundances for the inflow stations during 1981 and 1982 (see METHODS section for abundance criteria).

4.8.1 - 4.8.2). *D. pulex* was positively related to oxygen, as was *C. bicuspidatus* for the combined inflow correlations. *Daphnia galeata* was unrelated to any of the environmental factors. *Bosmina longirostris* was positively related to temperature and chlorophyll-*a* and negatively related to dissolved oxygen in both data sets (Tables 4.8.1 - 4.8.2). The dominant rotifers, *Polyarthra* and *Syncheata* were positively related to chlorophyll-*a* in both data sets and also to conductivity and fish abundances in the Las Vegas Bay correlations. *Syncheata* also showed a positive relationship to temperature in the Las Vegas Bay correlations.

4.8.2 Fish

A non parametric correlation analysis was also used to evaluate the influence of environmental factors on fish abundances for the same data sets. There was a significant positive relationship between fish abundances and temperatures and chlorophyll-*a* for the combined inflow correlations (Table 4.8.3). Fish abundances were also positively related to these variables and also to conductivity in the Las Vegas Bay correlations.

4.9 Effects of Experimental Food Enrichment on Growth and Reproduction of *Daphnia pulex*

The correlation analysis indicated that chlorophyll-*a* was an important factor influencing abundances of zooplankton in Lake Mead. This relationship was, nevertheless, highly variable due to the effects of other factors like fish predation, and seasonality on zooplankton abundances during the summer months when chlorophyll-*a* concentrations were highest. A feeding experiment was, therefore, conducted during July and August of 1981 to more directly evaluate the effects of different

Table 4.8.1. Correlation matrix between abundances of dominant zooplankton taxa and various environmental factors for the combined inflow stations in Lake Mead.

Zooplankton Species	Temperature	Oxygen	pH	Conductivity	Chlorophyll-a	Fish Abundance
Cladocerans						
Daphnia pulex	-.74**	.33**	.10	-.08	-.47**	-.29**
Daphnia galeata	-.15	.00	-.07	-.22**	.06	-.05
Bosminia longirostris	.37**	-.26**	-.17	-.03	.35**	.18
Copepods (adults)						
Diaptomus siciloides	-.50**	.12	.12	-.08	-.40**	-.27**
Cyclops bicuspidatus	-.59**	.29**	.08	-.01	-.28**	-.30**
Rotifers						
Syncheata sp.	.14	.20*	.16	.03	.34**	.25**
Polyarthra sp.	-.02	.19*	.03	.17	.31**	.13

** P .001

* P .005

Table 4.8.2. Correlation matrix between abundances of dominant zooplankton taxa and various environmental factors for the Las Vegas Bay stations.

Zooplankton Species	Temperature	Oxygen	pH	Conductivity	Chlorophyll-a	Fish Abundance
Cladocerans						
Daphnia pulex	-.80**	.34**	.12	-.20	-.53**	-.29**
Daphnia galeata	-.02	-.04	-.05	-.03	.08	-.12
Bosminia longirostris	.51**	-.40**	-.18	.13	.40**	.16
Copepods (adults)						
Diaptomus siciloides	-.58**	.10	.16	-.38**	-.50**	-.24*
Cyclops bicuspidatus	-.67**	.34**	.15	-.07	-.30**	-.38**
Rotifers						
Syncheata sp.	.30**	.10	.15	.33**	.43**	.31**
Polyarthra sp.	.07	.17	.07	.21*	.29**	.25*

** P .001

* P .005

Table 4.8.3 Correlation matrix between relative fish abundances and various environmental factors for the Las Vegas Bay and combined inflow stations.

Stations	Temperature	Oxygen	pH	Conductivity	Chlorophyll-a
Las Vegas Bay	.51**	-.01	.05	.30**	.45**
Combined Inflow	.48**	-.11	.04	.08	.34**

** P .001

chlorophyll-a concentrations on the growth and reproduction of Daphnia pulex.

D. pulex was used in the experiment because it is a major component of the zooplankton and because it is an important food item for fish in Lake Mead (Deacon et al. 1972, Wilde and Baker 1981, Plaskett and Paulson 1982). D. pulex were reared in lake waters collected from the inner Las Vegas Bay (14a), middle Las Vegas Bay (14c) and Boulder Basin (15). Chlorophyll-a concentrations in the lake waters used in the feeding experiments were monitored daily and results are presented in (Fig. 4.9.1). Although chlorophyll-a was quite variable in the inner and middle Las Vegas Bay, there were substantial differences in average concentrations during the experiment (Fig. 4.9.1). Chlorophyll-a averaged 40 µg/l in the inner bay and 11 µg/l in the middle bay during the experiment. Chlorophyll-a concentrations in Boulder Basin were extremely low and averaged only 1 µg/l.

The growth rates of D. pulex were significantly different in waters from these three locations (Table 4.9.1). The highest growth rates occurred in the inner Las Vegas Bay followed by the middle Las Vegas Bay and Boulder Basin. The greatest differences in growth rates occurred between D. pulex reared in waters from the middle Las Vegas Bay and Boulder Basin. There were no significant differences in neonate production between D. pulex reared in waters from the inner and middle bay, except for brood 6 (Table 4.9.1). Chlorophyll-a concentrations in the middle bay were approaching levels in Boulder Basin during the time of production of the 6th brood. Reproduction of D. pulex reared in Boulder Basin waters was substantially lower than those reared in Las Vegas Bay waters.

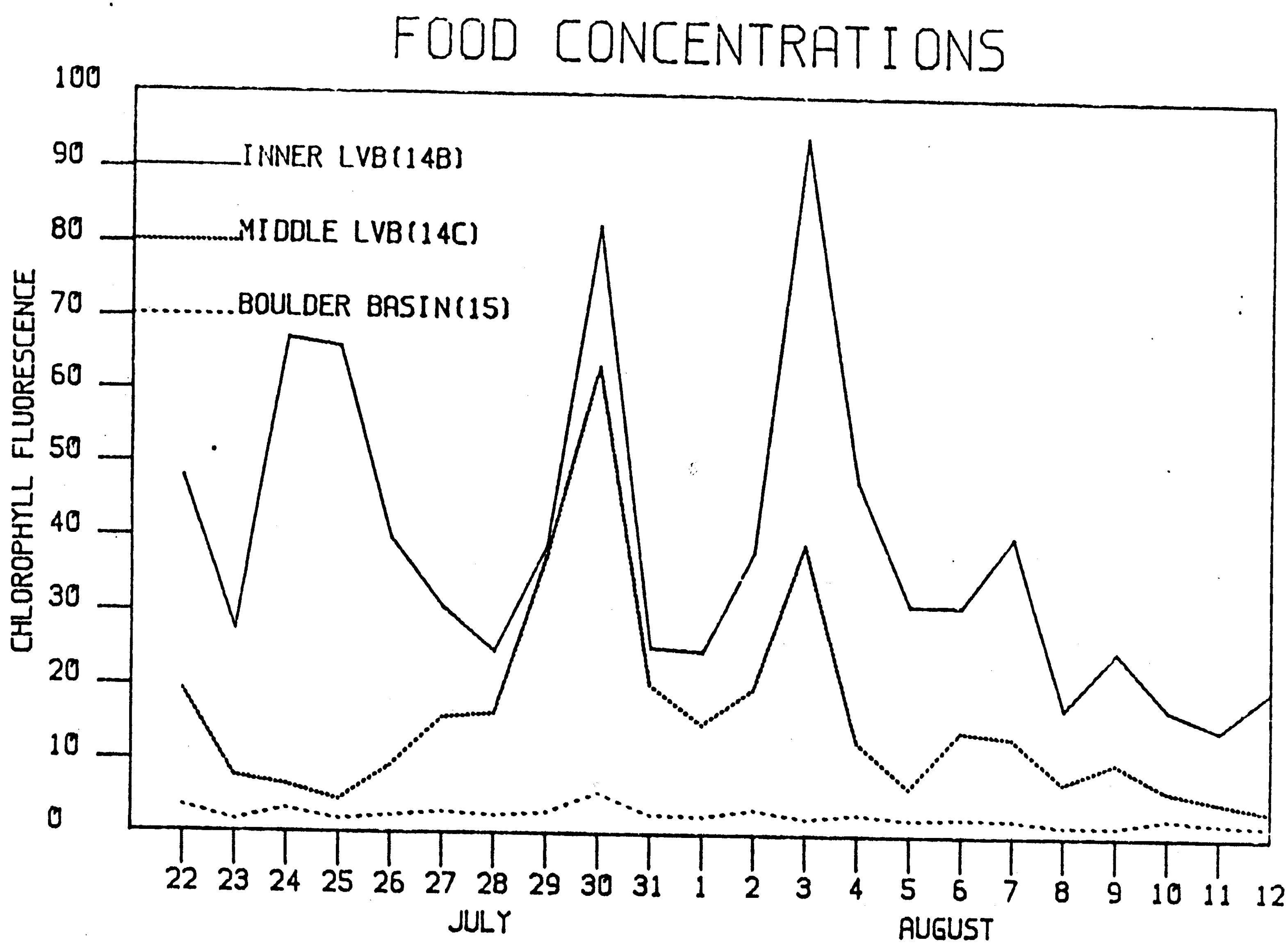

Figure 4.9.1. Chlorophyll-a concentrations for inner and middle Las Vegas Bay and Boulder Basin during the *Daphnia pulex* feeding experiments in 1981.

Table 4.9.1. Growth and reproduction of *D. pulex* in the inner and middle Las Vegas Bay and Boulder Basin. Values are average lengths, average number of neonates produced per brood, and total number of neonates. Significant difference between treatments were determined by Kruskal-Wallis Test. Horizontal lines indicate no significant difference.

Parameter	Location: Inner Las Vegas Bay	Location: Middle Las Vegas Bay	Location: Boulder Basin
$\bar{X}$ Chlorophyll-a (μg/l)	40	11	1
$\bar{X}$ Initial length (mm)	.73	.72	.66*
$\bar{X}$ Final length (mm)	3.17*	2.96*	2.26**
$\bar{X}$ Incremental growth rate (mm)	2.44*	2.24*	1.60**
$\bar{X}$ No. of Neonates Brood 1	8.8	8.4	6.2*
" " " " " 2	22.4	26.2	9.6**
" " " " " 3	29.4	32.8	6.0**
" " " " " 4	38.2	41.0	8.7**
" " " " " 5	35.8	37.2	13.0**
" " " " " 6	59.0**	22.2**	
Total No. of Neonates	822	839	184**

** significant at p = .01

* significant at p = .05

5.0 DISCUSSION

5.1 Reservoir Fertility and Productivity

The most prevalent limnological feature in Lake Mead during 1981 and 1982 was the extremely low phosphorus concentrations that existed in most areas of the reservoir. Ortho phosphorus concentrations averaged .002-.005 mg/l in most of the reservoir (Table 5.1.1). Total phosphorus concentrations averaged .005-.010 mg/l in the main basins (Boulder, Virgin, Gregg and Temple), the outer Las Vegas Bay. Overton and Echo Bay (Table 5.1.1). The main basin areas had moderate levels of total and inorganic nitrogen. Total nitrogen averaged .300-.400 mg/l and inorganic nitrogen was .200-.300 mg/l in most of the reservoir (Table 5.1.1). However, inorganic nitrogen levels were also reduced to very low levels during the summer months.

Most of the reservoir was severely deficient in phosphorus on the basis of total nitrogen:total phosphorus ratios (TN/TP). The TN/TP ratios exceeded 30:1 and ranged as high as 63:1 in the main basins (Table 5.1.1). N/P ratios greater than 10-15:1 are considered as the transition point from nitrogen to phosphorus limitation (Schindler 1977, Smith 1982).

Chlorophyll-a concentrations were extremely low in the main basins as a result of the phosphorus deficiencies. Chlorophyll-a averaged only 1-2 µg/l (Table 5.1.2), and seasonal and annual variations were minimal. Phytoplankton productivity averaged 300-500 mg C/m^2/day. Productivity was highest during the summer months, but rates never exceeded 1000 mg C/m^2/day.

Nutrient concentrations and productivity were higher near the

Table 5.1.1. Annual average nutrient concentrations (mg/1) and total nitrogen/total phosphorus ratios for 0 - 5 m integrated depths at select locations in Lake Mead during 1981 - 1982.

		Location/Station												
Parameter	Year	Inner* LVB (14a)	Middle LVB (14c)	Boulder Basin (15)	Virgin Basin (11)	Echo Bay (12c)	Overton (12b)	Muddy Arm (12a)	Virgin Bowl (13a)	Temple Bar (10)	Gregg Basin (9b)	Iceberg Canyon (9a)	Grand Wash (8b)	Gods Pocket (8a)
Total P	1981	.091	.025	.010	.006	.005	.008	.012	.015	.007	.008	.012	.011	.019
Ortho P	1981	.038	.005	.003	.002	.003	.003	.004	.003	.002	.002	.002	.002	.007
Total N	1981	.997	.390	.340	.369	.277	.321	.308	.347	.342	.320	.373	.381	.440
Inorganic N	1981	.578	.146	.133	.177	.127	.129	.122	.119	.184	.175	.171	.171	.209
TN/TP	1981	10.9	15.6	30.9	61.5	55.4	40.1	25.7	23.1	48.9	40.0	31.1	34.6	23.2
Total P	1982	.054	.012	.009	.006	.007	.007	.009	.012	.007	.008	.010	.010	.010
Ortho P	1982	.009	.003	.003	.002	.002	.002	.002	.002	.002	.002	.002	.002	.003
Total N	1982	.685	.392	.375	.376	.372	.422	.329	.339	.402	.380	.408	.394	.385
Inorganic N	1982	.340	.163	.161	.192	.178	.152	.136	.151	.173	.169	.159	.166	.181
TN/TP	1982	12.7	32.7	41.6	62.7	53.1	60.3	36.6	28.3	57.4	47.5	40.8	39.4	38.5

* 0 - 2.5 m integrated depth

inflow areas in the Upper Arm, Overton Arm and Las Vegas Bay. Inflows from the Colorado River caused a slight increase in phosphorus concentrations at stations upstream of Gregg Basin (Table 5.1.1). However, these areas were still deficient in phosphorus. TN/TP ratios ranged from 20-40:1 at the Colorado River inflow stations (Table 5.1.1).

Although the Colorado River was the principal source of total phosphorus to Lake Mead, a large percentage of this was bound to suspended sediments and unavailable for phytoplankton. Moreover, about 75-80% of the phosphorus loading occurred during a three-month period from August-October. The Colorado River forms a deep interflow in Lake Mead during summer and fall due to cold river temperatures and high discharges (Paulson et al. 1980). The interflow transports suspended sediments and associated phosphorus into the metalimnion and hypolimnion where siltation rapidly removes these materials from the water column. Minimal release of phosphorus and mixing with epilimnetic waters occurs downstream of the immediate inflow areas. The Colorado River thus had a minimum effect on phosphorus concentrations and productivity in the Upper Arm. It did, however, cause some increase in chlorophyll-a in Iceberg Canyon and upstream areas where concentrations averaged 2-4 μg/l (Table 5.1.2). Phytoplankton productivity in Iceberg Canyon was also slightly higher than the main basins.

The Virgin River provided significant amounts of total phosphorus to the Overton Arm. However, this too, was associated primarily with suspended sediments. The largest inputs occurred during brief flood periods. About 50% of the total phosphorus loading in 1981 occurred during July and August as a result of floods. Bio-available and ortho phosphorus loadings from both the Virgin and Muddy Rivers were minor

Table 5.1.2. Annual average chlorophyll-a (μg/l) for 0 - 5 m integrated depths and phytoplankton productivity (mg C/m^2/day) at select locations in Lake Mead during 1981 - 1982.

Parameter	Year	Location/Station Inner* LVB (14a)	Middle LVB (14c)	Boulder Basin (15)	Virgin Basin (11)	Echo Bay (12c)	Overton (12b)	Muddy Arm (12a)	Virgin Bowl (13a)	Temple Bar (10)	Gregg Basin (9b)	Iceberg Canyon (9a)	Grand Wash (8b)	Gods Pocket (8a)
Phytoplankton Productivity	1981	2724	1612	596	339	-	432	349	393	326	465	542	-	-
Chlorophyll-a	1981	27.1	5.1	1.3	0.9	1.0	1.4	2.1	2.5	1.0	1.8	2.6	2.5	3.7
Phytoplankton Productivity	1982	2657	1309	400	-	-	-	-	-	-	-	-	-	-
Chlorophyll-a	1982	19.7	4.3	1.3	1.0	1.1	1.3	2.1	2.7	1.4	1.9	3.3	3.1	3.5

* 0 - 2.5 m integrated depth for chlorophyll-a

relative to the other sources. However, these inflows did cause a slight increase in total phosphorus and chlorophyll-a concentrations in the Muddy Arm and the Virgin Bowl (Table 5.1.2).

The inner Las Vegas Bay was the only area of Lake Mead where nutrient concentrations were sufficient to sustain high productivity. Total phosphorus concentrations averaged .091 mg/l in 1981 and .054 mg/l in 1982 in the inner Las Vegas Bay (Table 5.1.1). Total nitrogen concentrations were also higher in the inner bay than other areas of the reservoir. The higher nutrient concentrations were due to inputs from Las Vegas Wash. Las Vegas Wash was a major source of phosphorus, and it provided about 10% of the nitrogen inputs to Lake Mead. Most of the phosphorus inputs were supplied as ortho phosphorus which is directly available to phytoplankton.

The Las Vegas Wash inflow also forms a density current in Las Vegas Bay, but considerable mixing occurs during spring and summer when wash temperatures are high (Baker and Paulson 1981). Total phosphorus concentrations exceeded .200 mg/l and total nitrogen ranged to 2.2 mg/l in the inner Las Vegas Bay during summer of 1981. Total phosphorus and total nitrogen concentrations were somewhat lower in 1982 due to decreased loading from Las Vegas Wash. Ortho phosphorus concentrations were considerably lower in 1982 as a result of phosphorus removal at the City of Las Vegas and Clark County Sewage Treatment plants.

It does not seem that phosphorus removal had a significant effect on nutrient limitation or algal growth in the inner Las Vegas Bay. TN/TP ratios averaged 11:1 in 1981 and 13:1 in 1982 indicating that the area was either nitrogen limited or co-limited in both years. Chlorophyll-a concentrations and phytoplankton productivity were high during both years of the study. Average phytoplankton productivity was nearly identical during 1981 and 1982. Chlorophyll-a concentrations were lower in 1982 than in 1981, but levels were nearly identical to those reported for the inner Las Vegas Bay during 1979 when phosphorus loading was much higher (Brown and Caldwell 1981). The supply of phosphorus from Las Vegas Wash is apparently still sufficient to sustain high productivity in the inner bay.

Phosphorus removal appears to have had some impact on total phosphorus concentrations and chlorophyll-a in the middle Las Vegas Bay. Total phosphorus averaged .025 mg/l in 1981 and .019 mg/l in 1982. Chlorophyll-a concentrations were slightly lower in 1982 than 1981. Phytoplankton productivity was also slightly lower in 1982 than in 1981 (Table 5.1.2) and lower still than rates reported during 1977-78 when productivity averaged 2239 mg C/m^2/day (Paulson et al. 1980). TN/TP ratios were higher in 1982 indicating that phosphorus has become more limiting, which in turn, seems to be the cause for this change in productivity.

Total phosphorus concentrations and chlorophyll-a in Boulder Basin were low prior to phosphorus removal, and there was not much change between 1981 and 1982. However, phytoplankton productivity was lower in 1982 (Table 5.1.2), and rates in Boulder Basin are now comparable to those in the upper basin. There has been a steady decline in phytoplankton productivity in Boulder Basin since 1977-78 when rates averaged 1301 mg C/m^2/day (Paulson et al. 1980). Productivity decreased to an average of 956 mg C/m^2/day in 1980 (Brown and Caldwell 1981), 596 mg C/m^2/day in 1981 and down to 400 mg C/m^2/day in 1982 (Table 5.1.2). The decline in productivity closely parallels historic phosphorus loading from Las Vegas Wash. Loading began to decline in 1978 when the county initiated chemical treatment to increase the capacity of their secondary plant (Brown and Caldwell 1981). Annual phosphorus loadings have dropped steadily since then and are now 70-80% lower than during the mid-1970s. This is the principal cause for the decline in phytoplankton productivity in Boulder Basin.

5.2 Factors Regulating Zooplankton Abundances

The average densities of major zooplankton groups (cladocerans, copepods and rotifers) in Lake Mead were consistently higher near the inflow areas (Table 5.2.1). The highest densities occurred in the inner Las Vegas Bay followed by inflow stations in the Overton Arm and the Upper Arm. Zooplankton densities consistently decreased down-reservoir from the inflows, and densities were lowest in the main basin stations. These patterns were evident during both years of the study. Zooplankton densities were similar at the various sampling locations between years. Cladoceran densities were, however, somewhat lower in the inner Las Vegas Bay and other Lower Basin stations during 1982. Copepod densities were also lower at locations down-reservoir of the middle Las Vegas Bay. Rotifer densities were slightly higher in the Lower Basin during 1982.

The spatial variations in zooplankton densities closely paralleled changes in chlorophyll-a and productivity. Empirical relationships between zooplankton and phytoplankton standing crops have been demonstrated for other lakes (McCauly and Kalff 1981). The feeding experiments that we conducted with D. pulex in the Lower Basin stations indicated that their growth and reproduction were limited by food concentrations in Boulder Basin during the summer. Bartanen (1983) has shown that food concentrations in Boulder Basin are also limiting

Table 5.2.1. Annual average zooplankton (No./liter) and relative fish abundances at select locations in Lake Mead during 1981 - 1982.

		Location/Station												
Parameter	Year	Inner LVB (14a)	Middle LVB (14c)	Boulder Basin (15)	Virgin Basin (11)	Echo Bay (12c)	Overton (12b)	Muddy Arm (12a)	Virgin Bowl (13a)	Temple Bar (10)	Gregg Basin (9b)	Iceberg Canyon (9a)	Grand Wash (8b)	Gods Pocket (8a)
Cladocerans	1981	19.3	3.8	1.3	0.7	1.3	2.5	2.8	8.1	1.4	2.2	6.9	4.7	9.[illegible]
Copepods	1981	30.3	15.3	11.9	8.2	9.0	8.5	10.0	13.6	8.1	6.7	13.3	14.5	10.[illegible]
Rotifers	1981	37.7	1.9	0.3	0.5	0.7	1.9	10.8	14.6	0.4	0.4	7.4	5.2	11.[illegible]
Total Zooplankton	1981	87.3	21.0	13.5	9.4	11.0	12.9	23.6	36.3	9.9	9.3	27.6	24.4	31.1
Cladocerans	1982	7.8	2.5	1.8	0.7	1.2	2.0	1.4	10.0	0.6	0.9	9.9	6.0	8.9
Copepods	1982	34.5	10.3	7.6	5.8	5.9	7.7	2.3	19.5	4.4	6.9	12.9	12.5	11.0
Rotifers	1982	45.5	5.7	2.3	0.5	0.6	1.2	11.4	18.0	0.7	2.4	10.1	6.3	24.0
Total Zooplankton	1982	87.8	18.5	11.7	7.0	7.7	10.9	15.1	47.5	5.7	10.2	32.9	24.8	43.9
Fish	1981	3.4	2.4	1.4	1.0	1.0	2.2	2.4	3.4	1.1	1.2	3.2	2.8	3.4
Fish	1982	4.0	2.0	1.1	1.2	1.0	1.7	2.6	3.6	1.3	1.1	3.3	2.9	3.0

populations of *D. pulex* during other periods. He conducted a series of *D. pulex* feeding experiments during February-June 1982 and November-February 1983 using Boulder Basin water with enrichments of the algae *Chlamydomonas reinhardi* at 10^3 and 10^5 cells/ml. Growth of *D. pulex* increased significantly with each enrichment clearly showing that natural food concentrations were limiting. Similar trends were also evident in reproduction, although little or no reproduction occurred in a few months, apparently as a result of natural reproduction cycles of *D. pulex*. We found minimal differences in growth and reproduction of *D. pulex* reared in waters from the inner and middle Las Vegas Bay. Chlorophyll-*a* concentrations averaged 40 µg/l in the inner bay and 11 µg/l in the middle bay during the feeding experiments. It appears that chlorophyll-*a* concentrations somewhere between levels in Boulder Basin (1 µg/l) and the middle Las Vegas Bay are limiting populations of *D. pulex*.

Richman (1958) found that growth and reproduction of *D. pulex* increased with increasing concentrations of *C. reinhardi* between 2.5 x 10^4 and 1 x 10^5 cells/ml. McMahan and Rigler (1963) and others have found that filtering rates of *Daphnia* are constant (high) at low food densities, but that above a critical food concentration, or incipient limiting concentration, filtration decreases with increased food concentrations. These experiments demonstrate that there is an upper threshhold where food concentrations are no longer limiting. Kring and O'Brien (1976) have shown that the incipient limiting concentration for *D. pulex* is less than 10^5 cells/ml. This was the upper food concentration used by Bartanen (1983) and his reported growth rates at 10^5 cells/ml were probably near maximum. In our experiment, *D. pulex* growth in the inner and middle Las Vegas Bay treatments was comparable to that found by Bartanen (1983) at the higher food concentrations (10^5 cells/ml) when similar experimental temperatures were used.

It is clear from our feeding experiments and others (Richman 1958, Burns and Rigler 1967, Weglensak 1971, Haney 1973, and Demott 1982) that food is limiting growth and reproduction of *D. pulex* in the majority of Lake Mead. Las Vegas Bay and to some extent the inflow areas above Iceberg Canyon and Virgin Bowl are the only areas where productivity is sufficient to sustain optimal growth and reproduction of this species. It is difficult to generalize these results to other species, but the spatial variations in abundances of dominant taxa suggest that they are also significantly influenced by chlorophyll-*a* concentrations.

The densities of dominant taxa were considerably higher in the inflow areas, and the highest densities generally occurred in the inner Las Vegas Bay during their periods of peak abundance. The cladocerans *D. pulex* and *D. galeata* and the copepods *Diaptomus siciloides* and *Cyclops bicuspidatus* achieved maximum densities during the winter and spring. During these periods, these species were most abundant near the inflow stations. Densities were often two-three times greater in Las Vegas Bay than the Overton Arm and Upper Arm inflow areas. However, the *Daphnia* species and dominant copepods were reduced to extremely low levels at the inflow stations during summer, and their abundances were often higher at the deep, unproductive main basin stations. Conversely, densities of *Bosmina longirostris* and the dominant rotifers, *Polyarthra* and *Syncheata*, increased during the summer-fall months, although their abundances were highly variable. These species were also most abundant at the inflow stations.

The correlation analysis clearly reflected the seasonal variations in abundances of the dominant taxa. D. pulex, D. siciloides and C. bicuspidatus densities were inversely related to temperature, chlorophyll-a and fish abundance, whereas the rotifers and B. longirostris were positively related to these variables. These succession patterns at first seem to simply reflect seasonal changes in reservoir water temperatures. Temperatures began to increase in March and April, and thermal stratification was well developed by late-May and June. Thermal stratification did not develop at inflow stations less than 15 m in depth, and water column temperatures were therefore, warmer than main basin stations that did stratify. Our sampling did not include an analysis of the vertical distribution of zooplankton, but Burke (1977) had shown that zooplankton densities in Boulder Basin were highest at 15-20 m during the summer. The temperature tolerances of certain species (e.g. Daphnia and the copepods) could be exceeded at the inflow stations due to the lack of a "thermal refuge" as exists in the metalimnion or hypolimnion. The fact that such a "refuge" exists at the deep stations could explain the persistence of these species, although at very low densities, in the main basin areas.

Daphnia and dominant copepod populations, however, began to decline during spring when reservoir temperatures were cool and well within the thermal tolerances for these taxa. Most zooplankton are eurythermal and generally exhibit higher growth and reproduction as temperatures increase. Bartanen (1983) found this to be the case for D. pulex reared under enriched food concentrations at ambient temperatures in Boulder Basin waters. Neonate production and growth rates were highest during the summer when temperatures were at their maximum. Daphnia and Cyclops bicuspidatus undergo rather extensive vertical migrations in Lake Mead during summer (Burke 1977). During these migrations, they are subject to vertical temperature variations comparable to those that occur seasonally in the epilimnion. It is, therefore, unlikely that temperature is the sole, or even most important factor regulating succession patterns of zooplankton in Lake Mead.

The correlation analysis showed that the spatial and seasonal variations in zooplankton densities were also related to relative fish abundances. Daphnia and the dominant copepods were inversely related to fish abundances, whereas Bosmina and rotifers were positively related. Fish were numerous in the inflow areas during spring and summer periods but rare in the main basin areas throughout the study (Table 5.1.3). It was not possible to distinguish individual fish species from the echosoundings, but it is likely that threadfin shad was the principal fish present in the inflow areas. Electrofishing conducted in littoral areas of Las Vegas Bay during 1970-71 showed that shad abundances were low during the winter, increased in spring and reached a maximum during summer (Deacon et al. 1972). Age I and Age II shad comprised the majority of the catch during spring. The Age II shad spawned in May and June (Deacon et al. 1972), and the Age 0 offspring were the most abundant fish in the reservoir during summer (Allan and Roden 1978). During this period, they occurred primarily in the epilimnion and metalimnion (Deacon and Tew 1973, Paulson and Espinosa 1975).

Threadfin shad are planktivorous and known to exert a considerable influence on the structure of reservoir zooplankton communities. ~~Rinne et al. (1981) found that zooplankton standing crops were significantly affected by shad predation in shallow, productive inflow areas of the Salt River Reservoirs.~~ The spring-summer decline of Daphnia from shallow, uplake areas of Bull Shoals Reservoir was caused by threadfin shad predation (Applegate and Mullan 1969). Daphnia were able to persist down lake due to greater depths that provided a refuge from shad which occurred primarily in the epilimnion. The abundance of Bosmina longirostris increased during summer in areas where Daphnia were cropped by threadfin shad. Large grazers like Daphnia utilize a broad spectrum of food resources and typically dominate the plankton where predators are rare (Brooks and Dodson 1965). B. longirostris is less affected by predation due to its small size. Cramer and Marzolf (1970) found similar succession patterns in Tuttle Creek Reservoir. Gizzard shad selected for C. bicuspidatus adults and copepodites, and Daphnia spp. but did not utilize Polyarthra or other rotifers. Copepods and cladocerans declined in abundance but rotifers increased in Tuttle Creek Reservoir during summer due to selective predation.

The succession patterns in Bull Shoals Reservoir and Tuttle Creek Reservoir are similar to those we observed in Lake Mead. The spring-time decline of Daphnia and the copepods from the inflow areas coincided with an increase in fish abundance. The fish were presumed to be primarily, but not exclusively, threadfin shad. Copepods and cladocerans are important components of threadfin shad diets in Lake Mead during spring (Deacon et al. 1972). Predation by shad and other fish species seems to be the most likely explanation for the spring-time disappearance of these taxa from the inflow areas. In the absence of these superior competitors, the B. longirostris and rotifer populations were apparently able to exploit the higher productivity and increase in abundance during summer months. Fish were rare in the main basin areas, and predation had minimal impacts on zooplankton populations. However, productivity was extremely low and limited the abundance of all zooplankton groups.

5.3 Implications for the Striped Bass Fishery

Threadfin shad provide the major forage base for striped bass in Lake Mead (Allan and Roden 1978, Albert and Baker 1983) and in most other freshwater impoundments (Stevens 1958, Goodson 1964, Edwards 1974, Matthews and Hill 1983). Threadfin shad are ideal forage because they seldom exceed a size beyound that utilized by adult striped bass or other predators (Noble 1981). They are extremely prolific (Johnson 1971) and can usually withstand heavy predation pressure. Shad occur primarily in limnetic areas of reservoirs (Houser and Dunn 1967, Johnson 1970) which is the principal habitat for adult striped bass (Combs and Peltz 1982, Matthews and Hill 1983). The success of most striped bass fisheries is closely linked to the abundance and stability of threadfin shad populations.

Threadfin shad were adundant in Lake Mead when striped bass were introduced in 1969. Adult shad (Age I and Age II) were prevalent in littoral areas during the spring, and large numbers of juveniles dispersed into limnetic areas in summer (Deacon et al. 1972). They were particularly abundant in Las Vegas Bay and Boulder Basin (Deacon and Tew 1973, Allan and Roden 1978) but were also numerous in Virgin Basin (Baker and Paulson 1983). Juvenile shad comprised most of the limnetic population (Paulson and Espinosa 1975), although adults were also frequently captured in mid-water trawls (Allan and Roden 1978). Shad occurred primarily in the epilimnion and metalimnion to depths of 15-20 m (Deacon and Tew 1973, Allan and Roden 1978). They dispersed into deeper waters at the onset of fall mixing, and large schools overwintered in the deep basins (Allan and Roden 1978).

Threadfin shad remained fairly abundant in Lake Mead through 1975, but the limnetic population declined considerably between 1976 and 1980 (Baker and Paulson 1983). Echosounding conducted in our current investigation clearly demonstrates that the limnetic areas are now virtually devoid of shad and other fish life. This decline in the limnetic shad population has had a tremendous impact on production of adult striped bass.

Adult striped bass undergo rather extensive seasonal migrations in reservoirs. They move into staging areas below tributaries and rivers in fall, remain there over winter and then ascend into the inlets to spawn during spring (Combs and Peltz 1982). Adults return to the main body of the reservoir during summer where they occur primarily in deep limnetic areas. These migrations reflect behavioral patterns inherited from anadromous stocks and thermal preferences of the species (Combs and Peltz 1982). Adult striped bass occupy reservoir depths where temperatures range from 18°-22°C during summer months (see Cox and Coutant 1981). In order to satisfy these temperature requirements in Lake Mead, adults would have to move to depths of 15-25 m in limnetic areas, or to areas near the Colorado River inflow during summer. Suitable thermal habitats obviously exist in most of the reservoir, but forage is scarce in all but a few of these areas. The middle Las Vegas Bay and Colorado River inflow area seem to be the only locations where the forage and thermal requirements of adult striped bass currently come close to being met. There is little doubt that the lack of shad in limnetic areas is a major factor limiting the population of adult striped bass in Lake Mead.

Reproduction, nonetheless, is adequate to maintain large numbers of juvenile and subadults in the population. Striped bass spawning seems to occur primarily in the inflow areas during April and May (Allan and Roden 1978). Temperatures range from 18-22°C during this period which is optimum for hatching of striped bass eggs. Eggs hatch in about 29 hours at 22°C (Setzler et al. 1980). Newly hatched striped bass live in open waters and zooplankton (usually nauplii) comprise their principal diet. Zooplankton densities of about 100 organisms/liter are required to achieve good growth and survival of larval striped bass (Eldridge et al. 1981). Zooplankton densities in the inflow areas were in this range during spring and summer, but densities were extremely variable and often dropped below optimum levels. Larval striped bass typically exhibit high survival because they can tolerate periodic food deprivation during early development (Rogers and Westin 1981). The eggs have unusually large oil globules that allow larve to survive as long as 30 days without food (Eldridge et al. 1981). This gives larval striped bass a distinct advantage in fluctuating plankton environments, like the inflow areas, because they can survive periods when zooplankton densities drop below optimum levels (Rogers and Westin 1981). It might also allow larval striped bass to survive in dilute environments like the main basin areas. There is some evidence that in-reservoir spawning occurs in these areas of Lake Mead (Allan and Roden 1978). Zooplankton densities in the main basins are far below that required for survival of larval striped bass. However, the egg reserves could supply larvae with sufficient energy to either exploit larger volumes of water in search of plankton, or find plankton patches, thereby allowing for some survival. This could account for the sightings of juvenile striped bass in the unproductive areas of Lake Mead.

Larval striped bass form small schools once they reach lengths of about 13 mm and move inshore where they remain during the first summer (Setzler et al. 1980). Juvenile striped bass prefer areas with sand/gravel bottoms. They remain planktivorous during the first year and seem to prefer Daphnia, Cyclops and Diaptomus (see Setzler et al. 1980). These taxa were fairly abundant in the inflow areas of Lake Mead during fall, winter and spring periods and probably allowed for good survival of juveniles through their first year.

Zooplankton generally do not comprise a large portion of subadult (Age I and Age II) striped bass diets (Setzler et al. 1980). However, in Lake Mead, zooplankton are important items in the diets of both Age I and Age II fish during late winter and spring (Albert and Baker 1983). Crayfish are also utilized during these periods. It is unlikely that subadults can sustain good growth on zooplankton, even at the higher densities in the inflow areas. Little is known about the distribution and abundance of crayfish in Lake Mead, but they seem to be fairly abundant in some areas of the reservoir (Allan and Roden 1978). This offers some forage for subadults, but again it does not seem adequate to sustain growth. There is a marked decrease in condition factors of subadult striped bass during spring when invertebrates comprise the majority of the diet (Albert in prep).

Juvenile threadfin shad are the preferred forage for subadults in Lake Mead (Albert and Baker 1983), and condition factors increase during summer when shad predominate in the diet (Albert in prep.). Juvenile shad are particularly vulnerable to predation by subadults during summer because their distributions overlap. Subadults occupy reservoir depths where temperatures range from 20-24°C during summer (Coutant and Carroll 1980). They can tolerate temperatures as high as 28-30°C with minimal effects on their feeding or growth rates (Cox and Coutant 1981). Subadults can thus utilize the epilimnion and productive inflow areas where shad densities are highest. This results in tremendous pressure on the juvenile shad populations. The productive inflow areas seem to be the only locations where shad production is sufficient to sustain the cropping by subadults. However, the shad population is maintained at critically levels because the inflow areas comprise such a small percentage of the surface area in Lake Mead.

5.3.1 Relationship to Productivity

The decline of the threadfin shad population in Lake Mead is related to changes in phytoplankton productivity. Limnological studies conducted during 1970-71 (Everett 1972) showed that productivity ranged from 700-1200 mg C/m^2/day throughout the Lower Basin during spring and early summer. Productivity was low in the Upper Basin and ranged from 200-400 mg C/m^2/day during these periods. In September 1970, productivity ranged between 3000-3200 mg C/m^2/day throughout the Lower Basin and 2000-3000 mg C/m^2/day in the Upper Basin. Zooplankton densities were highest in the Lower Basin, and peak abundances occurred during spring and early summer (Everett 1972). Zooplankton densities decreased to low levels throughout the reservoir during summer. This coincided with the time when large schools of juvenile shad dispersed in limnetic areas (Deacon and Tew 1973).

Phytoplankton productivity in Las Vegas Bay during 1977-78 was comparable to that in 1970-71 (Paulson et al. 1980). In Boulder Basin, productivity was similar during late summer and fall, but lower during winter and spring in 1978. Productivity in the Upper Basin during winter and spring of 1977-78 was nearly identical to that in 1970-71, but rates were much lower during late summer and fall periods of 1978. Densities of zooplankton in Boulder Basin were lower during the spring and early summer of 1978 than in 1971 (Wilde 1981). However, zooplankton were still more abundant in the Lower Basin than the Upper Basin (Paulson et al. 1980). No data were collected on shad abundance during the 1977-78 study.

Productivity in Las Vegas Bay during the spring and summer of 1981-82 was comparable to that in 1977-78, but rates during fall were lower during 1981 and 1982. This was also the case in Boulder Basin during 1981. Productivity in Boulder Basin was low throughout 1982, and rates were equivalent to those in the Upper Basin. Zooplankton densities were uniformly low throughout Boulder Basin and the Upper Basin. The productive inflow areas were the only locations where zooplankton still showed a pulse during the spring and early summer periods.

In the past decade, productivity has declined throughout the reservoir during late summer and fall and has decreased during all periods in Boulder Basin since 1977-78. It is not known what caused the decline in late summer-fall productivity in the Upper Basin, but it most likely reflects a change in phosphorus loading or mixing patterns of the Colorado River inflow. The decrease in productivity in Boulder Basin closely follows reductions in phosphorus loading from Las Vegas Wash. This has had the greatest impact on the shad population because it affected the entire area from Boulder Canyon to the middle Las Vegas Bay. Productivity is no longer sufficient to stimulate zooplankton production during the spring and early summer. This provided a substantial food base for threadfin shad when they moved into littoral areas to spawn during spring and for juvenile shad when they dispersed to limnetic areas during summer. Such conditions still exist in the inflow areas, but this only comprises about 10% of the surface area in Lake Mead. Clearly, this is not adequate to maintain a forage base necessary to support a productive striped bass fishery.

It will be necessary to restore the productivity, at least during spring and early summer, in the main basin areas to affect a positive change in the striped bass population. This could best be achieved by increasing phosphorus inputs during the winter months when density currents would transport the phosphorus into the main basins where it would mix with the entire water column. A decrease in the level of phosphorus removal at the sewage treatment plants, or phosphorus fertilization in the Colorado River during winter months would elevate phosphorus concentrations in both basins. This, in turn, would increase phytoplankton productivity to levels more suitable for optimum zooplankton production during the spring and early summer.

The main basin areas need not be especially productive to support higher zooplankton production. Our findings indicate that an increase in productivity to levels comparable to those that currently exist in the middle Las Vegas Bay would result in a marked increase in the growth and reproduction of dominant zooplankton. An increase in zooplankton densities in such large volumes as the main basins would provide a substantial food base available for juvenile shad. Shad, like many other clupeids, are capable of utilizing plankton in large, relatively dilute water bodies (Lasher 1975). In Lake Mead, shad congregate near the thermocline (Deacon and Tew 1973) where zooplankton are most abundant during the summer (Burke 1977). They also undergo a diel vertical migration through the epilimnion and ascend to depths near the surface at night (Deacon and Tew 1973). These behavioral patterns apparently allow shad to efficiently crop plankton from most of the epilimnion. The successional patterns observed by Everett (1972) suggest that zooplankton were cropped from the epilimnion of main basin areas by mid-summer during the early 1970's.

Although threadfin shad prefer zooplankton when available (Gerdes and McConnell 1963, Applegate and Mullan 1969), phytoplankton and detritus also comprise important components of their summer diets in Lake Mead (Deacon et al. 1972), and other reservoirs (Haskell 1959, Gerdes and McConnell 1963, Baker and Schmitz 1971). Shad are capable of ingesting relatively small phytoplankton cells by filter feeding in open waters (Haskell 1959). The occurrence of numerous phytoplankton taxa in shad diets from Lake Mead indicates similar feeding behavior (Deacon et al. 1972). Deacon and Tew (1973) also reported that shad were densely congregated near the thermocline during late summer and fall. They believed that shad were drawn to this region to feed on detritus that accumulated during summer. Haskell (1959) contends that phytoplankton and detritus are dietary supplements to principal foods, like zooplankton, that have higher nutritional and caloric values. Shad usually exhibit little growth on detritus due to the poor nutritional quality (Pierce et al. 1981), but if ingested in sufficient quantities, it may allow for survival during periods when zooplankton availability is low. Phytoplankton and detritus would both increase if productivity were restored in the main basin areas. This would be important in survival of shad during late summer after zooplankton were cropped from the epilimnion.

An increase in the limnetic shad population would primarily favor production of adult striped bass by providing forage in areas where their thermal tolerances could also be met. Juvenile and subadult striped bass reside in near shore habitats (Boynton et al. 1981) and do not exhibit the seasonal migratory behavoir characteristics of adults (Combs and Peltz 1982). Subadults primarily utilize juvenile shad (Matthews and Hill 1983, Plaskett and Paulson 1982) indicating they are not capable of ingesting or capturing adults. There is no documented example of overexploitation of the forage base in impoundments by subadult striped bass. Overexploitation typically follows recruitment of a strong year class and is usually preceeded by temperature-induced winter kills in southern reservoirs (Matthews and Hill 1983), or in the case of Lake Mead, by declining productivity (Baker and Paulson 1983). It is, therefore, unlikely that an increase in the limnetic shad population will simply result in greater production of subadults. Rather, it appears to be the key to restoring a more stable age distribution in the population which is essential for a recovery of the fishery.

It is, nevertheless, difficult to determine if the striped bass population can be restored to levels that existed during the mid- and late-1970s. It would be advisable to conduct an experimental fertilization in one part of the reservoir before attempting full scale fertilization. Such a test could best be conducted in the Lower Basin if measures can be taken to reduce the level of phosphorus removal at the wastewater treatment plants. If this were combined with a comprehensive limnological and fisheries monitoring program, it would provide a basis for evaluating more extensive efforts such as fertilization of the Colorado River.

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How long from the time nutrients are released to when they affect fish populations?