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NUTRIENT INTERACTIONS AMONG RESERVOIRS ON THE COLORADO RIVER

by

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INTRODUCTION

Interactions among physical, chemical and biological processes in reservoirs can significantly alter the characteristics of the discharge (Neel 1963, Wright 1967, Hannan 1979) that, in turn, can influence the ecology of the river downstream (Ward and Stanford 1979). Investigations of the Colorado River system reveal that reservoir-induced changes in the river can also affect downstream reservoirs. The formation of Lake Powell in 1963 was accompanied by reductions in suspended sediment and nutrient loading and changes in the seasonal temperature and discharge cycles of the Colorado River. In this paper, we evaluate how these changes have influenced the nutrient and trophic status of Lake Mead, the large reservoir located 450 km downstream from Lake Powell.

COLORADO RIVER SYSTEM

Impoundment of Lake Mead in 1935 by Hoover Dam and Lake Powell in 1963 by Glen Canyon Dam created two of the largest reservoirs in the country. Lake Mead and Lake Powell are comparable in terms of volume and surface area (Table 1), but differ considerably in morphometry. Lake Powell is extremely sinuous, whereas Lake Mead is separated into two large basins by Boulder Canyon (Fig. 1). The area above Boulder Canyon is collectively referred to as the Upper Basin and encompasses the Virgin Basin, Overton Arm and the Upper Arm. The Lower Basin includes Boulder Basin and Las Vegas Bay and extends to Hoover Dam. The discharge from Lake Powell provides about 98% of the inflow to Lake Mead. The remainder is derived from the Virgin and Muddy Rivers, which discharge into the Overton Arm, and Las Vegas Wash, which discharges secondary-treated sewage and industrial effluents into Las Vegas Bay. More detailed descriptions of Lake Mead and Lake Powell are presented in Hoffman and Jonez (1973) and in Johnson and Merritt (1979), respectively.

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Table 1. Morphometric characteristics of Lake Mead and Lake Powell derived from Hoffman and Jonez (1973), and Johnson and Merritt (1979).

Parameter	Lake Mead	Lake Powell
Maximum operating level (m)	374	1128
Maximum depth (m)	180	171
Mean depth (m)	55	51
Surface area (km^2)	660	653
Volume ($m^3 x 10^9$)	36	33
Maximum length (km)	183	300
Maximum width (km)	28	25
Shoreline development	10	26
Discharge depth (m)	100	70
Approximate storage ratio (years)	4	2
Year of impoundment	1935	1963

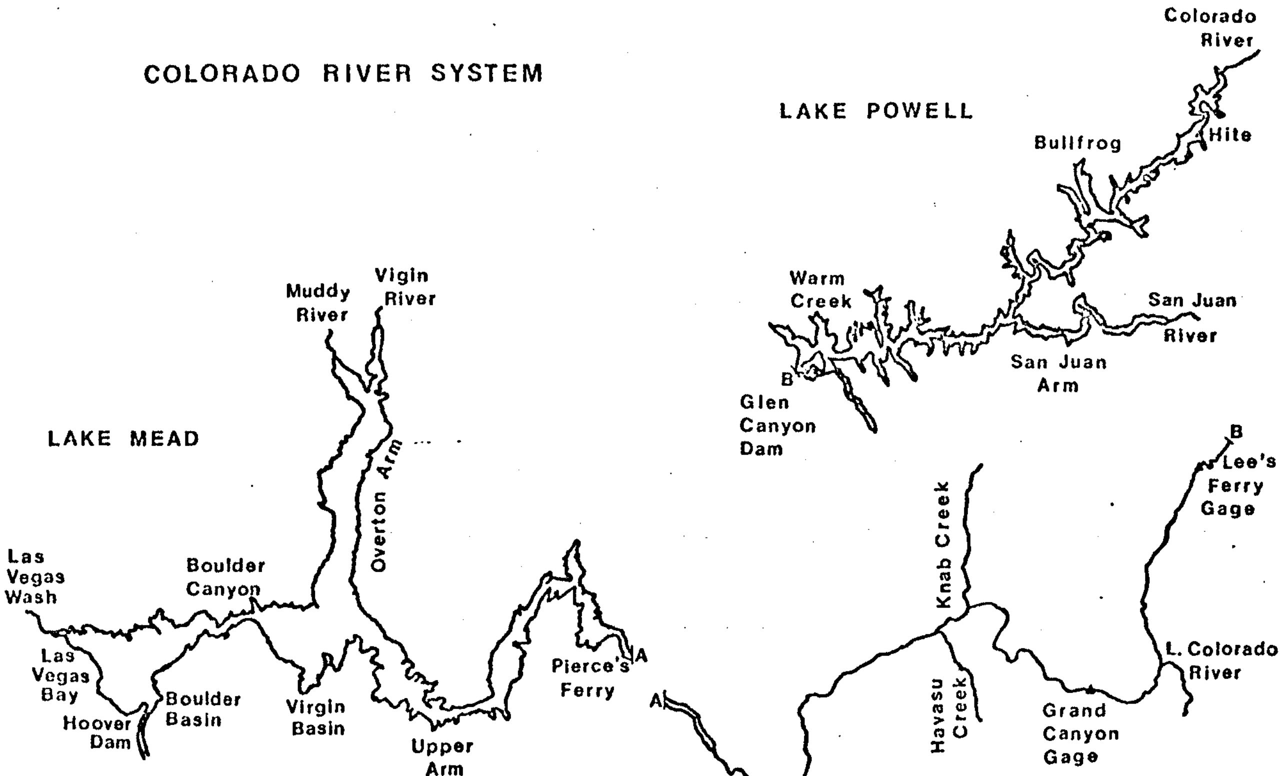

Figure 1. Map of the Colorado River system from Lake Powell to Lake Mead.

DATA SOURCES

Suspended sediment, nitrate and temperature data for the Grand Canyon gaging station were taken from "Quality of Surface Waters for the United States. Part 9. Colorado River Basin", and discharge data were obtained from "Surface Water of the United States. Part 9. Colorado River Basin". U.S. Geological Survey Water Supply Papers (1940-1967). After 1967, these data were obtained from "Water

Resources Data for Arizona or Nevada" prepared jointly by the U.S. Geological Survey and state agencies. Limnological data on Lake Mead were derived from our recent investigations (Paulson, Baker and Deacon 1980).

WATER QUALITY IN THE COLORADO RIVER

Discharge and Temperature

The discharge cycle in the Colorado River prior to 1963 was strongly influenced by spring runoff which resulted in extremely high flows in May and June (Fig. 2). Regulated releases from Lake Powell have eliminated the spring discharge peak and stabilized flows throughout the year. River temperatures have increased by about 5°C during late-fall and winter, but decreased by nearly 10°C during the rest of the year (Fig. 2). Discharge temperatures at Glen Canyon Dam average about 8°C. In the summer, temperatures increase to 10-11°C at the Grand Canyon gaging station and to 15-18°C at Pierce's Ferry, where the river enters Lake Mead. However, river temperatures are still nearly 10°C colder than for comparable periods prior to the formation of Lake Powell.

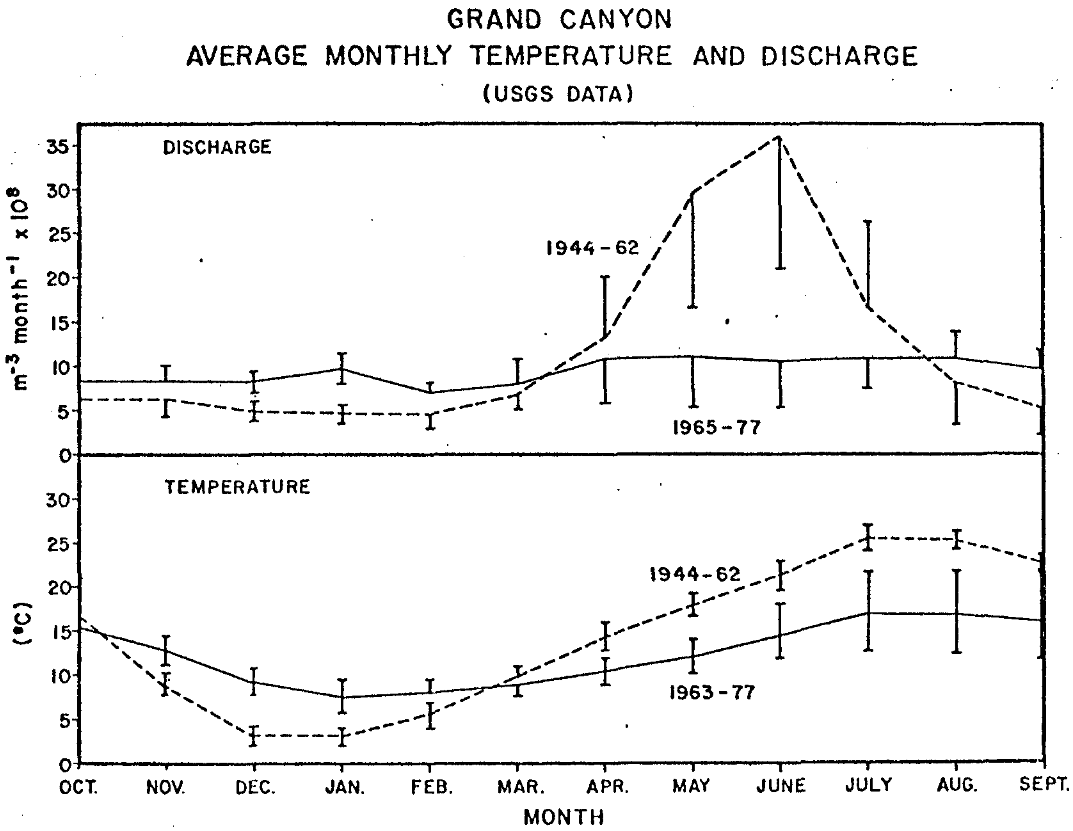

Figure 2. Average monthly temperature and discharge at Grand Canyon gaging station prior to and after formation of Lake Powell. (USGS data).

Suspended Sediments

The most obvious change in the Colorado River since Lake Powell was formed is the marked reduction in suspended sediment loads (Fig. 3). In years of high runoff, up to 140 million metric tons of suspended sediment flowed into Lake Mead and most of this occurred during the spring. Lara and Saunders (1970) estimated that 47% of this material was deposited in the Pierce's Ferry area, but extensive siltation has occurred elsewhere in the Upper Basin and in parts of the Lower Basin. The suspended sediment loads were reduced by 70-80% after Lake Powell was filled to operating levels in 1966. Most of the suspended sediments that currently enter Lake Mead are derived from tributaries in the Grand Canyon.

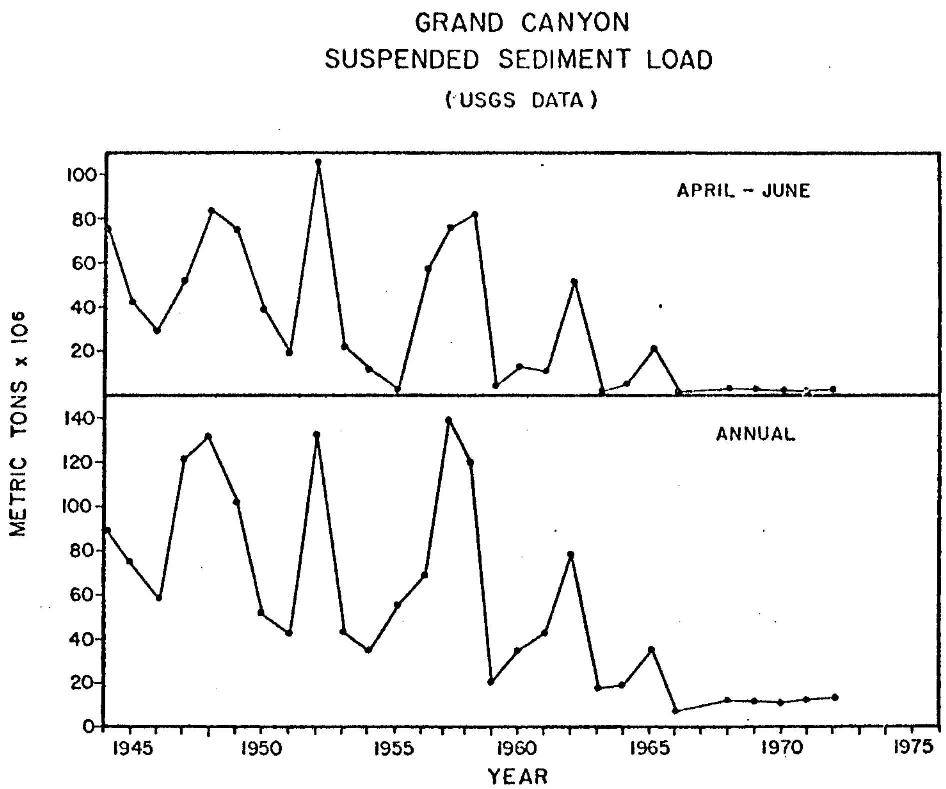

Figure 3. Annual and spring suspended sediment loads at Grand Canyon gaging station. (USGS data).

Nutrient Loading

Long-term nutrient data are rarely available to assess the influence of newly formed reservoirs on nutrient concentrations in the river. The U.S. Geological Survey has monitored nitrate concentrations in Grand Canyon for several years, but, unfortunately, they did not collect phosphorus data.

Nitrate loads (flow x concentration) decreased significantly from those in the 1950's and 1960's immediately after Lake Powell was formed (Fig. 4). Nitrate loads then increased during 1966-1969 but have since decreased and appear to be approaching a steady state. There were no appreciable changes in conservative element loads, as typified by sodium and potassium, over these periods; nor were the changes in nitrate loads related to flows which were stabilized after 1963 (Fig. 4). The unique trends observed for nitrate apparently reflect biological processes operating in Lake Powell.

Initially, the new reservoir must have retained a high percentage of the inflowing nitrate which caused a reduction in loading to Lake Mead. The increased nitrate loads to Lake Mead in 1966-1969 could be due to lower retention, or possibly release of nitrogen from the sediments in Lake Powell. Chemical analyses of Lake Mead sediments indicate that those deposited immediately after impoundment lost nitrogen for a brief period (Prentki, Paulson and Baker 1980). Although the mechanisms for this are not understood, a similar, transient loss of nitrogen from Lake Powell sediments could account for the unique pattern of nitrate loss in the first five years of impoundment.

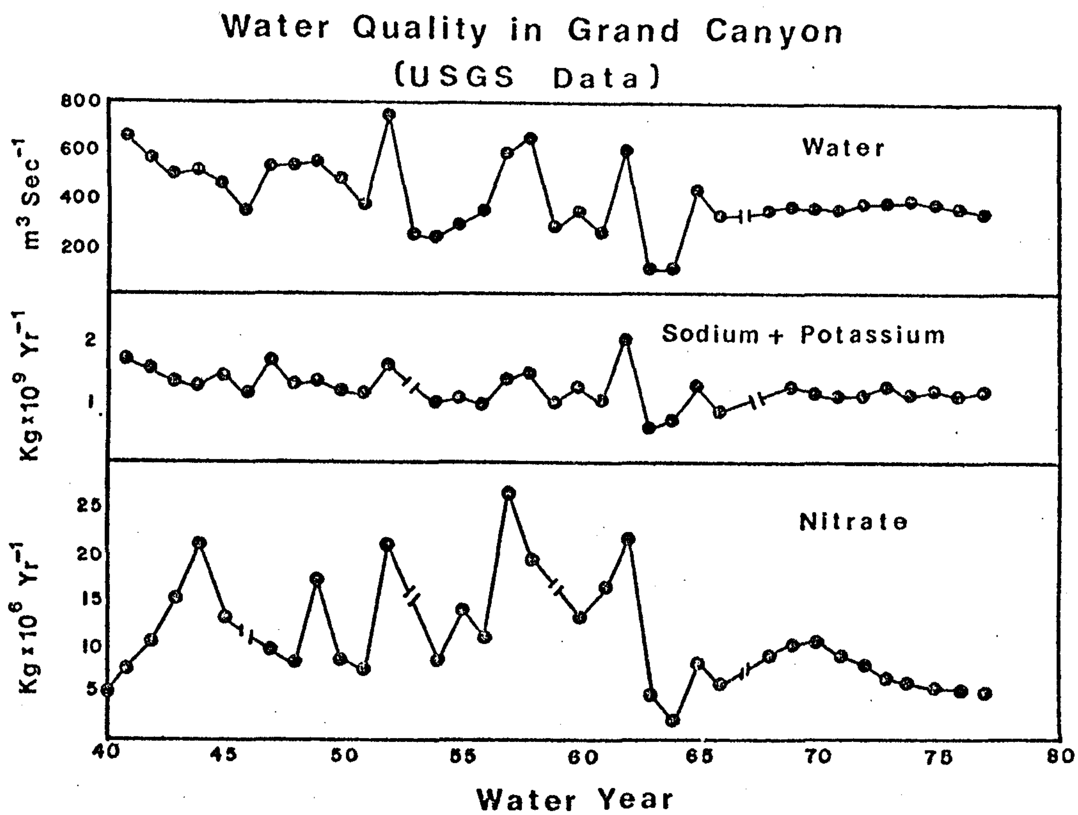

Figure 4. Annual discharge, nitrate and conservative element loads at Grand Canyon gaging station. (USGS data).

NUTRIENT DYNAMICS IN LAKE MEAD

A nutrient budget we constructed for Lake Mead in 1977-1978 (Paulson et al. 1980) revealed that the Colorado River provides 85% of the inorganic nitrogen input, but Las Vegas Wash contributes 60% of the phosphorus input to the reservoir (Table 2). Down-lake flow of water from the Upper Basin through Boulder Canyon effectively confines the high phosphorus input from Las Vegas Wash to the Lower Basin and provides the major nitrogen source to that basin. The disproportional loading of nitrogen and phosphorus at distant ends of Lake Mead, combined with the unusual reservoir morphometry cause each basin to operate like different lakes.

There are marked differences in phytoplankton productivity and nutrient concentrations in Virgin and Boulder Basins (Fig. 5). Areal productivity and average phosphorus concentrations are twice as high in Boulder Basin as in Virgin Basin. Average nitrate concentrations

Table 2. Nitrogen and phosphorus loading for Lake Mead (October 1977-September 1978).

Nutrient ($kg \cdot yr^{-1}$)	Loading: Colorado River	Loading: Las Vegas Wash
Nitrate (N) x 10^5	45.63	3.49
Ammonia (N) x 10^5	1.42	3.24
Total Inorganic Nitrogen (N) x 10^5	47.05	6.73
Phosphate (P) x 10^3	56.80	136.60
Total Phosphorus (P) x 10^3	198.70	263.10

are comparable in each basin during the winter, but nitrate is reduced to undetectable levels in Boulder Basin by June and remains low through September. Nitrate concentrations are reduced to about 100 $\mu g \cdot l^{-1}$ in Virgin Basin by mid-summer, despite low phosphorus concentrations. Nitrogen loading to the Lower Basin is reduced accordingly because it is derived primarily from nitrate in the epilimnion of the Upper Basin. The reduction of this input and relatively high productivity in the spring result in development of nitrogen limitation in the Lower Basin during the summer and cause a decrease in productivity of that basin in June and July.

The late-summer increase in productivity in Boulder Basin, and to a lesser degree in Virgin Basin, coincided with a decrease in average epilimnetic temperatures (Table 3). This caused the thermocline to drop by 10-15 m during July to September. Significant amounts of nitrate are stored in the metalimnion of each basin (Table 3) and erosion of the thermocline results in mixing of this nitrate into the epilimnion. In Virgin Basin, this causes a slight increase in productivity, but because of the phosphorus deficiency,

Table 3. Integrated average epilimnion temperatures, thermocline depth and metalimnetic nitrate concentrations in Boulder Basin (BB) and Virgin Basin (VB).

	Temperature (°C)		Thermocline (m)		Metalimnetic Nitrate ($\mu g \cdot l^{-1}$)	
	BB	VB	BB	VB	BB	VB
June 1978	23.6	23.5	10-12	10-13	305	257
July 1978	26.9	26.4	10-13	12-15	193	273
August 1978	25.2	24.7	16-18	16-18	162	314
September 1978	22.1	21.6	27-30	28-30	158	256

most of this nitrate supply accumulates in the epilimnion (Fig. 5). However, in the Boulder Basin, where phosphorus concentrations are higher, the mixing provides a nitrogen input sufficient to trigger higher productivity in late-summer.

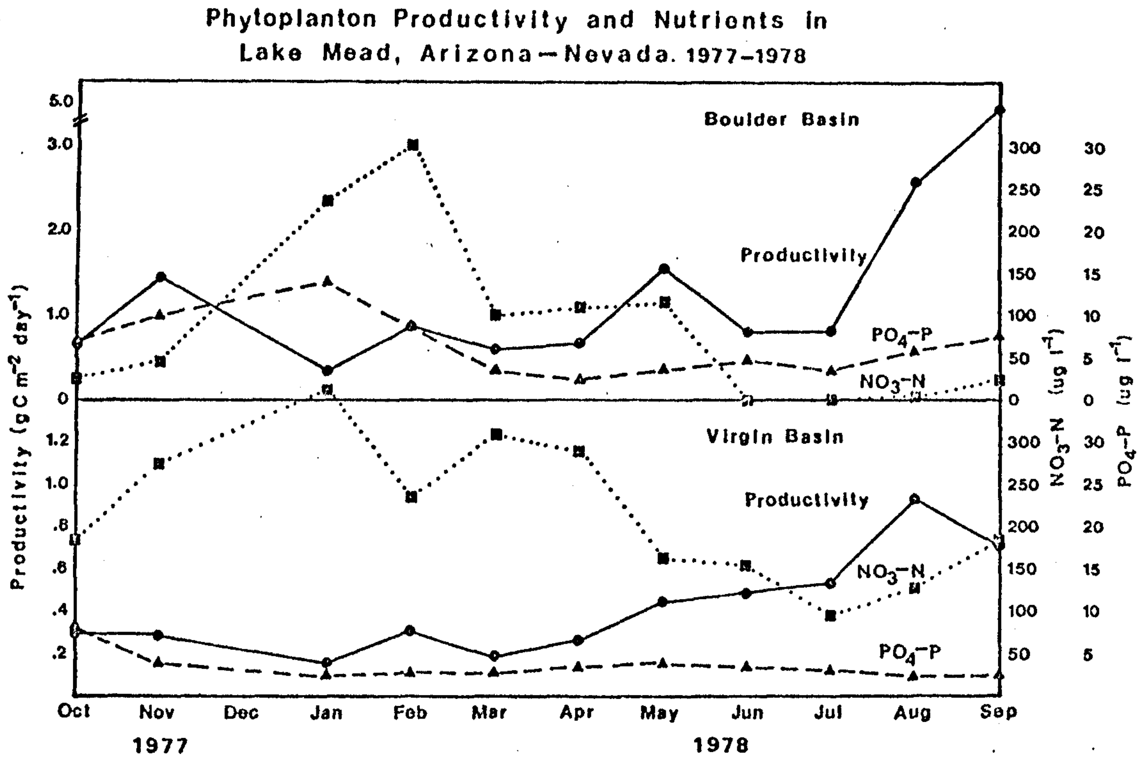

Figure 5. Areal phytoplankton productivity (0-15m) and average nutrient concentrations (0-10m) in Boulder and Virgin Basins of Lake Mead.

INFLUENCE OF LAKE POWELL ON LAKE MEAD

Nutrient Status

The distinct limnology in each basin of Lake Mead is partly due to high phosphorus loading from Las Vegas Wash to the Lower Basin. However, the formation of Lake Powell has also contributed to this, particularly in regard to patterns of nutrient limitation. The reduction in nitrate loading after 1963 and since 1969 have directly contributed to development of nitrogen limitation in the Lower Basin. Nitrate concentrations at Hoover Dam decreased considerably during 1960-1965, increased slightly during 1969 and 1970, but have since decreased to extremely low levels in the summer (Fig. 6). These changes closely parallel changes in nitrate loading from the Colorado River (Fig. 3). Also, high nitrate loss from the hypolimnion discharge of Hoover Dam further reduces nitrate concentrations in Lake Mead (Paulson, Baker and Deacon 1979). The net result is the Lower Basin became nitrogen-limited during the summer in the early 1970's and has remained so since then.

Lake Powell had an equally significant influence on nutrient limitation in the Upper Basin. The Colorado River used to form a turbid overflow in Lake Mead that extended over most of the Upper Basin during the spring (Anderson and Pritchard 1951). This is no longer evident due to reductions in spring discharge and suspended sediment loads and a decrease in river temperature which causes the river to flow deeper in Lake Mead. Johnson and Merritt (1979) have shown that the Colorado River now forms a turbid overflow in Lake

Powell, which is remarkably similar to the one that used to occur in Lake Mead.

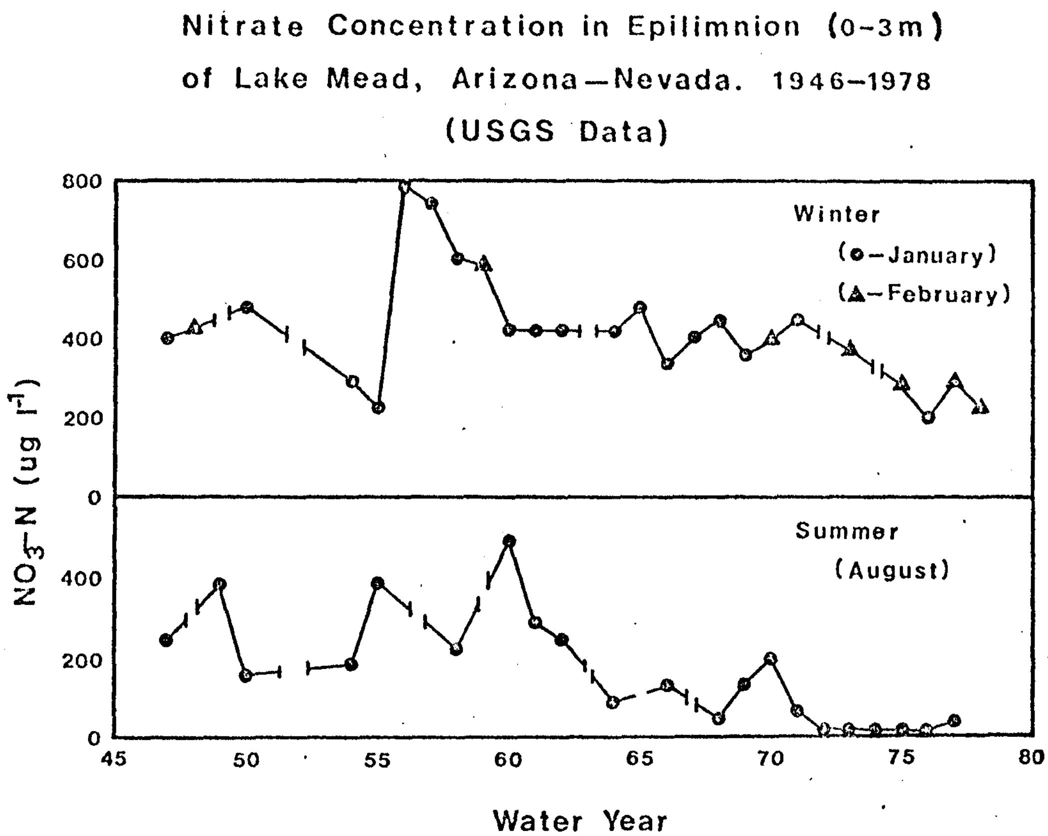

Figure 6. Winter and summer nitrate concentrations at the Hoover Dam intake towers in Lake Mead. (USGS data).

The spring overflow that enters Lake Powell is high in dissolved phosphorus and stimulates higher productivity in the upper end of the reservoir (Gloss, Mayer and Kidd 1980). Phosphorus desorption from suspended clays sustains the dissolved phosphorus pool as the overflow moves down the reservoir (Mayer and Gloss 1980). Approximately 70% of the dissolved phosphorus input is retained in Lake Powell due to uptake by phytoplankton and possibly coprecipitation with calcite (Gloss et al. 1980). The phosphorus input to Lake Mead has been reduced accordingly which has caused the Upper Basin to become more phosphorus-limited since the formation of Lake Powell.

Trophic Status

Long-term productivity estimates are not available for Lake Mead, but our recent measurements (Paulson et al. 1980) indicate that reductions in nutrient loading from the Colorado River have caused changes in the productivity of each basin. There is a definite decrease in productivity (annual and summer) from the Upper Arm to Virgin Basin and an increase from there to Hoover Dam (Fig. 7).

The low but fairly constant phosphorus input (5 $\mu g \cdot l^{-1}$) from the Colorado River sustains the higher productivity in the Upper Arm, but phytoplankton quickly deplete this phosphorus which limits productivity in Virgin Basin. Phosphorus loading from Las Vegas Wash also

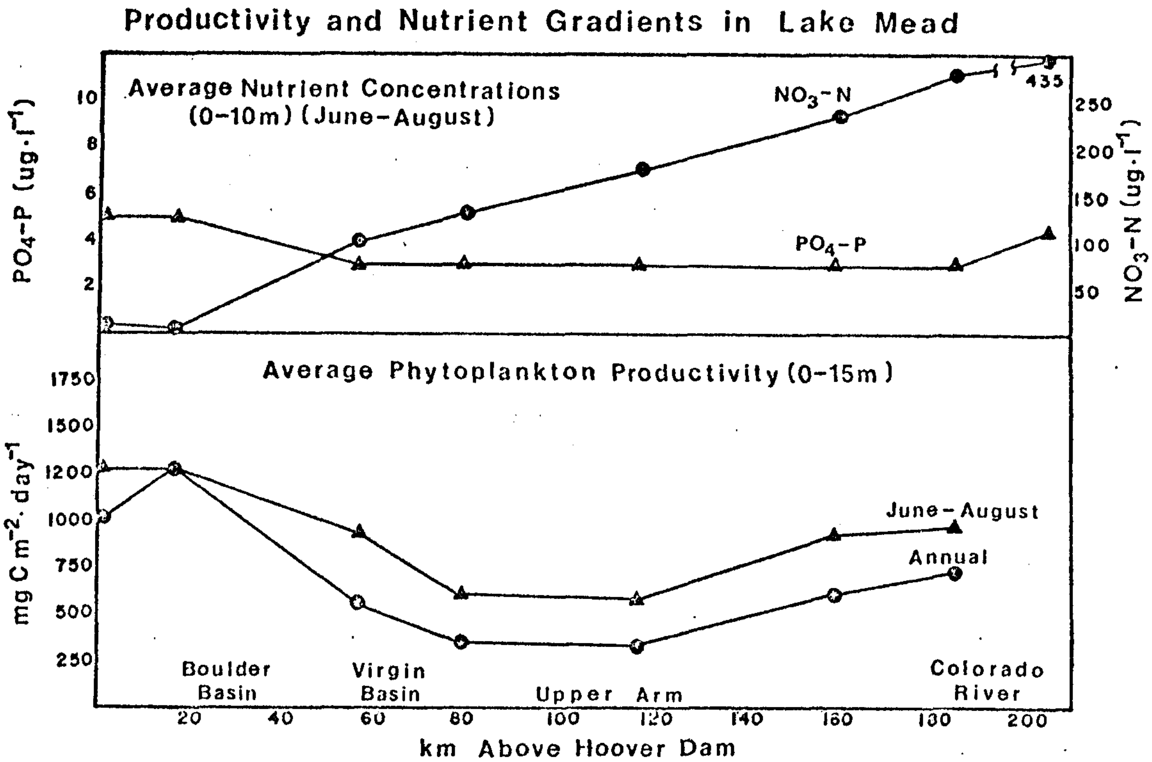

Figure 7. Phytoplankton productivity (0-15 m) and nutrient (0-10 m) gradients in the Colorado River channel of Lake Mead.

initiates higher productivity in the Lower Basin, but nitrogen ultimately sets the upper limit in the summer. From the existing productivity and nutrient gradients in Lake Mead, it is possible to draw some inferences regarding historical patterns of productivity in each basin.

The productivity gradient in the Upper Arm would have existed before Lake Powell was formed, but productivity would have been higher with the gradient extending further down-lake because of higher phosphorus loading from the Colorado River. Phosphorus loading from Las Vegas Wash was low at that time, and it is unlikely that the Colorado River provided sufficient phosphorus to sustain high productivity into the Lower Basin. However, the Lower Basin was probably very productive in the late 1960's with increased phosphorus loading from Las Vegas Wash and higher nitrate loading from the Colorado River. It appears that nitrogen limitation has since decreased productivity in the Lower Basin during the summer.

SUMMARY

The limnological changes that occurred in Lake Mead after Lake Powell was formed clearly illustrate the interactions that exist among main stem reservoirs. In multi-reservoir systems, biological retention of nutrients in one reservoir will directly reduce inputs to the downstream reservoir. If these are limiting nutrients, as nitrogen or phosphorus usually are, productivity will decrease accordingly. This has profound implications for reservoir management because such reductions in productivity might be desirable if the downstream reservoir was excessively productive, or undesirable if it sustained a heavily utilized sport fishery. Multi-reservoir systems, therefore, must be managed collectively to insure that operation of one reservoir does not adversely influence water quality or beneficial uses of downstream reservoirs.

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