A MATHEMATICAL MODEL OF PRIMARY PRODUCTIVITY AND LIMNOLOGICAL PATTERNS IN LAKE MEAD

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ABSTRACT

The temporal and spatial changes in chemical and biological properties of Lake Mead have been investigated, thereby indicating the sources of water pollution and the time of highest pollution potential. Planktonic organisms have been shown to indicate the presence of water problems. Macro- and micro-nutrient analyses have shown that primary productivity is not inhibited by limiting concentrations. A mathematical model has been developed, tested with one set of independent data, and shown worthy of management utility. Although the model works very well for the Lake Mead area, the physical reality of the MLR equation should be tested on independent data.

CHAPTER 1

INTRODUCTION

Progressive increases in concentration of dissolved solids in the Colorado River from Lake Powell to Imperial Dam seem to alter plankton dynamics and biological productivity of the river. Also, changes in biological productivity and nutrient concentrations occur within the same reservoir. Quantification of the relationship between physical and biological components of the system are necessary to diagnose eutrophication trends and the carrying capacity of the reservoirs and river reaches.

The Colorado River in the Lower-Basin States is highly saline compared with other major rivers in the world. Between the Green River in Wyoming and the Imperial Dam, there is a 2-3 fold increase in dissolved solids concentration in the River (Table 1). High salinity of the water and the lack of a reliable model to predict future trends are major constraints in deriving alternative developmental plans for urbanization, recreation, and water uses in the Lower-Basin. The Department of Interior estimated that domestic, industrial, and agricultural activities in the Upper-Basin States has caused a rise in salinity of about 240 ppm at Lee Ferry (Iorns, Hembree, and Oakland,

Table 1. Average Annual Total Dissolved Solids Concentrations[a] at Selected Stations (1960-1970) -- Presented at Federal-State Enforcement Conference on the Colorado River, Las Vegas, Nevada, February 15-17, 1972.

Year	Cameo Colo	Green River Wyo	Lee Ferry Ariz	Grand Canyon Ariz	Hoover Dam Ariz-Nev	Parker Dam Ariz-Cal	Imperial Dam Ariz-Cal	Northerly Intern Boundary
1960	429	347	593	629	671	631	777	--
1961	469	319	710	784	697	669	820	--
1962	338	276	525	536	685	699	818	--
1963	582	302	934	1,030	677	681	791	--
1964	498	296	811	913	722	679	824	1,331
1965	369	322	572	636	809	765	916	1,332
1966	519	382	517	566	743	755	896	1,330
1967	468	287	621	681	675	689	842	1,322
1968	439	363	647	691	699	692	846	1,307
1969	436	315	602	667	776	748	920	1,298
1970	388	389	631	718	776	784	927	1,264

[a]All values in milligrams per liter.

1965). Since that time, salinity in the lower Colorado has increased about 300 ppm. Part of this increase may be attributed to changes in sediment dynamics, growth of phreatophytic-type vegetation, and riparian growth. There are large areas along some reaches of the river where deposited sediments have resulted in major ecological changes and to some extent provided excellent conditions for vigorous plant growth. Salinity increase in the river is attributed to two mechanisms: salt loading, and salt concentration. Source points of loading are as shown in Figure 1. Increased salt load is also due to urban, industrial, and agricultural developments and the discharge of pollutants associated with these activities. Salt concentration results from evaporation, transpiration, and diversions.

Changes in salinity and direct and indirect introduction of domestic and industrial effluent into the system relate directly to biological productivity and eutrophication trends. It is anticipated that future developments that add new types of inputs through use and/or result in diversion have a direct relationship to pollution trends in the system, its social and physical carrying capacity, and consequently, its regional and national importance as an economic, social, and political unit. The man-made reservoirs and river reaches represent aquatic systems with extreme conditions. States of water bodies

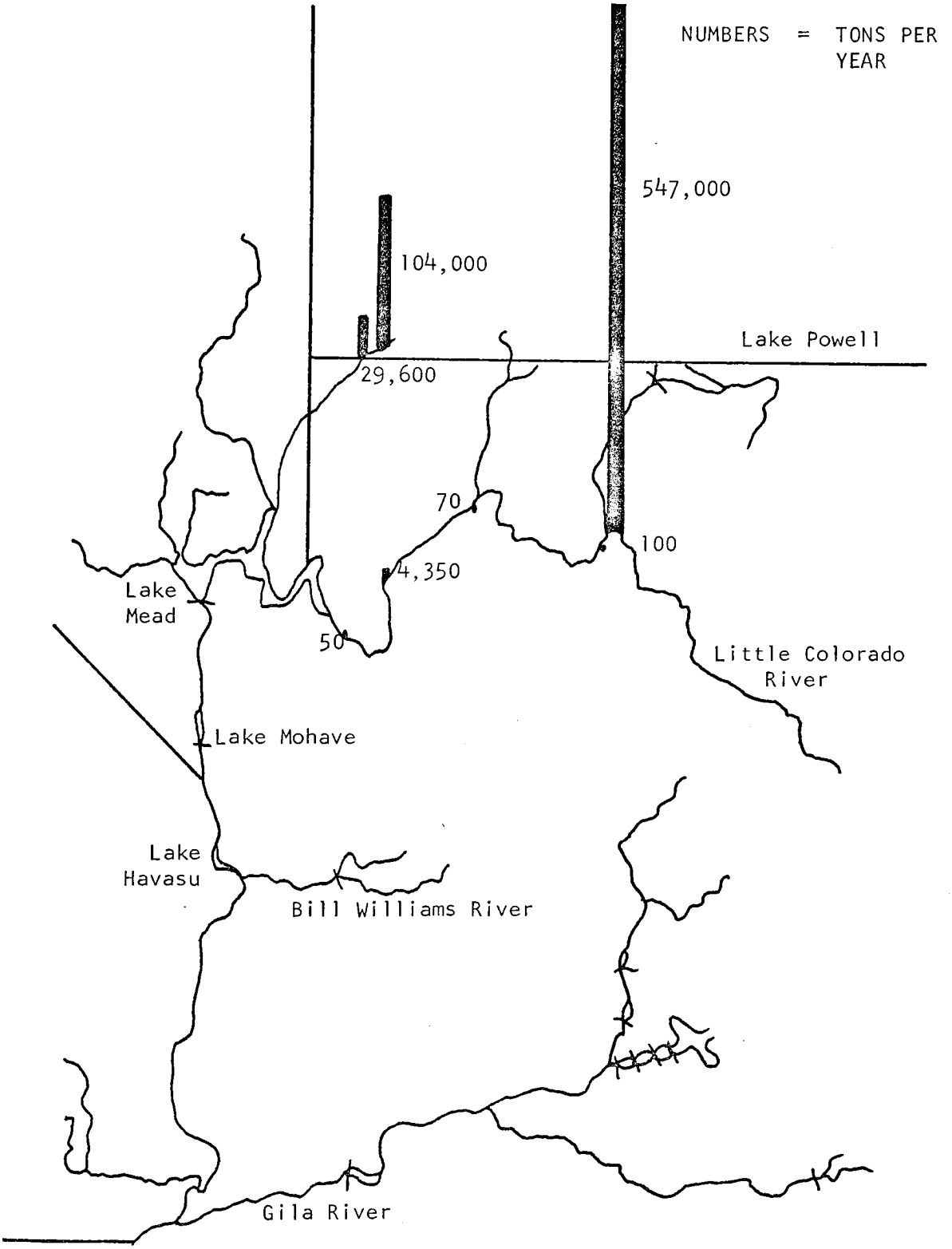


Figure 1. Location of Salt Springs

vary from oligotrphic to eutrophic in the same lake at different locations and different times. Lakes and other surface waters are frequently divided into one of two types, oligotrophic or eutrophic. It is generally agreed that oligotrophic lakes are relatively unproductive and receive small amounts of aquatic plant nutrients, while eutrophic lakes are highly productive and experience high fluxes of aquatic plant nutrients (Table 2). The word eutrophication has many problems in its definition because of recent usage. Originally the term described the general nutrient condition in German bogs. The term later was used to describe a stage in the life span of a lake. Today the term is used to describe the flux of aquatic plant nutrients and/or the amount of plant or animal production. Still others use the term to relate nutrient flux to water quality. In general, we can say that eutrophication is an aspect of the natural process of the aging of an aquatic system that can be accelerated due to man's developmental activities.

Lake Mead is the largest surface water body in the basin and it represents a system with wide variability in limnological conditions. The present states of the Lake need analysis to depict the influences of past activities and to develop a sound base for forecasting the effects of developments.

Table 2. Classification of Lakes by Eutrophication

Characteristic	Oligotrophic	Eutrophic
Primary productivity	Low	High
Nutrients (No_3 Po_4)	Low	High
Depth	Deep with steep sides, volume of hypolimnion > epilimnion	Shallow with gentle slopes, volume of hypolimnion < epilimnion
Water transparency	High	Low
Apparent color	Blue	Green to yellowish brown
Suspended matter	Low	High
Dissolved organics	Low	High
Hardness and total dissolved salts	Variable but often soft with low TDS	Usually high in Ca++ ions and TDS
Bottom deposits	Poor in organic deposits	High in organic deposits
Dissolved O_2	DO_2 found throughout water column to bottom	Little or no DO_2 in hypolimnion
Plankton	Poor in nos. of individuals; High diversity of species	Rich in nos.of individuals; Low diversity of species
Deep benthic fauna	Rich in species; Poor in quantity	Poor in species; Rich in quantity; Anaerobic forms (Chironomids dominant)

Table 2.--Continued

Characteristic	Oligotrophic	Eutrophic
Rooted aquatic plants	Sparse	Abundant
Fish fauna	Whitefishes, suckers, trout, small mouth bass	Sunfishes, carp, catfishes, large mouth bass

Objectives

A generalized objective of this study is to analyze the biotic and abiotic components of Lake Mead, and to develop methodology for diagnosing changes in biological productivity as it relates to physical and chemical changes in the aquatic system.

Specifically, the objectives were:

1. To establish a water sampling procedure for assessing temporal and spatial changes in chemical and biological properties of the river-reservoir system.
2. To measure primary productivity rates (ppr) and conduct counts of plankton populations at several sampling locations in Lake Mead.
3. To determine macro- and micro-nutrient concentrations at each sampling location.
4. To derive functions relating ppr to physical and chemical changes in the system.

Related Investigations

Since the completion of Hoover Dam in 1936, a series of extensive investigations have taken place in Lake Mead. Starting in 1937, the National Research Council (NRC) studied the complexities of the density currents of the Lake and published three volumes (NRC, 1949). The findings continue to be used as reference on sediment dynamics in

the Lake. However, since the filling of the reservoir, circulation and sediment transport patterns have changed. Smith, Vetter, and Cummings (1948) conducted a comprehensive survey of the sedimentation process in Lake Mead. Their study dealt with sediment distribution rates, texture, bacteriology, and chemistry. Anderson (1950) and Anderson and Pritchard (1951) began a massive effort to define the physical limnology of Lake Mead. They concluded that salinity and temperature over one month must be treated as conservative and non-conservative properties respectively in circulation studies. The Virgin Basin was shown to act as a large "mixing bowl" that dampens seasonal variations in salinity of the Colorado River waters as they flow into Lake Mead. Below Virgin Basin the water was reported to be nearly uniform with respect to salinity. The increase in flow from Las Vegas Wash has recently been shown by Everett (1971) and Slawson (1972), using cross-spectral analysis, to alter the salinity values at Hoover Dam. The seasonal and trend increases in salinity at Las Vegas Wash have been shown to immediately increase the salinity values at Hoover Dam. The lag time between the increases at Las Vegas Wash and Hoover Dam was less than one month. The U. S. Weather Bureau (1953) supported the circulation and sedimentation studies by establishing the wind patterns over the reservoir.

By the end of the 1950's, the emphasis in Lake Mead had shifted from sedimentation studies to water-loss investigations. Harbeck (1958) expanded the work of Anderson and Pritchard (1951) and estimated evaporation losses at seven feet of water per year.

The research interest in the 1960's was directed toward the water pollution problems developing in the Boulder Basin Region (Figure 14, p. 48). The Bureau of Reclamation (1965) investigated the water quality of Boulder Basin during the months of April and May. Based upon dissolved oxygen (DO), CO_2, pH, electrical conductivity (EC), and temperature, they concluded that the impoundment created by Hoover Dam did not adversely affect the water quality of Lake Mead. The conclusion is a poor generalization since the effect of Hoover Dam is aggravated by the Las Vegas Wash inputs. The Environmental Protection Agency (EPA) (1967) gave a general indication of the problem developing in the Las Vegas Wash area. However, their findings were based upon phytoplankton counts. Numbers of individuals are a poor parameter to quantify water pollution since it has no relation to the primary productivity rate. In 1968(a), EPA conducted a general biological survey of the Lower Colorado River. Using the number of individuals, i.e., algae/ml they indicated that Las Vegas Wash had the highest number of algae/ml and that the number of algae/ml decreased with distance from Las Vegas Wash.

This report has since been shown to be incorrect in its interpretation. Reports by Everett and Qashu (1971) using sensitive radio-active ^{14}C primary productivity rates (ppr) have shown that photosynthesis increases toward Hoover Dam and that the problem is not located solely in Las Vegas Wash.

In 1970, the Bureau of Reclamation published another review of the water quality in Lake Mead. Using chlorophyll "a" as an indicator, they showed that the chlorophyll concentrations were much higher in Las Vegas Wash than Boulder Basin. The highest values were obtained in May. The problem with chlorophyll is that it works reasonably well for relatively pure cultures of one type of organism. However, with mixed populations of organisms, particularly where there is a shift in frequency of species, it is found that frequently the correlation between the chlorophyll content and the total numbers or mass of algae is very poor (Lee, 1970). The Bureau (1970) data show the problem to be reduced by August when in fact it should be intensified with the warming of the surface water (Everett and Qashu, 1971).

The Lower Colorado Region Comprehensive Framework Study (1971) published eighteen volumes covering interests and problems in the Lower Colorado River system. Volume XV, dealing with water quality, pollution control, and health factors, used number of algae/ml as their rationale.

They wrote that although Las Vegas Wash measured 7.0 mg/l of nitrates--140 times greater than the 0.05 mg/l criterion for streams entering reservoirs set by the National Committee on Water Quality Criteria (EPA, 1968b)--"conditions within the main body of the Lake are acceptable."

In December of 1971(a), the EPA seemingly under considerable pressure, analyzed the problem in Las Vegas Wash using chlorophyll "a" as the criterion for water quality. They showed that the pollution decreased away from the Wash. Their algal growth potential, which they did not describe or give values to, showed that waters below Hoover Dam had a higher growth potential than Las Vegas Bay. They then said that this growth rate demonstrated that low phosphate concentrations limit algal growth in Lake Mead. This is obviously contradictory since higher phosphate values are found in the Wash area. The EPA conclusions are based upon chlorophyll "a" as an indicator of algal growth rate. Chlorophyll "a" at best is a measure of biomass and does not reflect growth rates. EPA failed to recognize that Las Vegas Wash did not behave independently of the rest of Boulder Basin.

Riesbol, Minkley, and Kilmartin (1971) completed a cursory study in Lake Powell for the Bechtel Corporation. The study generally looked at plankton, fish, and the need for hydrodynamic studies. Anderson (1971) published the first report of a "Collaborative Research on Assessment of

Man's Activities on the Lake Powell Region," which is an integrated chemical, biological, and hydrodynamic study leading to a predictive model. Using ^{14}C techniques, sampling in the first year was done at one, two, four, six, and eight meters. A considerable loss of information in defining the vertical ppr profile could be expected when the depth of sampling is arbitrarily chosen.

Chemical, bacteriological, and biological investigations have been done by Everett et al. (1970-71) in the Grand Canyon from Lee Ferry to Diamond Creek. Several sources of chemical and bacteriological contamination were found. The research is continuing in an effort to develop models for diagnosing bacteriological and chemical changes due to the intensity of river use for recreation.

The Environmental Protective Agency (1971b, c, d, e) published a summary and three appendices on the Mineral Quality Problem in the Colorado River System. On the basis of these documents at the Federal-State Enforcement Conference on the Colorado River, Las Vegas, Nevada, February 15-17, 1972, the EPA was unable to obtain an agreement with other State and Federal Agencies on a salinity standard. The states made it quite clear that sound basic research on the functional relationship of salinity to water quality problems was needed before any management decision could be made. Our participation in that Conference was to show that an understanding of the ionic species change,

accounting for the salinity problem was the major concern. The physiological damage to aquatic and riparian organisms varies with the ionic species, and not as the total salinity changes. The source of the ionic species could be more easily identified by understanding the composition of the salinity values. Our final comment at that Conference was to show the inadequacy of basing standards on a mean value. The extremes associated with a mean value are primarily responsible for biological damage.

CHAPTER 2

THE AQUATIC SYSTEM

Conceptual Model

The impact of water resourcesdevelopment projects on aquatic eco-systems, measured in terms of accelerated eutrophication and resulting economic and social losses, has become a matter of rising concern both in the United States and abroad. If we consider the potential combined effects of increased domestic sewage, salinity increases, and agricultural drainage effects we are led to conclude that the environment in the Lower Colorado River would experience a greatly accelerated eutrophication. There is little doubt that a serious need exists for methods and tools which will permit assessment of the shifts in rates of eutrophication and in the merits or demerits of alternatives for control of eutrophication. Realizing the need for such a capability in dealing with eutrophication, we find it necessary to understand biotic and abiotic relationships in the aquatic system. A simplified aquatic model (Figure 2) deals with a nutrient source, primary producers (phytoplankton), and primary consumers (zooplankton). Usually very general parameters such as temperature are the variables of interest. Most of the inputs

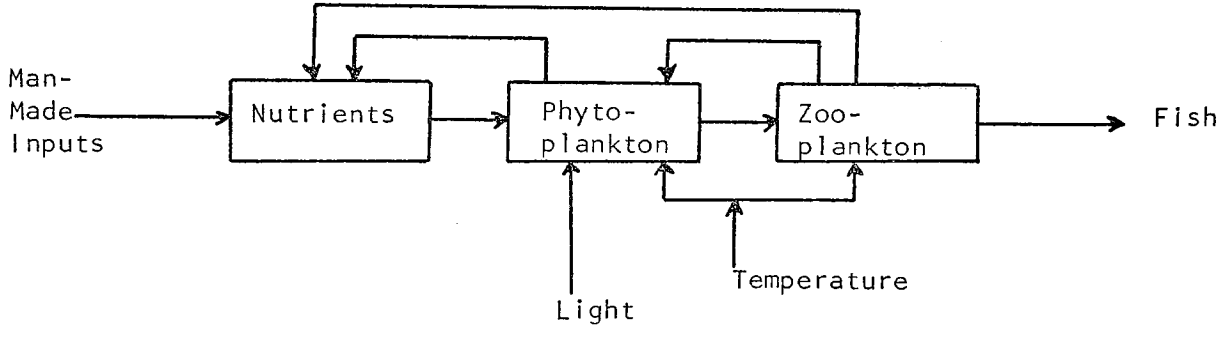


Figure 2. Simplified Aquatic Model

are lumped, i.e., fish grazing is represented by one factor. Models of fish population dynamics have been expanded by Patten (1969).

A more complete model of an aquatic ecosystem is given in Figure 3. The higher plants have been omitted. Although we can conceptually "understand" the paths in Figure 3, obtaining functional relationships is difficult because of the lack of complete simultaneous data acquisition.

The flow diagram (Figure 4) shows the interaction (I) of the components. Limnologists are aware of the complexities in trying to represent the various nutrient phytoplankton and zooplankton systems as a black box. There are many chemical and biological phenomena taking place in the system that are not fully appreciated and are not presented (i.e., phytoplankton affinity for different nitrogen compounds).

Review of Functional Relationships in Modeling

Considerable work is reported on the development of eutrophication models. Some of the early work was done by Davidson and Clymer (1966) using analog and digital approaches. These authors had to make many assumptions:

1. All physical, chemical, and biological variables were uniformly distributed through the volume of water of concern.

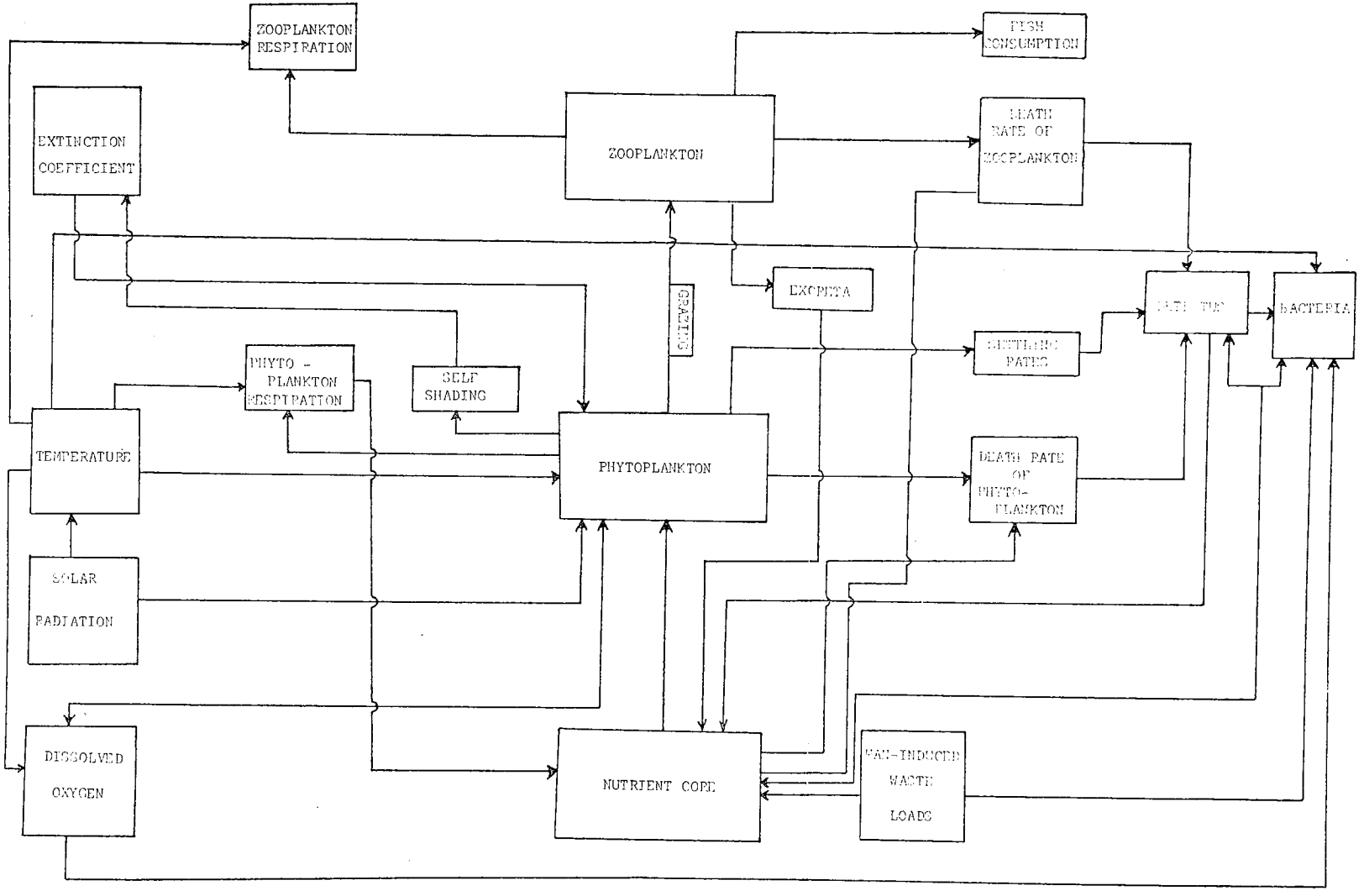


Figure 3. The Aquatic Ecosystem

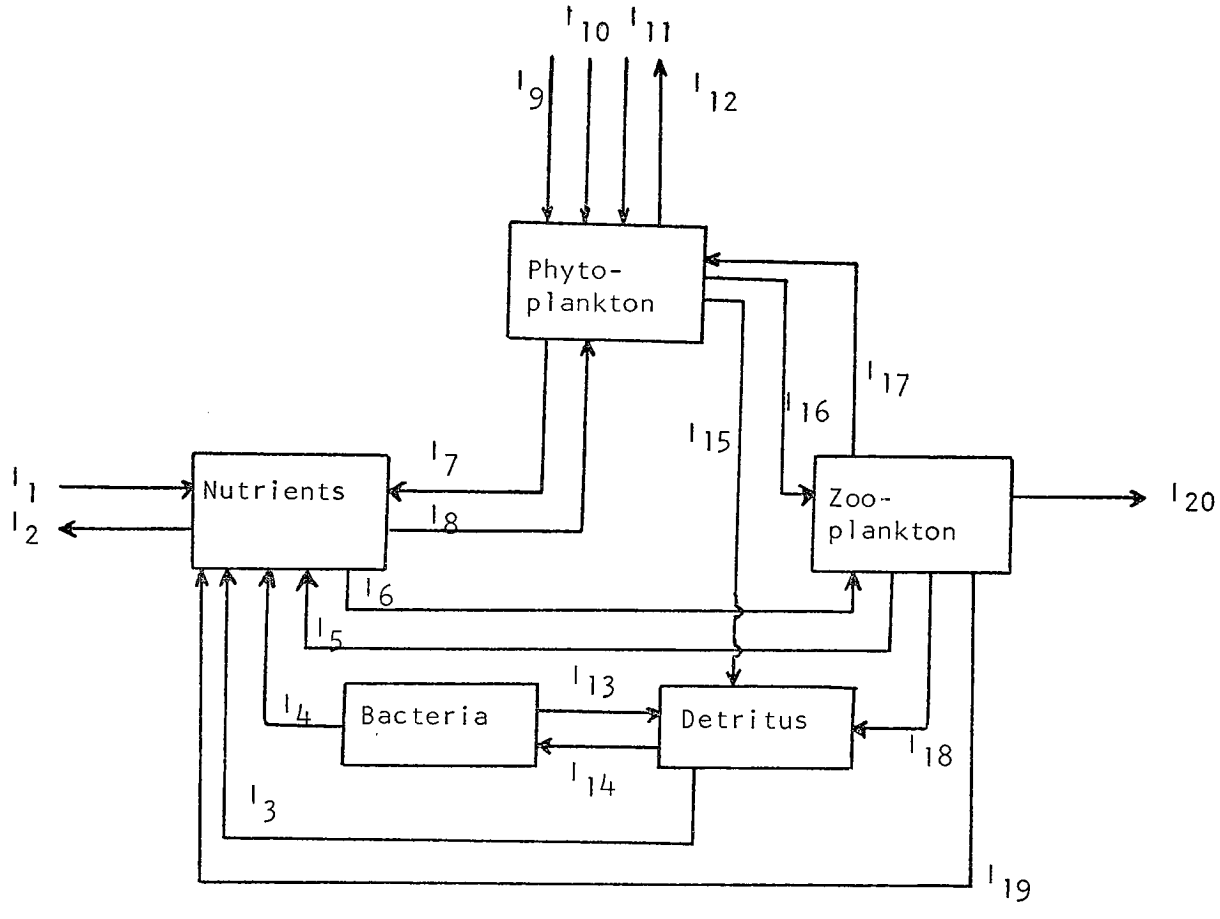


Figure 4. Ecosystem Flow Diagram

2. All variables were averages of 24 hours since diurnal frequencies were not of interest.
3. All species present can be lumped into two classes: phytoplankton and zooplankton, each having assigned constants over all species, ages, and times of year.
4. There was one critical nutrient.
5. Growth and reproduction need not be distinguished.
6. Illumination and water temperature have sinusoidal annual cycles.

Davidson and Clymer then developed a set of equations for a mathematical model. Their generalized equation is:

$$P = K_1 \ (N^{limit}) - K_2 Z - K_3 - K_4 T \qquad (2.1)$$

where

P = phytoplankton population density

Z = zooplankton population weight density

N = nutrient concentration (limiting element)

T = water temperature °C

K_1 = phytoplankton growth rate due to photosynthesis

K_2 = death rate of phytoplankton eaten by zooplankton

K_3 = all other contributors to death rate of phytoplankton

K_4 = rate of energy needed for respiration.

The result of their efforts showed considerable opportunity and desirability for ecosimulation studies.

Cole (1967) at Battelle Northwest expanded upon the work of Davidson and Clymer. Temperature, death rates, and grazing rates were varied in the analysis. The Water Resources Engineers, Inc. (Chen and Orlob, 1968) published a report on a proposed ecologic model for a eutrophying environment. They used the rate law of chemical kinetics, "the rate at which a specific reaction proceeds is some product function of its reactant concentrations." In the case of photosynthesis (α), they expressed the rate as follows:

$$\frac{d\alpha}{dt} = K \times f(A) \times f(I) \times f(CO_2) \times f(N) \times f(P) \qquad (2.2)$$

where K is a coefficient and f(A), f(I), $f(CO_2)$, f(N), and f(P) ... are respectively functions of advection, light, carbon dioxide, nitrogen, phosphate, etc.

In particular cases, the concentration of some factors may be relatively large so that the level of the abundant material may be treated as practically constant. This could result in an apparent rate equation of only a single concentration factor. This factor becomes "limiting" according to Liebig's classical "Law of the Minimum" and Blackman's concept of "Limiting Factors." Odum (1963) has extended Liebig's Law of the Minimum to include the

limiting effect of the maximum (i.e., an excess of chloride could be toxic or inhibit algal growth).

DiToro, O'Connor, and Thomann (1970) were able to develop a hybrid phytoplankton model at Manhattan College, Bronx, N. Y. DiToro followed the equations presented by Riley (1965) and Steele (1965). The principle of conservation of mass was the basis upon which the mathematical development was structured. All equations were developed in terms of adding to or subtracting from a source or sink.

Chen (1970) made a plea that a "multidisciplinary" background be required to bring scattered bits and pieces of accumulated information to bear on the broader problem of management of aquatic environments. He reviewed the Water Resources Engineers' approach and suggested some equations for a eutrophication model. For example, he suggested that biomass of phytoplankton is transported by movement of water. In addition, phytoplankton increase is attributed to reactions depending on light, temperature, and nutrient conditions. Also, phytoplankton decrease as a result of continuous respiration, settling, and grazing by zooplankton. Terms to account for these effects were presented in the differential equation:

$$d\frac{(VPi)}{dt} = T + AE\frac{dpi}{dx} + (H_i - r - s)\ PiV - \frac{1}{Yz}\ gp_{fi}zV \qquad (2.3)$$

where V is volume of the element (L^3); P_i is mass concentration of algae in group i (M/L^3); t is time (T); T is

total advective mass transfer of biomass (M/T); A is cross-sectional area of the element (L^2); E is effective diffusion coefficient (L^2/T); x is distance (L); H_i is specific growth rate of algae in group i (1/T); r is per cent of mass respired per unit of time (1/T); s is per cent of mass settling per unit of time (1/T); Y_z is yield coefficient of zooplankton (M/M); g is specific growth rate of zooplankton (1/T); P_{fi} is preference factor for algae, group i (dimensionless); and z is zooplankton biomass concentration (M/L^3). Each element is a part of a discritized network having both vertical and horizontal dimensions. In this way stratification and horizontal spatial variabilities can be included. For any given time interval, each element is considered to behave as a completely mixed reactor, allowing the mass of water quality constituents to be transported in and out by both advection and diffusion.

The Nutrient System

The essential elements for phytoplankton development listed by Hutchinson (1967) include C, N, O, P, S, K, Mg, Ca, Si, Na, Fe, Mn, Zn, Cu, B, Mo, Co, V, and the chemical species of each element (i.e., NO_2). Lists that include certain vitamins such as thiamin, cyanocobalamin, and biotin are documented. The relative importance of these nutrients has not been fully demonstrated.

Contributors to the nutrient core are natural sources and man-induced waste loads (Figure 4, I_1). Although industrial and agricultural effluent are included, the main source of nutrient is the domestic sewage in either the raw or treated stages. The irony of expensive secondary treatment is that organically bound nutrients are liberated by the bacteria through the process of decomposition. Both the nitrogen cycle (Figure 5) and the phosphorus cycle (Figure 6) in aquatic systems have been described by Russel-Hunter (1970).

Phosphorus, as a major contributor to eutrophication, is a prominent element in the hierarchy of water quality problems. Widely quoted figures given by Sawyer (1947) have contributed to popular conception. His study in the Madison Survey supports the belief that phosphorus is the key element in determining biological activity in a body of water. He showed that lakes producing nuisance blooms had average concentrations of organic phosphorus in excess of 0.10 ppm (100 μg/l). Inorganic phosphorus however, could create nuisance conditions in amounts in excess of .01 ppm (10 μg/l). Sawyer arrived at his conclusions concerning the key effects of phosphorus by a bioassay comparison to nitrogen. He showed that extensive algal growths were produced under laboratory conditions with plentiful supplies of phosphorus and deficient supplies of nitrogen. Undoubtedly nitrogen fixation, either bacterial

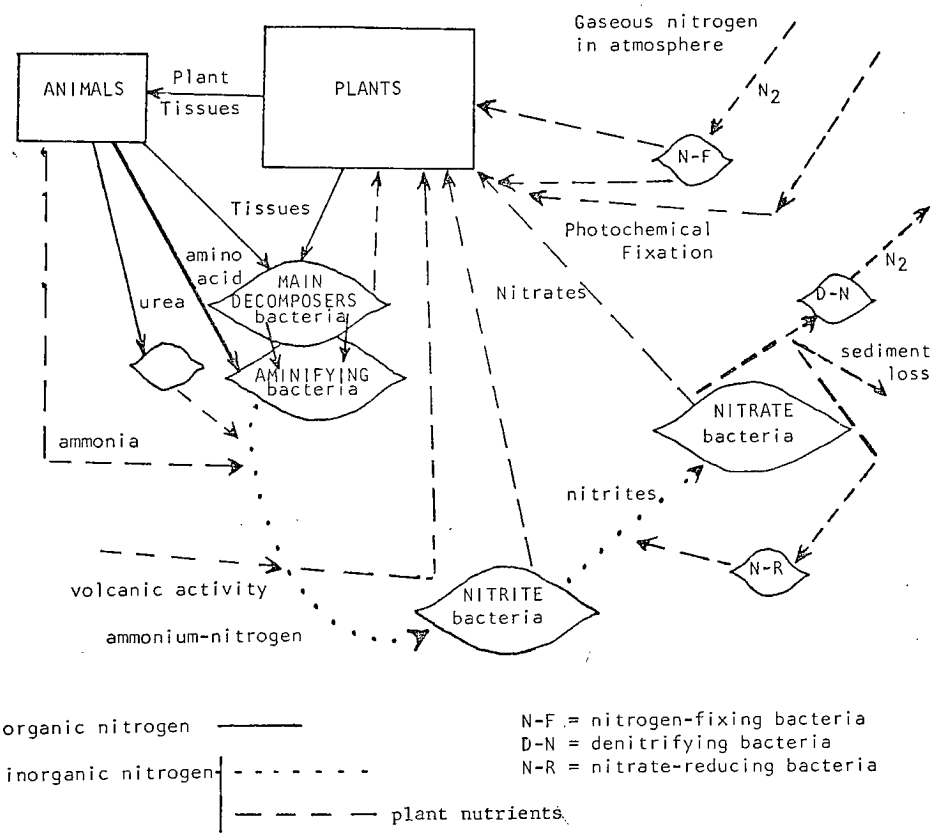


Figure 5. The Biogeochemical Cycle of Nitrogen Compounds in Aquatic and Other Environments -- After Russel-Hunter (1970).

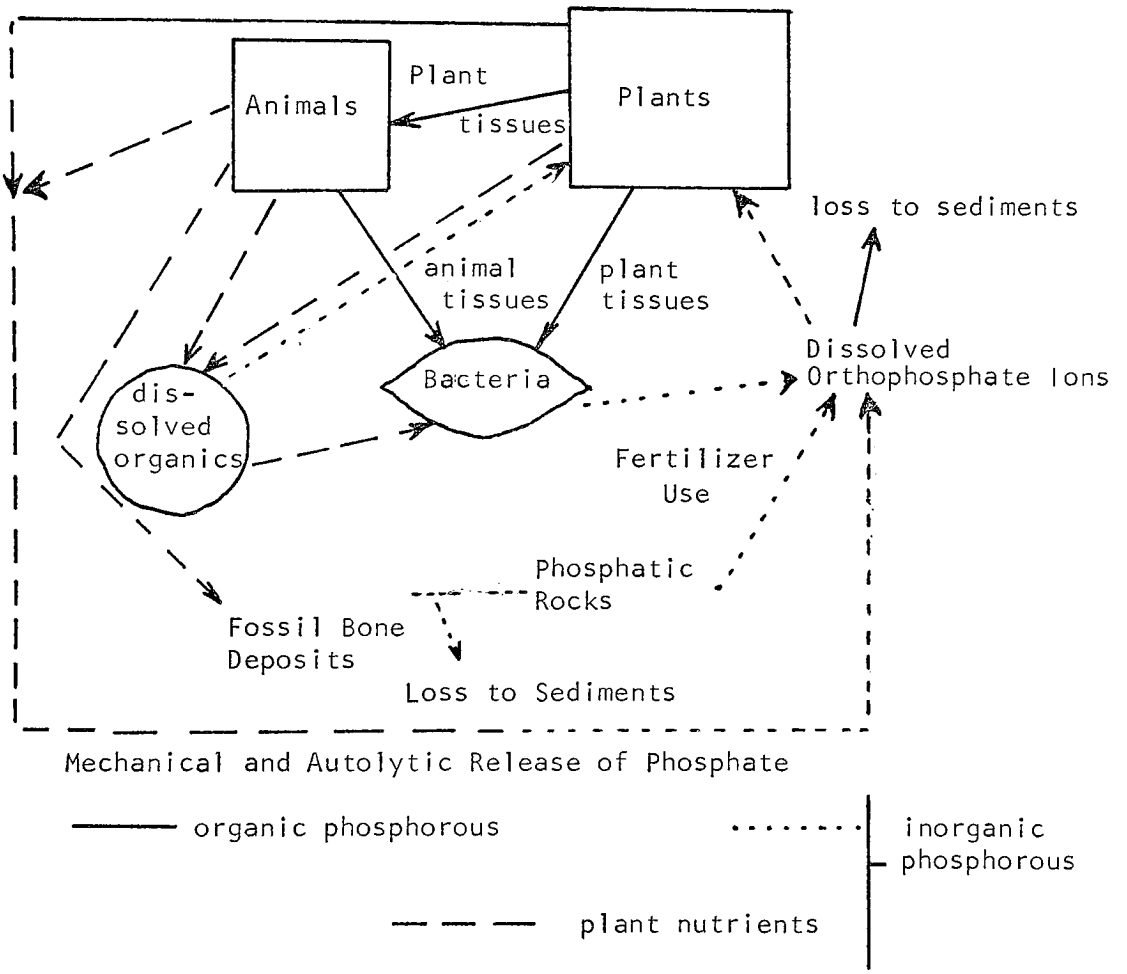


Figure 6. The Biogeochemical Cycle of Phosphorus -- After Russel-Hunter (1970).

or algal, bridges the deficiency and produces the nitrogen necessary for the synthesis of algal protein. In the absence of plentiful supplies of phosphorus, however, nitrogen fixation was found to be unimportant.

Thus, for many years the key importance of phosphorus to the growth of aquatic algae was taken as an absolute fact, and indeed the majority of water chemists and limnologists never did doubt that fact and do not do so now.

The first hints of the furor yet to come appeared in 1967 when Willy Lange, a chemist turned botanist at the University of Cincinnati, published a paper entitled "Effect of Carbohydrates in the Symbiotic Growth of Planktonic Blue Green Algae with Bacteria." His thesis showed that algae always exist in association with bacteria and that the association is mutually supportive. That is, the algae utilize carbon dioxide and sunlight to produce organic matter and oxygen by photosynthesis and the bacteria use oxygen in the decomposition of organic matter to produce carbon dioxide. Lange's experiments proved to his satisfaction that it was the presence of large amounts of organic material in water that made the production of huge amounts of carbon dioxide available for algal growth.

Then L. E. Kuentzel, a physical chemist, in 1969 after reviewing the literature on eutrophication, concluded that carbon, not phosphorus, was the element that

controls algal growth. Kuentzel felt that only bacterial action on organic matter could produce the amount of carbon dioxide required for rapid growth. He showed that in many cases of excessive growth, dissolved phosphorus was exceedingly small, in fact, lower than the levels presented by Sawyer.

In the 1970 Purdue Industrial Waste Conference, Pat Kerr, a plant physiologist at the Federal Water Quality Administration (FWQA), now EPA, Southeast Water Laboratory, presented results where she concluded that carbon was the controlling element.

Both the phosphorus and carbon schools agree that algae need, for growth, sources of inorganic carbon, phosphorus, nitrogen, and numerous other elements such as micronutrients. Both schools agree that algae and bacteria generally coexist, and the phosphorus school is willing to concede that the relationship may be symbiotic. But on almost all other points, they disagree (Table 3). This disagreement emanates from two basic areas of contention:

1. Precisely how much phosphorus do algae need for excessive growth?
2. What sources of carbon are available to algae?

The carbon school maintains that only very small amounts of phosphorus are needed, it points to the low dissolved phosphorus concentrations found in the water of

Table 3. Comparison of the Two Schools of Thought

Carbon-is-key school believes:	Phosphorus-is-key school believes:
Carbon controls algal growth.	Phosphorus controls algal growth.
Phosphorus is recycled again and again during and after each bloom.	Recycling is inefficient: some of phosphorus is lost in bottom sediments.
Phosphorus in sediment is a vast reservoir always available to stimulate growth.	Sediments are sinks for phosphorus, not sources.
Massive blooms can occur even when dissolved phosphorus concentration is low.	Phosphorus concentrations are low during massive blooms because phosphorus is in algal cells, not water.
When large supplies of CO_2 and bicarbonate are present, very small amounts of phosphorus cause growth.	No matter how much CO_2 is present, a certain minimum amount of phosphorus is needed for growth.
CO_2 supplied by the bacterial decomposition of organic matter is the key source of carbon for algal growth.	CO_2 produced by bacteria may be used in algal growth, but main supply is from dissociation of bicarbonates.
By and large, severe reduction in phosphorus discharges will not result in reduced algal growth.	Reduction in phosphorus discharges will materially curtail algal growth.

eutrophic lakes during algal blooms and believes that nutrients, including phosphorus, are recycled by organisms during growth and released for reuse during the periodic dieoff periods. On the other hand, the phosphorus school takes the position that algae require relatively substantial amounts of phosphorus and the incidence of low dissolved phosphorus was due to the uptake by the algal cells.

The carbon school believes that the availability of utilizable carbon is the key and that diffusional processes are too slow to permit atmospheric CO_2 to support massive growth, hence its interpretation of the importance of bacteria-produced CO_2. The phosphorus school points to the fact that algae can use, in addition to free CO_2, carbon dioxide produced by the dissociation of dissolved bicarbonates. Phosphorus supporters say that the dissociation occurs so rapidly that supply of carbon dioxide cannot possibly be limiting, and they ridiculed the carbon school emphasis on the need for respiratory supply.

Blue green algae are an index of eutrophication. They are able to develop under adverse pollution conditions, i.e., high salinity. But, by the time they begin to grow, inorganic nitrogen is often scarce and P is sometimes almost undetectable as a result of the nutrient uptake by the existing plankton. This paradox hardly supports the hypothesis that N and P are the only important components

responsible for the change in flora induced by eutrophication. Provasoli (1969) concluded that other factors must be at work; he showed that blue-greens are the only freshwater algae that show an affinity for Na and K. Since Na and K are found in excess in domestic sewage we could hypothesize that these elements control the species development. Many arguments have been made about the effects of Ca, Mg, Cl, and SO_4 values in the Great Lakes. However, no functional relationships have been reported. The indispensability of silicon for diatoms is well documented (Lund, 1965). The need for iron, manganese, boron, molybdenum, zinc, cobalt, copper, and vanadium has been recorded for a few single algae (Wiessner, 1962), but we cannot infer that all algae need them, nor do we know whether certain species, genera, or algal groups have peculiarly high requirements for any of them.

Further contributions to the nutrient core result from biological activity. Some zooplankton are omnivorous while others are herbivorous or carnivorous. Regardless, a certain percentage of the phytoplankton which is eaten is anabolized and certain portion is excreted (Figure 4, I_5).

All aquatic systems have a certain amount of dead and decaying organic matter called detritus. The detritus is decomposed by the bacteria (Figure 4, I_{14}) releasing nutrients (Figure 4, I_3). The insensitive Biochemical

Oxygen Demand (BOD) technique is a measure of the existing biologically oxidizable detritus. However, there are more sensitive tests for organic matter.

Acting on the organic matter in the water are the bacteria. Bacteria feed on the organic matter (Figure 4, I_{13}) and break it into inorganic elements (Figure 4, I_4). The bacteria create the oxygen demand through respiration. Different species of bacteria are capable of acting at different rates and liberating different elements from the organic matter. The needs of the bacteria (anabolism) differ with the species. But, the nutrient contributions of bacteria are poorly understood.

Certain nutrients are required for phytoplankton growth (Figure 4, I_8) It is well known that certain algae prefer specific nutrients (i.e., Cyanophyta have an affinity for high sodium and potassium levels). We also recognize that some algae are "luxury" consumers of certain nutrients. These algae have the ability to store large amounts of nutrient (i.e., phosphate) while only using a part of it.

The life cycle of algae varies with the species involved (Figure 7). Algae have been shown to reproduce in a 24 hour interval with massive blooms occurring in one week. The death rate depends upon the species of algae involved. This death rate can be natural (Figure 4, I_{15})

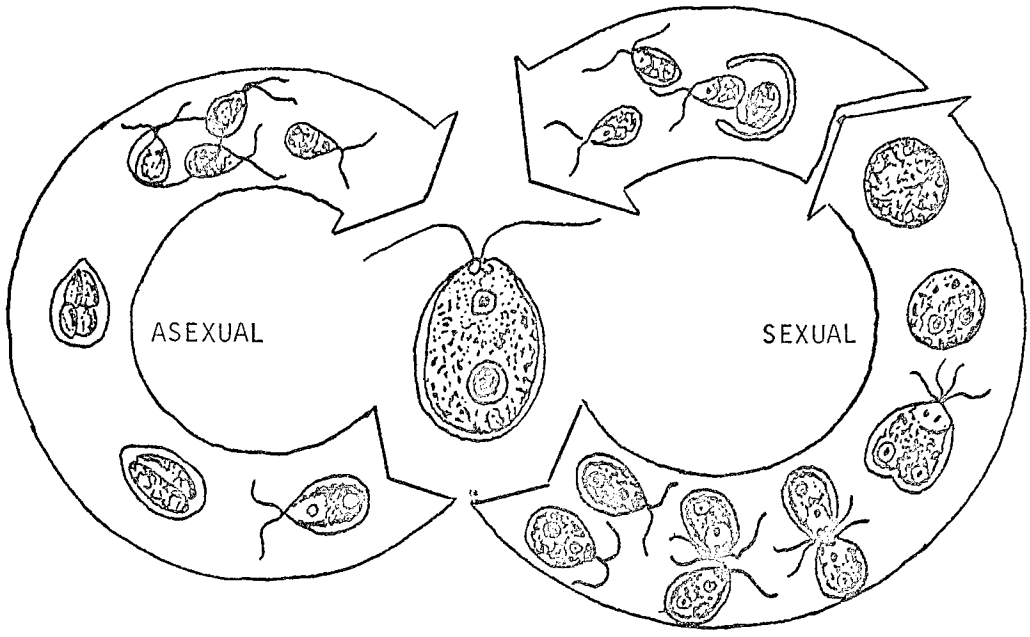


Figure 7. Simple Motile Green Alga, Chlamydomonas -- After Cockrum, McCauley, and Younggren (1966).

or accelerated because of eutrophication or toxic effects (Figure 4, I_7).

Each year a large amount of the nutrients are lost to the sediment (Figure 4, I_2). The sediment loss is due to many factors:

1. Nutrients can precipitate out and fall by gravity to the benthos.
2. Sediment in the system can adsorb nutrient and leach them out as the particles settle.
3. A portion of the phytoplankton and zooplankton that have died settle also into the sediment and their nutrient value is lost.

The Phytoplankton System

Phytoplankton are the microscopic wandering plants of the aquatic system. They are controlled largely by the incoming solar radiation (Figure 4, I_9). The radiation is necessary for the chlorophyll in the plants to carry on the process of photosynthesis. The saturated or optimal growth rate of phytoplankton (Figure 8) has been shown as a function of the solar radiation. The growth rate increases with solar radiation up to about .1 langleys/min. Above this intensity the growth rate is partially inhibited.

As the solar radiation passes through the water, two changes take place. The intensity of light is reduced and the quality of the light is changed (Figure 9). This

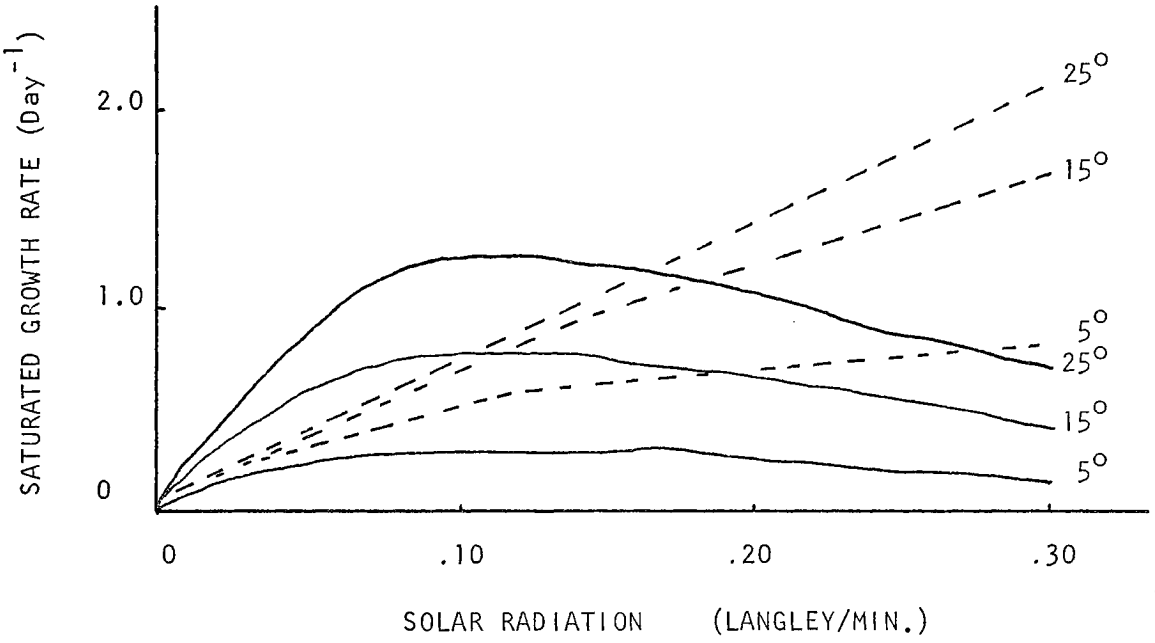


Figure 8. Phytoplankton Growth Rate as a Function of Incident Solar Radiation Intensity and Temperature -- After DiToro et al. (1970).

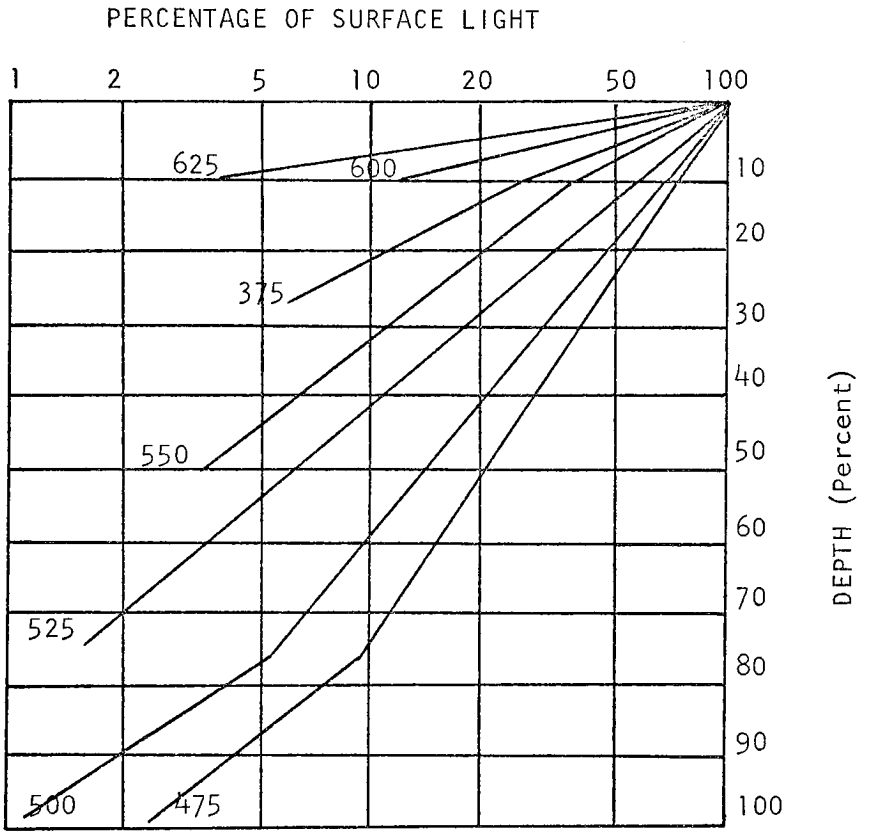


Figure 9. Depth to Which Light of Various Wave-Lengths Penetrates, Expressed as Percentage of the Surface Light -- After Rabinowitch and Govindjee (1969).

is a result of the absorption of the blue-green wavelengths near the surface. The light extinction (Figure 4, I_{11}) is controlled by sediment, thermal density layers, biological reflection, etc. It is important that the quality of the light penetration not be affected by impurities (i.e., sediment) since the phytoplankton absorb light at band-limited wave lengths (Figure 10).

The temperature of the water affects the respiration rate of the phytoplankton (Figure 4, I_{10}). Temperature investigations could become very complex if we were attempting to model solubilities and decomposition rates, etc. However, at this stage, water temperature is treated very generally.

Feeding on the phytoplankton are the herbivorous zooplankton (Figure 4, I_{16}). The zooplankton however, feed at different rates on the phytoplankton population (Table 4). Some species of phytoplankton such as filamentous blue-greens are not grazed by zooplankton. The limnological understanding of the preference of zooplankters for various phytoplankton is very vague.

The number of phytoplankton are reduced by natural and toxic mortality rates (Figure 4, I_{15}) as discussed earlier.

As the number of phytoplankton increase the biomass begins to block out the incoming light. This self-shading (Figure 4, I_{12}) reduces the available light for

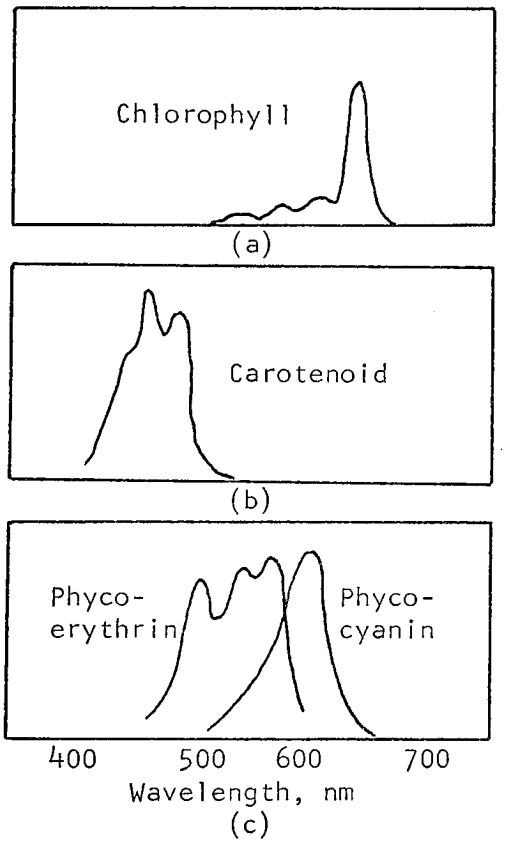


Figure 10. Absorption Spectra of Three Types of Chloroplast Pigments: (a) Chlorophylls; (b) Carotenoids; (c) Phycoerythrins and Phycocyanins -- After Rabinowitch and Govindjee (1969).

Table 4. Grazing Rates of Zooplankton -- After DiToro et al. (1970).

Organism	Grazing Rate (l/mg. dry wt.-day)
Rotifer	
Brachionus calyciflorus	0.6 - 1.5
Copepod	
Calanus sp.	0.67 - 2.0
Calanus finmarchicus	0.05
Rhincalanus nasutus	0.3 - 2.2
Centropages hamatus	0.67 - 1.6
Cladocera	
Daphnia sp.	0.2 - 1.6
Daphnia magna	0.2 - 0.3
Natural Association	
Georges Bank	0.8 - 1.10

photosynthesis and reduces the photic zone. The extreme case may be illustrated by the water hyacinth problem in Florida where the surface of the water is completely covered by these macrophytes.

As the phytoplankton respire they require a certain amount of energy for catabolizing. This reduces the amount of growth through anabolism during the day (Figure 4, I_7).

Since plankton are wandering species and are subject to currents and gravity, they begin to settle out (Figure 4, I_{15}). The number of phytoplankton in the photic zone are reduced through settling.

The Zooplankton System

The zooplankton diversity is present because of the existing phytoplankton, chemistry, and hydrodynamics of the system. Since zooplankton can be omnivorous it is very difficult to determine upon what they are feeding. Generally, however, the zooplankton are taken to graze upon the phytoplankton for their growth food source (Figure 4, I_{16}). The preference of zooplankton for food sources was discussed earlier.

As the zooplankton catabolize (Figure 4, I_{19}) they reduce their growth rate by a fraction that is primarily a function of temperature. It has been shown by Carlson (1968) that phytoplankton grow best when they are grazed by zooplankton. There is an optimum zooplankton population

that grazes at a rate permitting the optimum growth rate of phytoplankton for the existing physical and chemical conditions.

A certain percentage of the zooplankton must die (Figure 4, I_{18}). Independent of this natural mortality is the reduction of zooplankton by the small filter feeding fish (Figure 4, I_{20}), (i.e., shad, cisco, alewife, etc.). It is very difficult to determine if the zooplankton population is a result of the availability of phytoplankton or the feeding of small fish, or both to varying degrees.

Although the zooplankton feed on phytoplankton, a portion is utilized for zooplankton growth, the rest is excreted (Figure 4, I_{19}).

The zooplankton population consists mainly of Copepods, Crustaceans, and Rotifers, and each has a different life cycle. The growth stages, separated by molts in the life cycle of Copepods, are similar in all forms. The egg hatches as a typical nauplius larva. After six successive molts a metanauplius form gives rise to a Copepodite stage. There are usually five molts after the metanauplius to the Copepodite stage. The final molt from the fifth Copepodite stage results in adult males and females. Copepods have been shown to have one to seven generations in a year depending primarily upon the temperature of the water. Little is known about the longevity in Copepods, the littoral-benthic and pond species can live for nine

months in the laboratory and possibly longer in nature. The smaller Copepods live one to six months and in some cases may last two or three years (Hutchinson, 1967). The life cycle of the zooplankton is very complex with fish exercising a considerable control on the nature of zooplankton associations.

Attempts at modeling rotifers (Figure 11) are still in the infant stage. We generally say that the zooplankton have a constant death rate. The zooplankters can die because of natural mortality (Figure 4, I_6), toxic effects through phytoplankton (Figure 4, I_{17}), or grazing by larger carnivores (Figure 4, I_{20}).

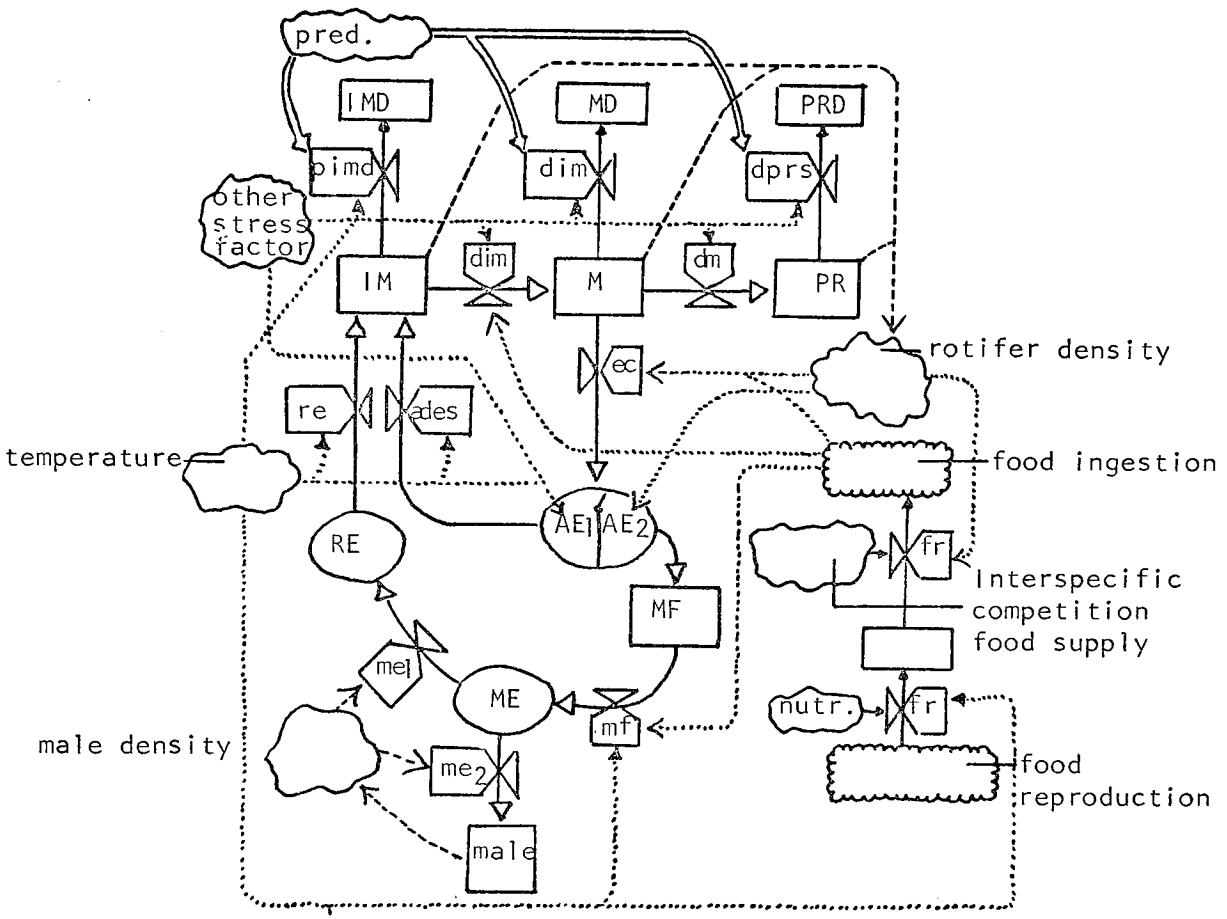


Figure 11. Flow Diagram for a Simulation Model of Rotifer Population

CHAPTER 3

THE STUDY AREA

Locations and Water Quality Considerations

Lake Mead, the largest reservoir in the Western Hemisphere, is located on the Colorado River (Figure 12). The impount is a canyon-type reservoir formed by Hoover Dam, a concrete arch gravity structure that has a maximum height of 726.4 feet. Although the Dam was completed in 1936, storage began during the previous year. Below the Dam, the tailrace releases show a weak seasonal oscillation in salinity (Figure 13). At full elevation, the reservoir extends a distance of 115 miles upstream and has a capacity of 31,047,000 acre-feet. A perimeter of 550 miles encompasses 158,000 surface acres with a maximum depth of 589 feet. The Lake is extremely irregular in shape. Boulder and Virgin Basins (Figure 14) contain about 60 per cent of the total storage in the reservoir.

The climate at Lake Mead is arid. Mean annual temperature at Las Vegas is 66°F (19°C) and mean annual precipitation is less than 5 inches, according to Weather Bureau Records. Maximum temperatures of 110°f (43°C) are non uncommon in July and August. Average minimum temperature in January is 30°F (-1°C). Winds are generally light.

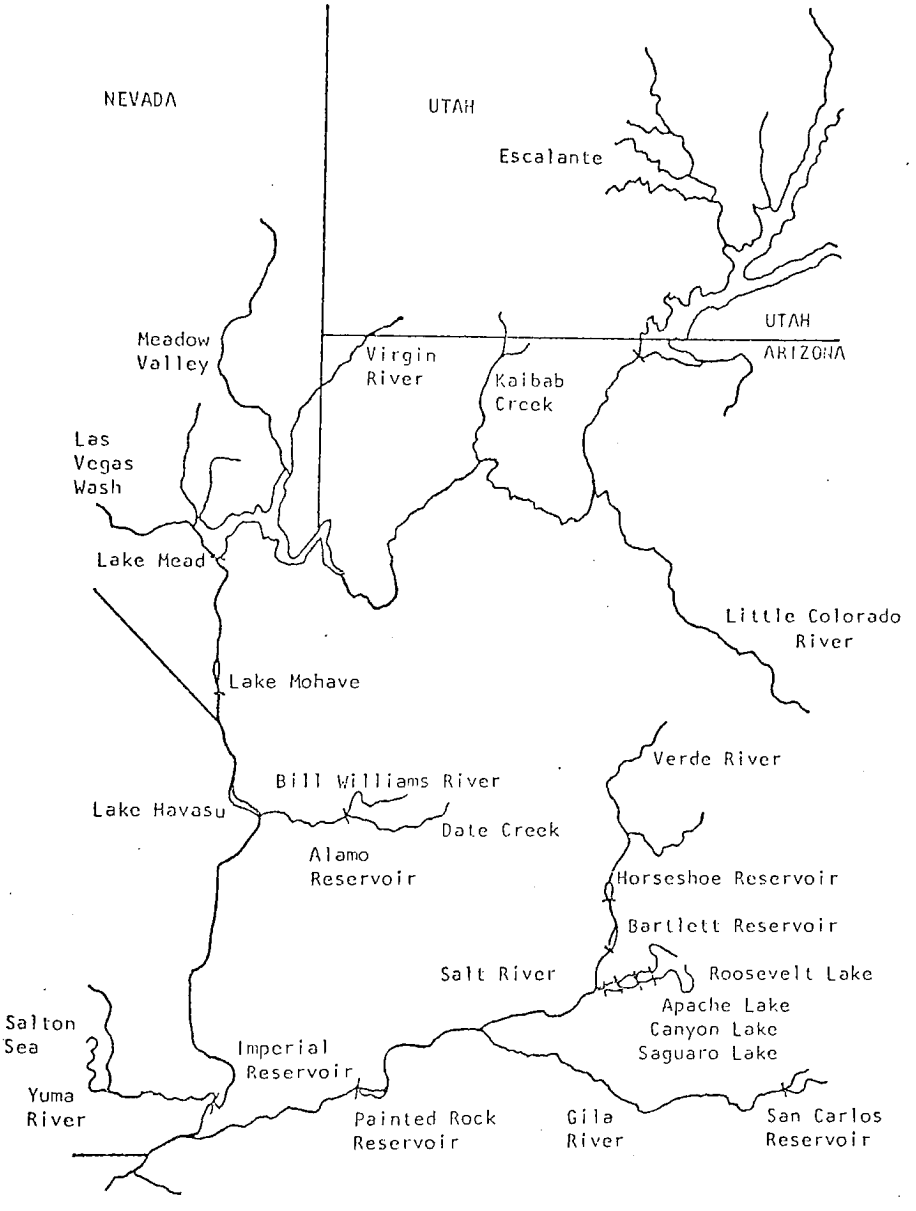


Figure 12. Map Showing the Colorado River Basin from Lake Powell to the Mexican Border

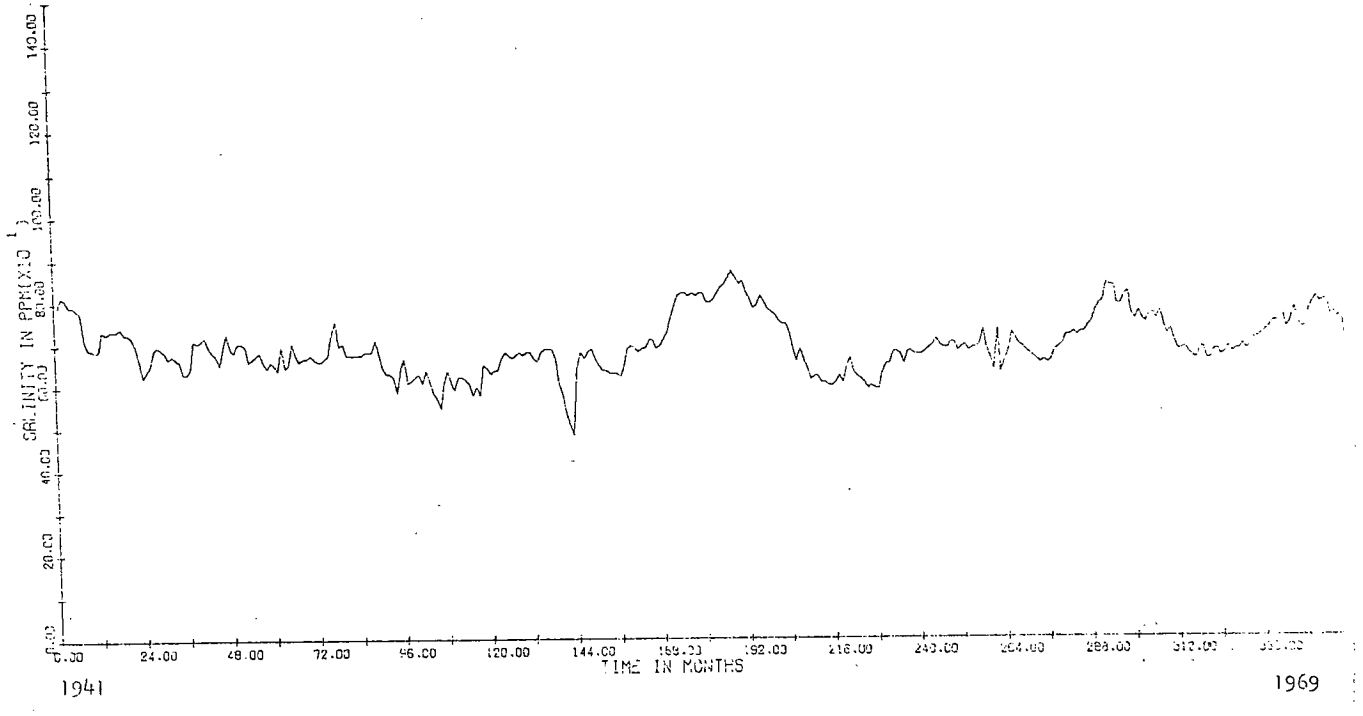


Figure 13. Salinity Releases at Hoover Dam -- After Slawson (1972).

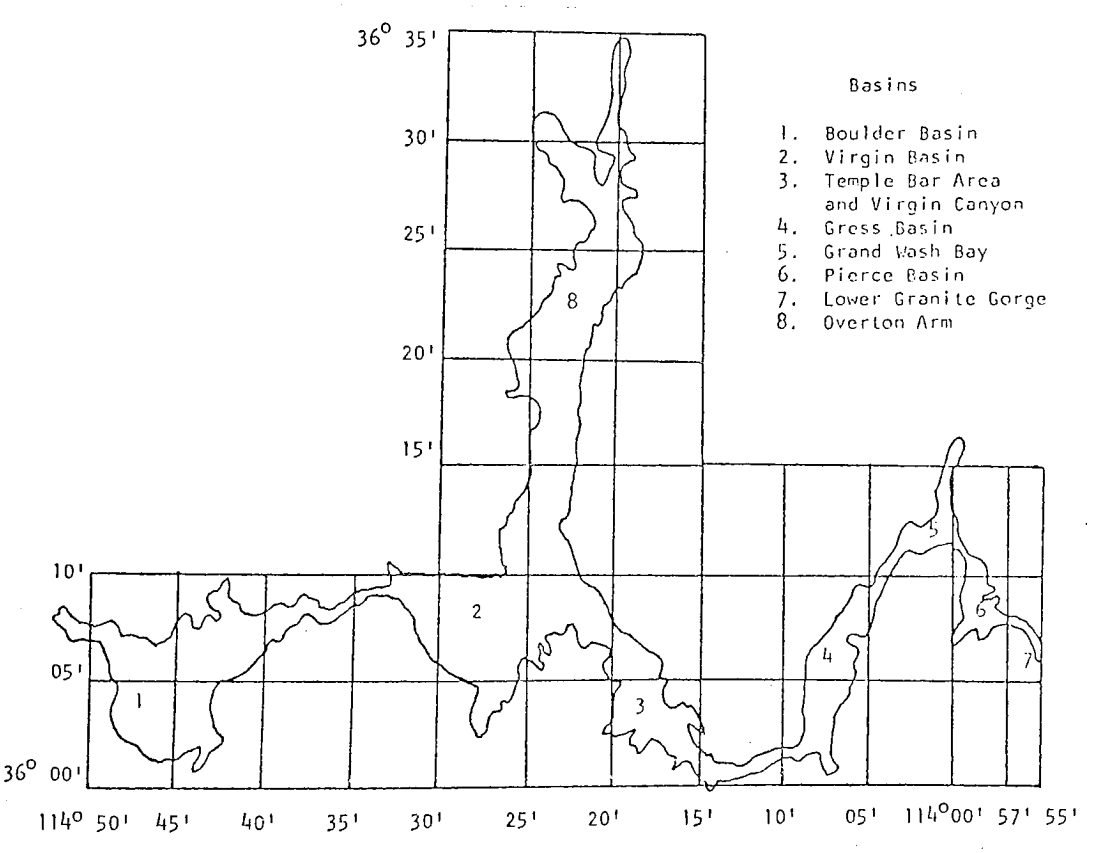


Figure 14. Map of Lake Mead Showing Basins

The water in Lake Mead is derived from one major source, the Colorado River, and three minor sources, the Muddy and Virgin Rivers and Las Vegas Wash. Earlier reports by the EPA (1968a) indicated that the upper reaches of Lake Mead had a limited algal population because sediments cause reduction of light penetration and adherence of particles to the algal cells, thus speeding their settling to the bottom. Nutrient contribution of the Colorado River to the upper reaches of Lake Mead is of concern.

The Colorado River contributes a mean April discharge of 15,200 cfs for 98 per cent of the total flow into Lake Mead. A seasonal oscillation in salinity at the Grand Canyon Station shows considerable watershed effect (Figure 15).

The Virgin River flowing into the northern end of the Overton Arm is characterized by large amounts of silt transported from the watershed. Although the mean April flow is about 246 cfs, the Virgin River contributes only 1.5 per cent of the flow and 2 per cent of the soluble phosphorus to Lake Mead. The yearly cycle of salinity increase indicates the contributions of salts from surface runoff (Figure 16).

The Muddy River flowing into the northwest end of the Overton Arm behaves much like the Virgin River on a lesser scale. The mean April flow of 38 cfs accounts for

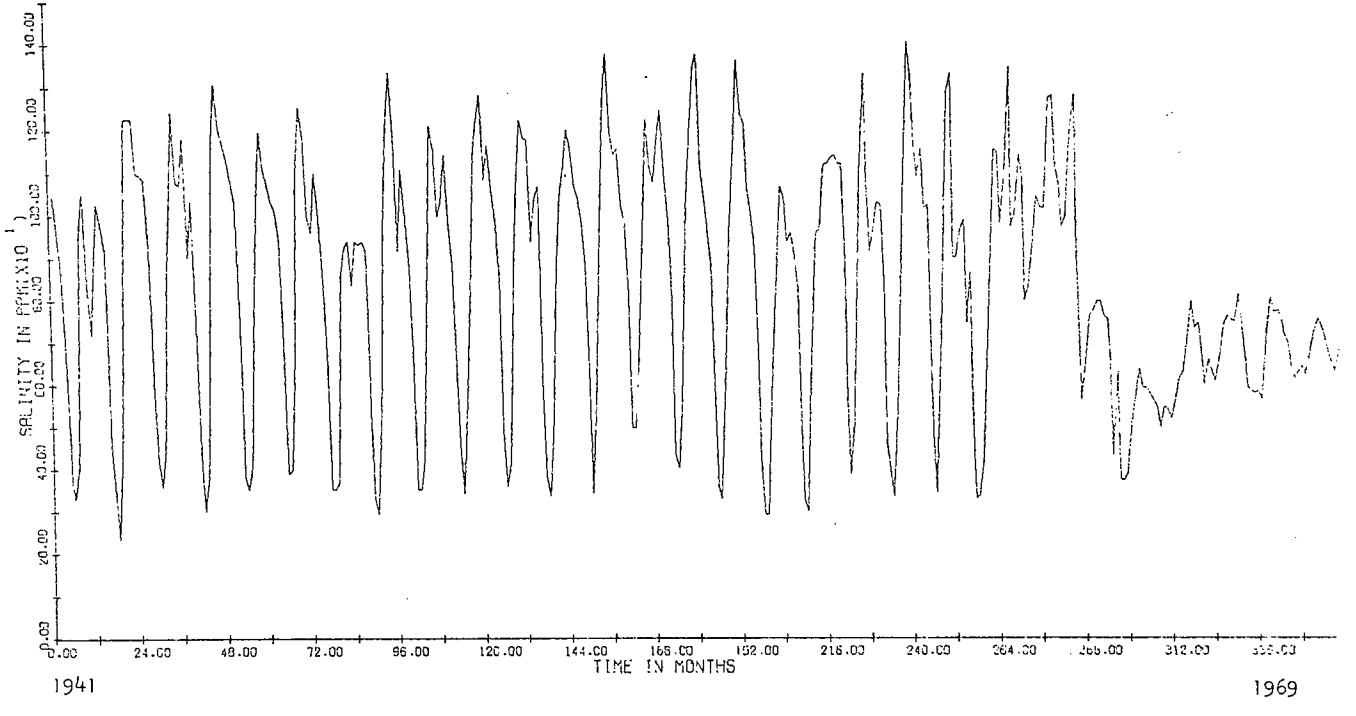


Figure 15. Salinity Values at Grand Canyon -- After Slawson (1972).

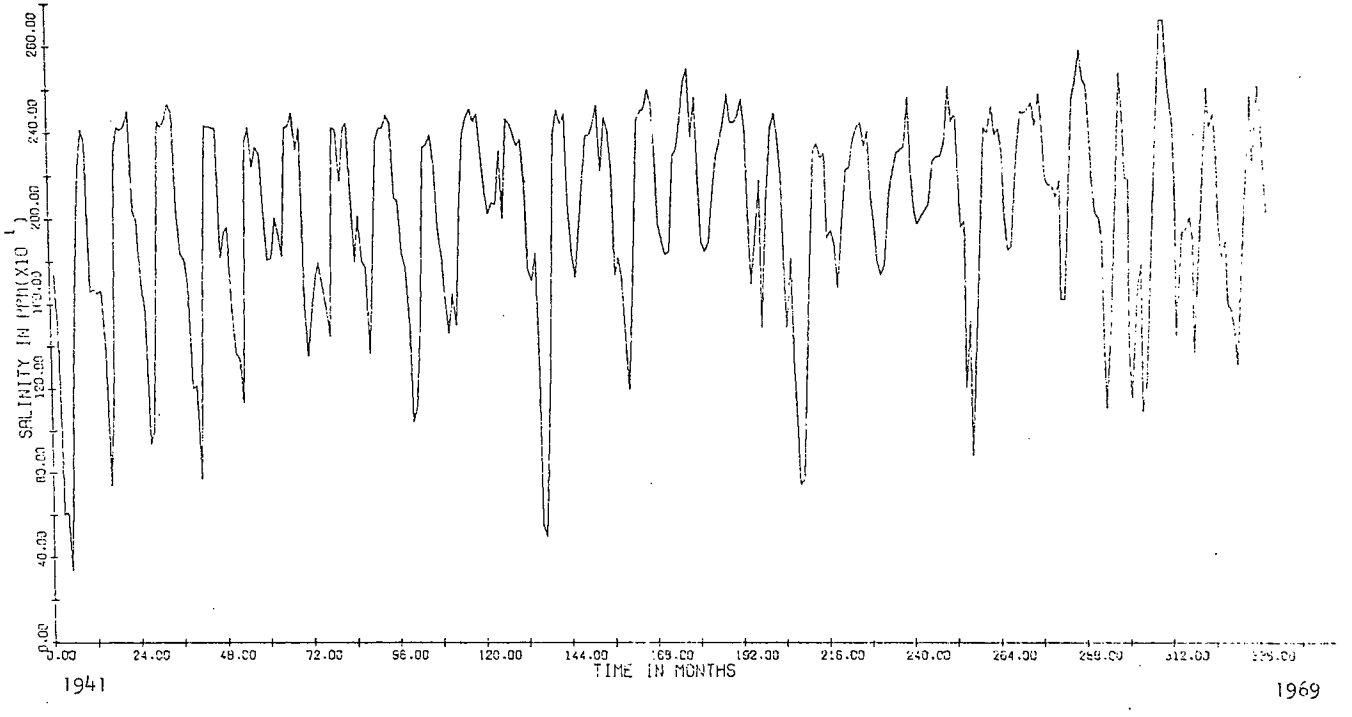


Figure 16. Salinity Values at the Virgin River -- After Slawson (1972).

one per cent of the total phosphorus and .3 per cent of the flow into Lake Mead.

Las Vegas Wash contributes about 35 per cent of the total soluble phosphorus to Lake Mead. The Wash has a mean April flow of 31 cfs and accounts for .2 per cent of the water input to the Lake. The discharge from Las Vegas Wash shows a definite seasonal oscillation with the highest flows occurring in the winter. One of the reasons for the increase in flow is the seasonal rainfall. The major reason is the influx of tourists who come to Las Vegas for the warm sunny winters. The 1971 report by Everett on the cause-effect relationship of Las Vegas shows a strong increasing trend in the discharge from Las Vegas Wash for the years 1959 to 1969.

Recreational Uses

The Lake Mead Recreation Area is a popular water-sports area. Much of the human influx is from tourist-oriented Las Vegas, Nevada. All commercial channels are being explored to bring Las Vegas guests to the reservoir. Although sightseeing is the most popular visitor activity, swimming, boating, water-skiing, and fishing are an important part of the recreational use. The Bureau of Reclamation provides guided tours through Hoover Dam. Over 615,000 visitors inspected the Dam in 1969.

The National Park Service (NPS), Boulder City, is responsible for the administration of the Lake Mead Recreation Area. The NPS has provided fourteen boat-launching ramps, two supervised swimming beaches, and has twelve concessions operating in the area. There are seventeen campgrounds and twenty-four picnic shelters around the Lake. Visitor use to the Lake Mead National Recreation Area in 1969 was over 6 million (Hoffman and Jonez, 1971).

Las Vegas Bay is heavily used for water-based recreation, including water contact sports. A marina is located on the Bay near the mouth of Las Vegas Wash. Excessive algal growths are causing distinct green color, odors, and nuisance conditions.

CHAPTER 4

EXPERIMENTAL DESIGN AND METHODOLOGY

State Estimation

The investigation at Lake Mead was directed toward providing some insight into a number of practical and academic problems. The simplest problem was to establish a station at Las Vegas Bay to monitor chemical, biological, and some hydrodynamic processes to provide a baseline for in-progress fish studies directed by Dr. J. Deacon, University of Nevada at Las Vegas.

The second problem was to determine the relative behavior of different parts of Lake Mead to quantify the extent of existing pollution in the reservoir. This was done by distributing the sample locations over the reservoir.

The third and most complex thrust of the study was to characterize the system through an analysis of state sets (Figure 17). To establish a state set of the system we had to quantitatively measure all of the "important" variables (chemical, biological, and hydrodynamic) at one time, at one depth, and at one location. Each state set was in fact an "in situ" bioassay. This insured that the change of state and the biological response had occurred under natural conditions. An intensive literature search

STATE SETS

Class I:	Variables	30
	Depths	2
	Times	6
	Locations	8

Number of State Sets in Class I: 2 x 6 x 8 = 96

Class II:	Variables	14
	Depths	8
	Times	6
	Locations	8

Number of State Sets in Class II: 8 x 6 x 8 = 384

Class III:	Variables	11
	Depths	10
	Times	6
	Locations	8

Number of State Sets in Class III: 10 x 6 x 8 = 480

Class IV:	Variables	2
	Depths	31
	Times	6
	Locations	8

Number of State Sets in Class IV: 31 x 6 x 8 = 1488

Figure 17. Four Classes of State Sets Investigated

resulted in a list of parameters that would describe the state of the system. Financial limitations resulted in the measurement of 30 independent variables, and 3 dependent variables. The dependent variables include: (1) time, (2) space, and (3) depth.

The independent variables (Figure 18) include biological, chemical, and physical parameters. The trade-offs associated with the sampling design in the Lake Mead investigation are typical. The advantages of the sampling method include: (1) reduced cost, (2) greater speed, (3) greater scope, and (4) greater accuracy.

The sampling theory suggests that it costs less to sample a small fraction of the aggregate. Sample data are inherently from a smaller volume and can result in information more quickly. A larger problem (scope) can be handled by small flexible sample programs. Since personnel of higher training can be directly in control of reduced work volume the accuracy of the results may be improved.

The steps recommended by Cochran (1963) in a sample survey should include: (1) objectives of the survey, (2) population to be sampled, (3) data to be collected, (4) degree of precision desired, (5) methods of measurement, (6) the frame (list of sampling units), (7) selection of the sample, (8) the pretest, (9) organization of the field work, (10) summary and analysis of data, and (11) information gained for future surveys. The sampling design in the

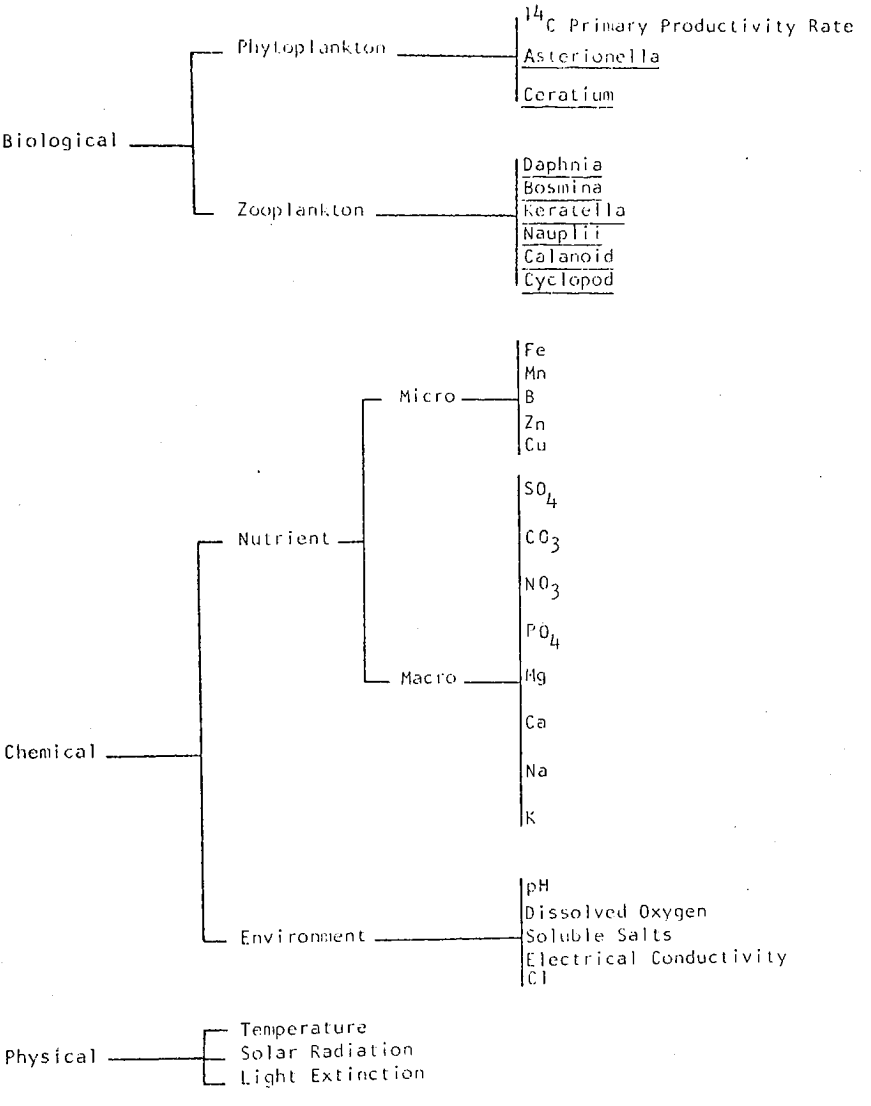


Figure 18. Independent Variables Investigated

Lake Mead investigation closely followed the steps listed above. Of greatest value in the list was the pretest carried out on Lake Mead in June, 1969. The chemical and biological results of the brief feasibility study not only provided insight into the changing parameters but also provided information for steps 2 through 9.

There are two approaches in a systematic sample design program. The first approach is an ex ante design, before the fact, based upon past and current knowledge of the system. The second approach involves an ex post design, after the fact, in which the results of a completed investigation can be used to evaluate the original sample design. Too often the ex post evaluation of the sample design is neglected at the end of an investigation.

Of major concern in the sample survey was the data network density. Since the feasibility study indicated considerable changes across the Lake, inputs to each of the basins of the Lake had to be monitored. Since all costs of transportation were absorbed by the Bureau of Reclamation, the major criterion for the sample site location was ex ante data provided by subjective attitudes that were modified by the feasibility study.

There was no compromise between the data network density and frequency of temporal sampling. The spatial distribution was foremost in our criteria. It was assumed that temporal changes would uniformly alter the magnitudes

of the ppr over the entire set of spatial sampling points. Since the time of thermal stratification and degeneration was not known, we were satisfied to sample once during the summer stable period and once during the winter instability period. The other sample dates were determined primarily by cost and convenience of those participating (i.e., holidays). The hydrodynamics of the Lake were (and are) poorly understood and so did not generally influence the exact times of sampling. More studies, however, are necessary in this direction.

Most investigators including Patrick (1971) concluded that laboratory manipulation of parameters introduces error. Patrick's work with the manipulation of light and temperature concluded that artificial light does not bring about as great an increase in diatom development as natural light. Patrick felt that optimum conditions for light and temperature form a fairly narrow range within the range of tolerance. Increases in temperature near the lower end of the range of tolerance improved the structure of the diatom community significantly while increases near the upper end of the range of tolerance produced severe degradation in community structure. Sampling locations were selected using the criteria of maximizing the number of sets of states. In other words, to maximize the interpretive quality of the data. The experimental design is

given in Table 5. The locations of sampling are shown on the map (Figure 19).

Sampling Dates

Field investigations were made from the summer of 1970 to the winter of 1972. The survey dates and season of the year are given in Table 6.

By scheduling the surveys as described above, data were collected during periods of the Lake's annual temperature cycle. The June and September surveys were indicative of thermal stratification while the other dates were designed to note the effects of winter and spring mixing.

Sampling and Measurements

Each of the eight water-quality stations was sampled identically. All water samples for analysis were collected using three- and six-liter, polyvinyl-chloride (PVC) Van Dorn samplers. The PVC sampler precludes any ion exchange. Methods of sampling and measurements are as follows:

1. Continuous temperature profiles to 54 meters were obtained using a Precision Scientific temperature probe.
2. The DO continuous readings were taken from a galvanic-cell oxygen analyzer manufactured by Precision Scientific. The meter was calibrated each day using the Azide-Modification of the

Table 5. Experimental Design -- See Map, Figure 19.

(S)	Stations	Las Vegas Wash	Bureau of Reclamation Raft	Beacon Island	Bonelli Landing	Echo Bay	Overton Arm	Temple Bar	South Cove
(n)	Depths(m)	0-31	0-31	0-31	0-31	0-31	0-31	0-31	0-31
(t)	Times	5	6	6	6	5	6	6	6
	Sets of State = Snt	5n	6n	6n	6n	5n	6n	6n	6n
(m)	Variables	30	30	30	30	30	30	30	30

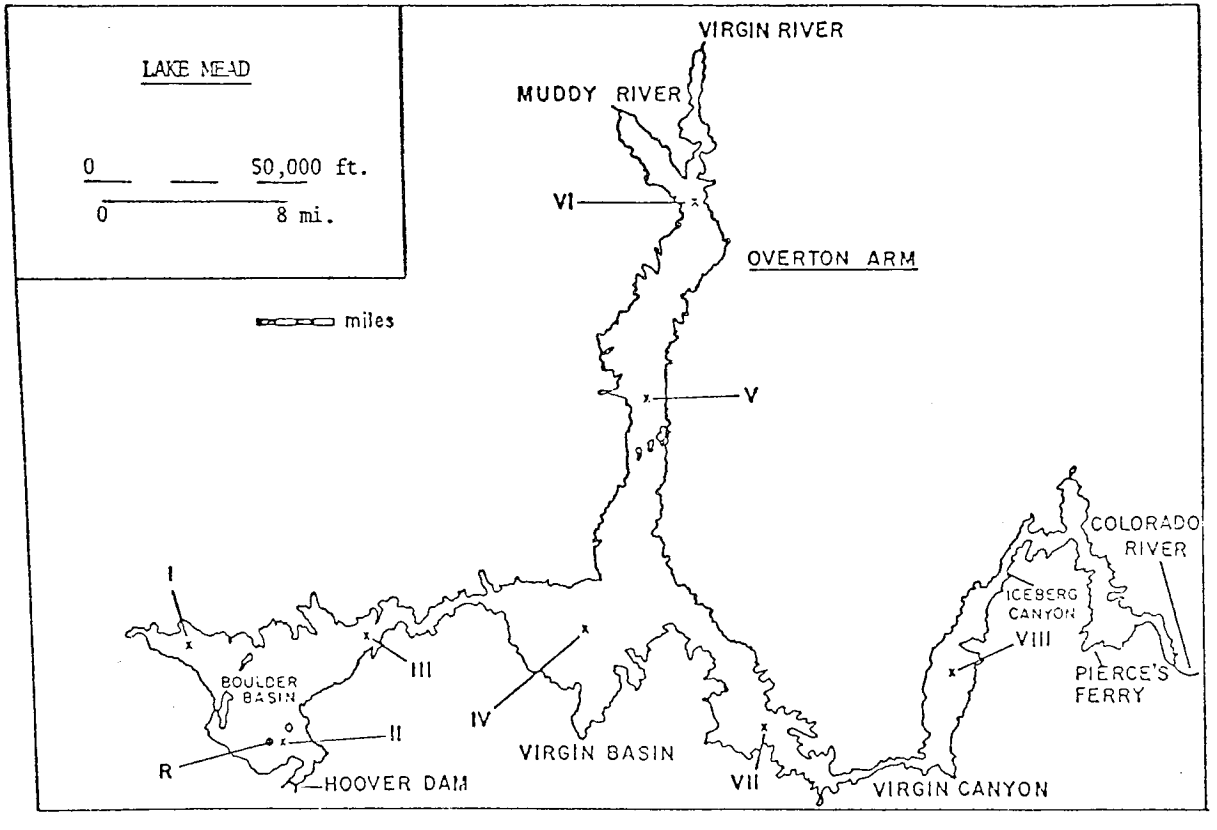


Figure 19. Location Map of the Sampling Stations on Lake Mead

Table 6. Survey Dates and Seasons

Season	Dates
Summer	September 6-11, 1970
Fall	November 24-29, 1970
Winter	January 23-27, 1971
Winter	February 25-27, 1971
Spring	April 3-8, 1971
Summer	June 4-8, 1971
Winter	January 8-13, 1972

Winkler technique as presented by Standard Methods (American Public Health Association, 1971).

3. A portable Beckman Electromate pH meter was used to obtain the hydrogen ion levels. The pH meter was also used to obtain the alkalinity values as described by Standard Methods (American Public Health Association, 1971).

4. Chlorophyll samples at five and thirty meters were taken. Two milligrams of magnesium sulphate were added to 1,000 ml of water and filtered through a .45-micron membrane filter.

5. Complete chemical analysis (Figure 18) was done on a 1-liter sample. The samples were kept in dark

glass bottles which had been washed with a dilute acid solution. Since micro-elemental analysis was also done, no preservatives were added. Samples for chemical analysis were taken at five and thirty meters.

6. Phytoplankton and zooplankton samples were taken at 0, 1, 3, 5, 7, 10, 15, 20, 25, 30, and 35 meters. The phytoplankton sample was placed in a six-dram vial and preserved with Lugol's reagent. Each of the zooplankton samples were concentrated from a six-liter sample to six drams using a fine mesh. A ten per cent formalin solution was used to preserve the zooplankton.

7. Light transparency was measured with a photo-electric cell rather than a Secchi disc. The cell gives considerably more accurate results and is corrected for changes in solar radiation. Also, the cell affords the opportunity to locate turbidity layers. Since this study was primarily concerned with the photic zone, we required an accurate light meter to determine the compensation depth. The compensation level is the depth at which one per cent of the incoming solar radiation can be measured.

8. Solar radiation was measured with a Belfort recording pyrheliometer that was calibrated each day with an Eppley pyranometer.

Primary Productivity--^{14}C Method

To determine the total algal production in a given water column, it is necessary to run a vertical series of measurements with samples from various depths. Each depth is subject to different light, temperature, etc. conditions and is indicative of a separate state. Water samples were taken at 0, 1, 3, 5, 7, 10, 15, and 20 meter depths using a 3-liter PVC Van Dorn sampler. The PVC sampler precluded any contact with bare metal which may be either detrimental to the algae (Doty and Ouri, 1958) or stimulating (Goldman, 1963). The water sample at each depth was divided into three containers: 125 ml light and dark bottles and a 500 ml sample for alkalinity and pH values. The transparent light bottle permitted the incoming solar energy to act on the chlorophyll, thus permitting photosynthesis. The dark bottle excluded all penetrating light. Care was taken not to expose water samples taken at any depth to the surface solar radiation since the intensity creates light injury to the phytoplankton. To protect the phytoplankton from light shock, the light bottles were placed in black covers during preparation periods and were kept in wooden boxes painted black on the interior and white on the exterior.

The principle used in the ^{14}C technique is the incorporation of a tracer (^{14}C) in the organic matter of phytoplankton during photosynthesis which is a measure of the rate of primary production. If the content of total

CO_2 of the experimental water is known, and if a definite amount of ^{14}C is added to the water, then by determining the content of ^{14}C in the plankton after the experiment the total amount of carbon assimilated can be calculated (Vollenweider, 1971).

From the alkalinity and pH determination the amount of C_{12} in the water is found. To the light and dark bottle .5 micro-curies of ^{14}C was added to the bottom of each bottle with a hypodermic needle and long cannula. The bottles were shaken by hand, stoppered, and returned via a calibrated line to the same depth, light, temperature, etc. condition for the incubation period.

The bottles were placed in the water as close to 10:00 a.m. as possible and removed after a four hour interval. The experimental bottles were withdrawn from the various depths and stored in a black box until the beginning of the filtration operation. The bottles were removed as quickly as possible from the water to reduce light energy and further photosynthesis. Fifty ml aliquots were then transferred through a filtration apparatus from the light and dark bottles onto 0.45 micron Millipore membranes. The samples were filtered as soon as possible after removal from the water. The filtration apparatus was connected to a negative pressure hand pump. Care was taken to rinse the 50 ml graduate cylinder and aspiration funnel to insure that all radioactivity passed onto the

membrane. After removal of the filters from the filtration unit they were placed onto waxed paper and stored until returned to the University.

CHAPTER 5

RESULTS AND DISCUSSION

Data Description

Up to the commencement of this study, available data were collected without coordination. It is fragmentary and of no utility for diagnostic purposes. Therefore, there was no quantitative understanding of the behavior of the systems and the stages leading to present conditions. The reasons for the limited value of previous investigations are: (1) the restricted spatial sampling, (2) the limited temporal sampling, and (3) the lack of essential information for identifying eutrophication trends.

Temperature

The annual temperature regime in Lake Mead describes a warm monomictic cycle. These lakes have a water temperature which is never below 4°C and freely circulate during the winter at or above 4°C. One of the typical temperature regimes is presented in Figure 20 for the Beacon Island station.

Thermal stratification is well documented in Lake Mead. In the summer months the solar radiation warms the surface waters of the reservoir. The warm water is less

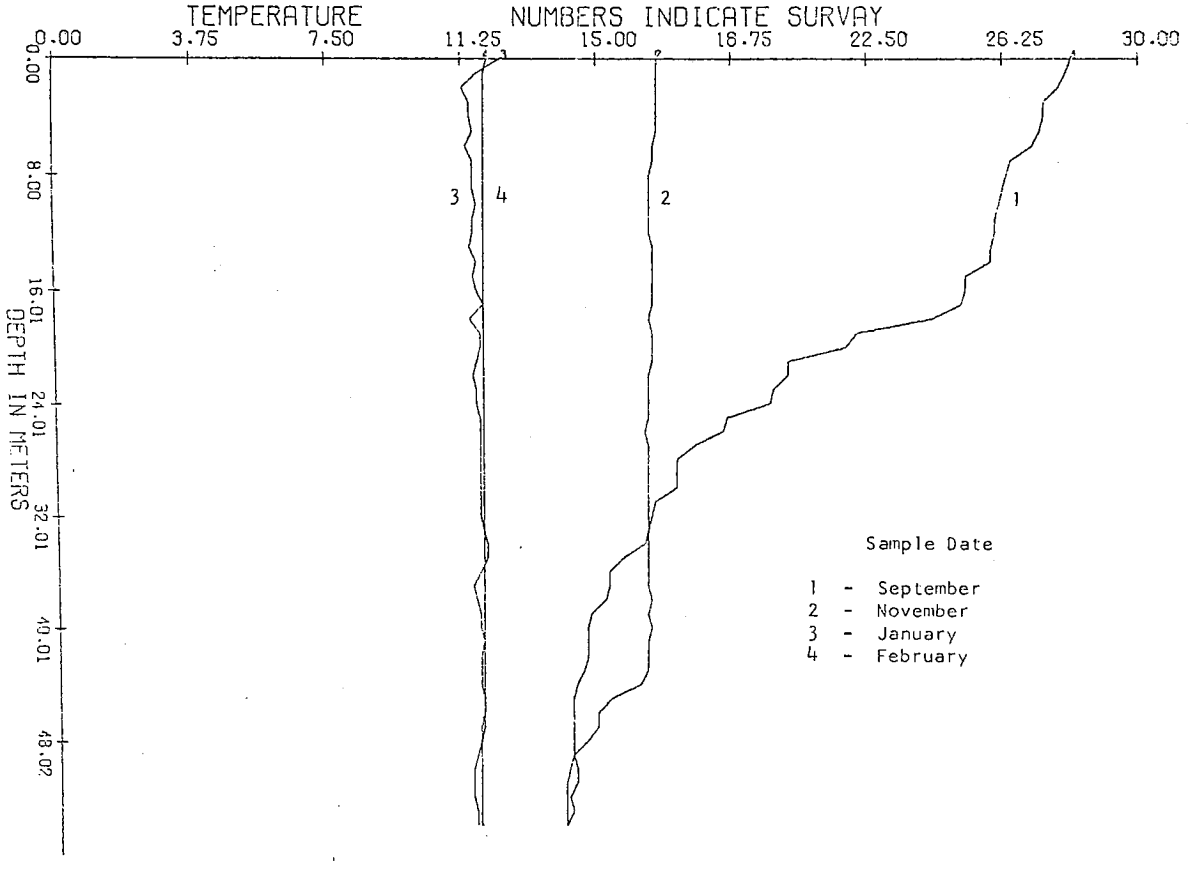


Figure 20. Temperature Cycle at Beacon Island

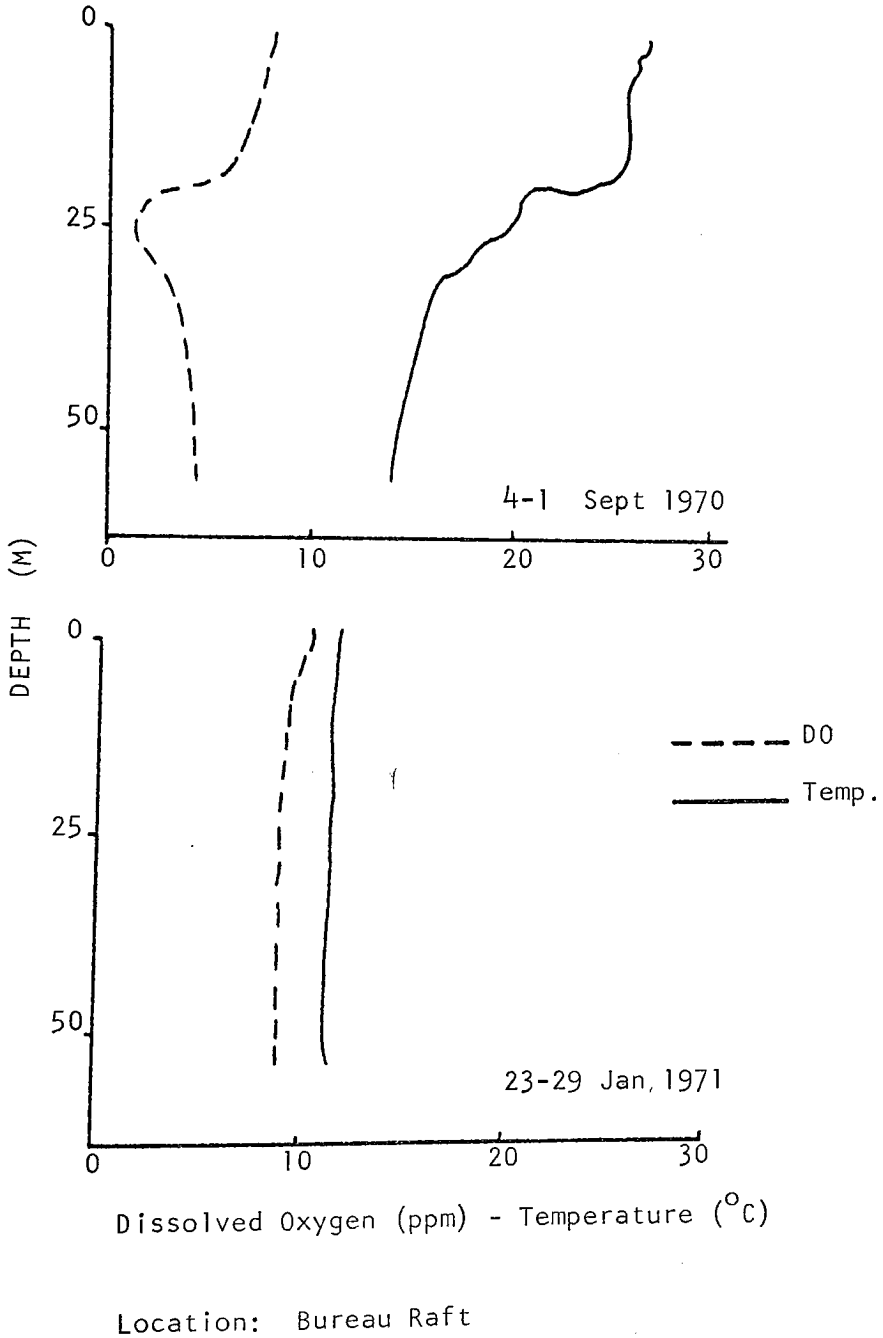
dense than the cooler bottom waters resulting in a thermal density layer.

Since water is a very poor conductor of heat, we generally observe a summer temperature profile as seen in Figure 21. The discontinuity layer is called the thermocline. It is characterized by a drop of 1°C in temperature for each depth increase of one meter. The upper warm layer of water is referred to as the epilimnion. The dense cooler waters below the thermocline are called the hypolimnion.

The temperature range was 10.1 to 28.4°C, with November, January, and February temperature profiles showing the isothermous nature of the Lake during winter turnover. It is at this time that nutrients released in the anaerobic hypolimnetic layers of summer are brought to the surface. The homogeneous winter temperatures are 11 ± 1°C. The June figures indicate the beginning of the thermocline. In September we can distinguish between the epilimnion, thermocline, and hypolimnion at each station. The thermocline in September was found between 18 and 28 meters and had a temperature range of 17 to 26°C.

Dissolved Oxygen (DO)

The dissolved oxygen cycle in Lake Mead can be described as a negative heterograde scheme (Figure 21). In this case we observe a minimum DO in the thermocline with



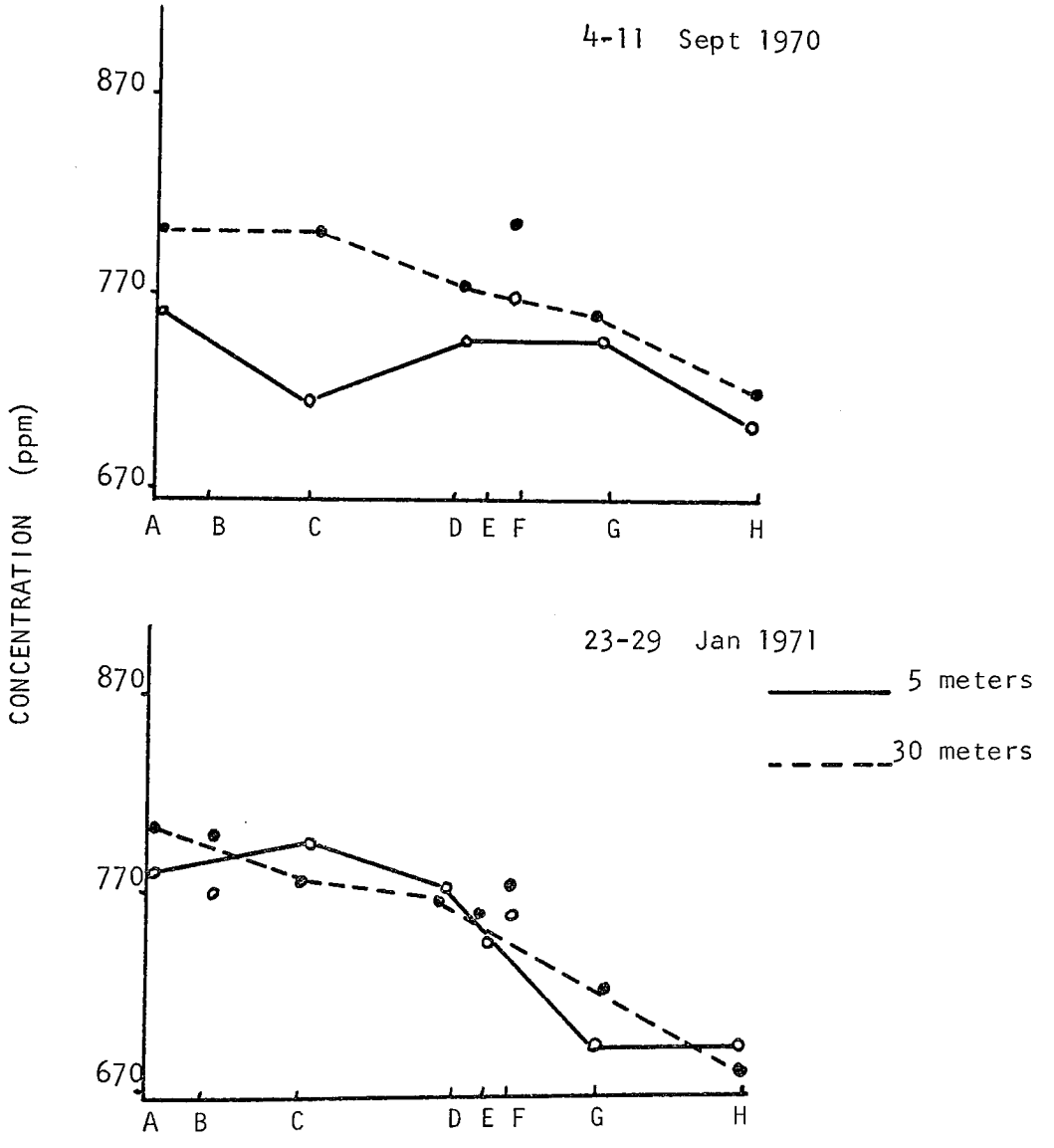
Location: Bureau Raft

Figure 21. September and January Dissolved Oxygen and Temperature Profiles

higher saturations in the epilimnion and hypolimnion. The DO pattern is similar at all stations during the seasonal changes. The range of DO is 1.8 to 13.0 ppm. The November, January, and February DO isopleths indicate that the winter turnover is reaerating the system. The September charts, however, show that the Lake goes into stress in the hypolimnion during summer stratification. DO values of two ppm at the thermocline depth indicate a high Biochemical Oxygen Demand (BOD). Since the DO level recovers from this zone of high oxygen demand we postulate that high levels of organic matter are oxidized at the thermocline level. As the algae sink under gravity they meet the denser cold waters capped by the thermocline. Here bacteria break the algae down, releasing ions, and using up DO through respiration. The DO levels in the hypolimnion in September are considerably below the recommended level for cold-water fish regeneration.

Soluble Salts

The September data (Figure 22) indicate across all the stations that with a well-developed thermocline we observe the highest values for soluble salts at 30 meters in the hypolimnion. There is approximately a 100 ppm increase in soluble salts from South Cove to the Bureau raft at all seasons of the year. During winter turnover the 5- and 30-meter values are very close. The range of soluble



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 22. September and January Soluble Salt Concentrations

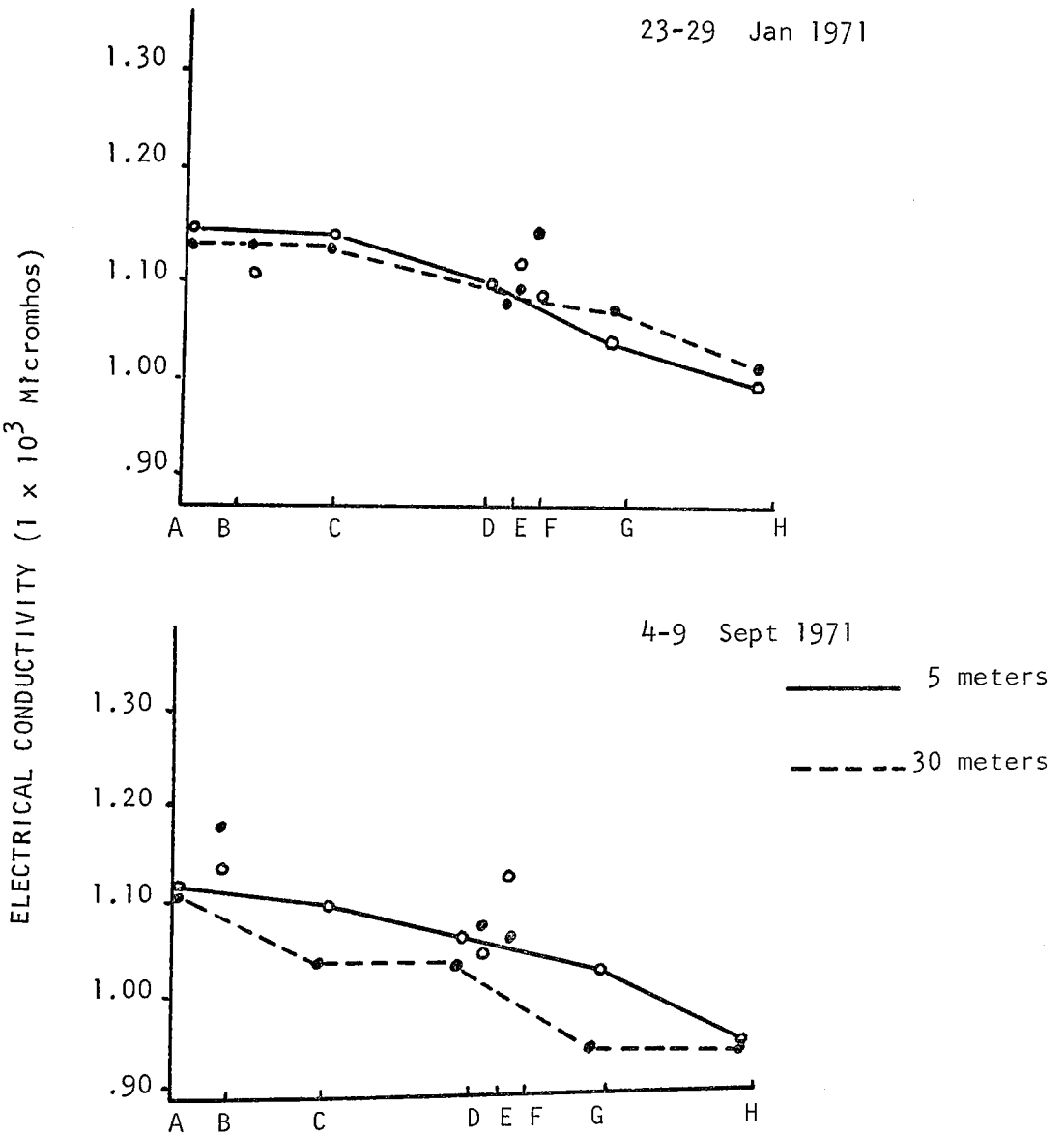
salts is from 600 to 840 ppm. The soluble salts in Vegas Bay do not appear to seriously increase the level at the raft. Higher jumps in soluble salts are noted between South Cove and Temple Bar.

Electrical Conductivity (EC)

EC does not appear to be affected by thermal stratification (Figure 23). There is a conductivity range of about 0.20×10^3 micromhos at each station throughout the year. The EC ranges between 0.95 and 1.25×10^3 micromhos over the eight stations. The specific conductance of an oligotrophic lake is less than 200 micromhos at 18°C. These levels of specific conductance place Lake Mead deep into the range of a eutrophic lake. Conductivity, however, is a very weak index of eutrophication.

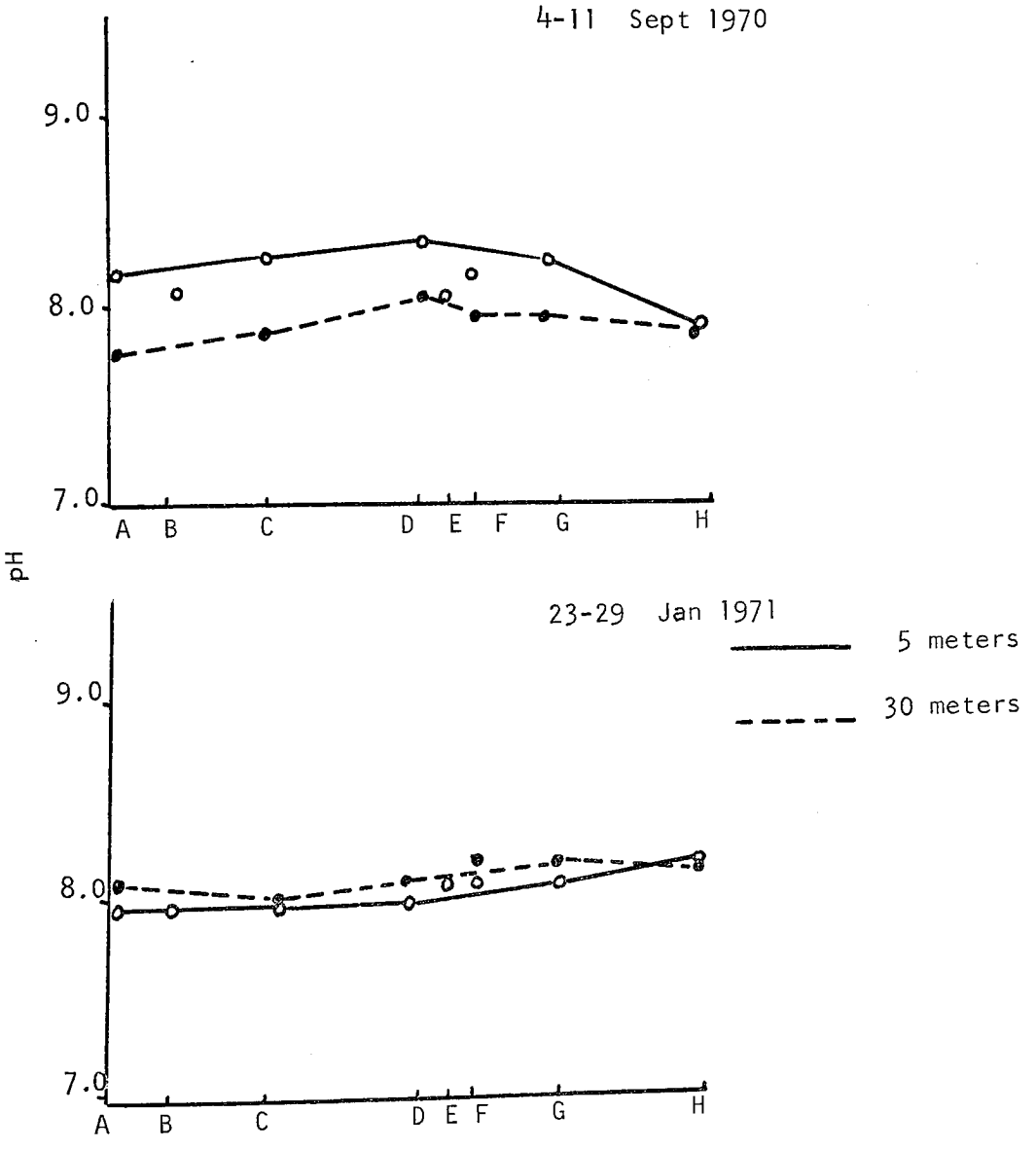
Hydrogen Ion Concentration (pH)

The pH generally decreases slightly across the basins (Figure 24). During summer stratification the lower pH values were consistently found in the hyplolimnion. The pH ranged between 7.8 and 8.4. We noted that the Las Vegas Wash station does not appear to be affecting the pH levels in Boulder Basin. There has been some debate as to the industrial effect on the pH of the groundwater in Boulder Basin.



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 23. January and September Values of Electrical Conductivity



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 24. September and January pH Changes

Chloride, Magnesium, Potassium, Sodium, and Calcium

Each of these elements appear to increase across the basins. This is primarily a result of salt loading and salt concentration. All of these elements except Mg appear to have much lower September values in South Cove. However, the levels of these element nutrients are very high. The level of chloride is five times as high as found in Lake Erie (Figure 25). The calcium levels show a strong response to thermal stratification (Figure 26).

Phosphate

The ortho-phosphate levels found in Lake Mead fall in the range of an oligotrophic lake (0.1 to 0.3 ppm). Boulder Basin appeared to be richer in PO_4 than Virgin Basin (Figure 27). The PO_4 levels at South Cove drop across Gregg's Basin. This could be a result of complexing and sedimentation or increased primary productivity. The minimum ortho-phosphate level for excessive crops of algae is equal to or greater than 0.01 ppm (Lee, 1970).

Nitrate

The nitrate values are much higher in September and November. There is no increase or decrease across the system; therefore, the Colorado River is responsible for introducing these high levels (Figure 28). The minimal nitrogen content for excessive algae bloom must be equal to

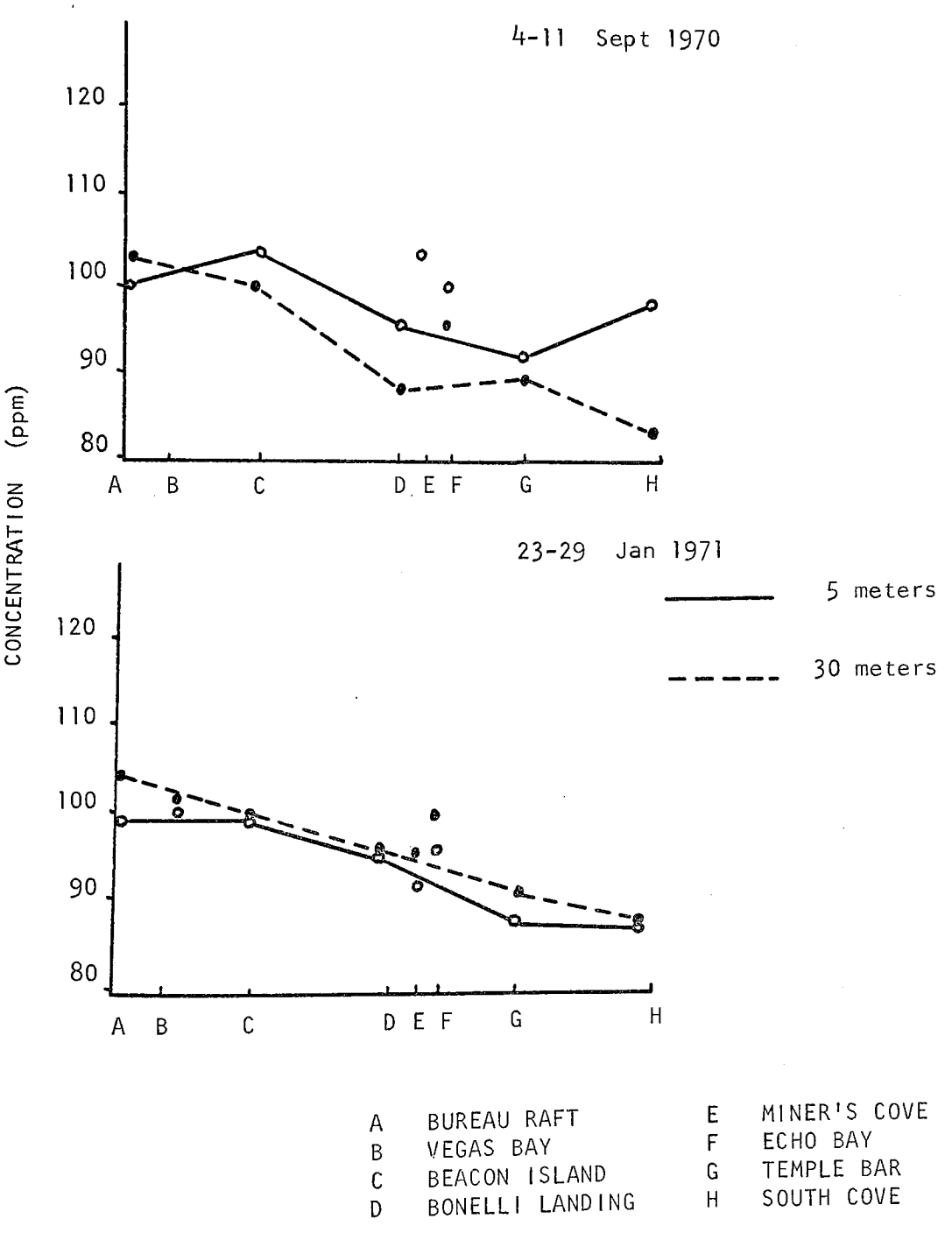
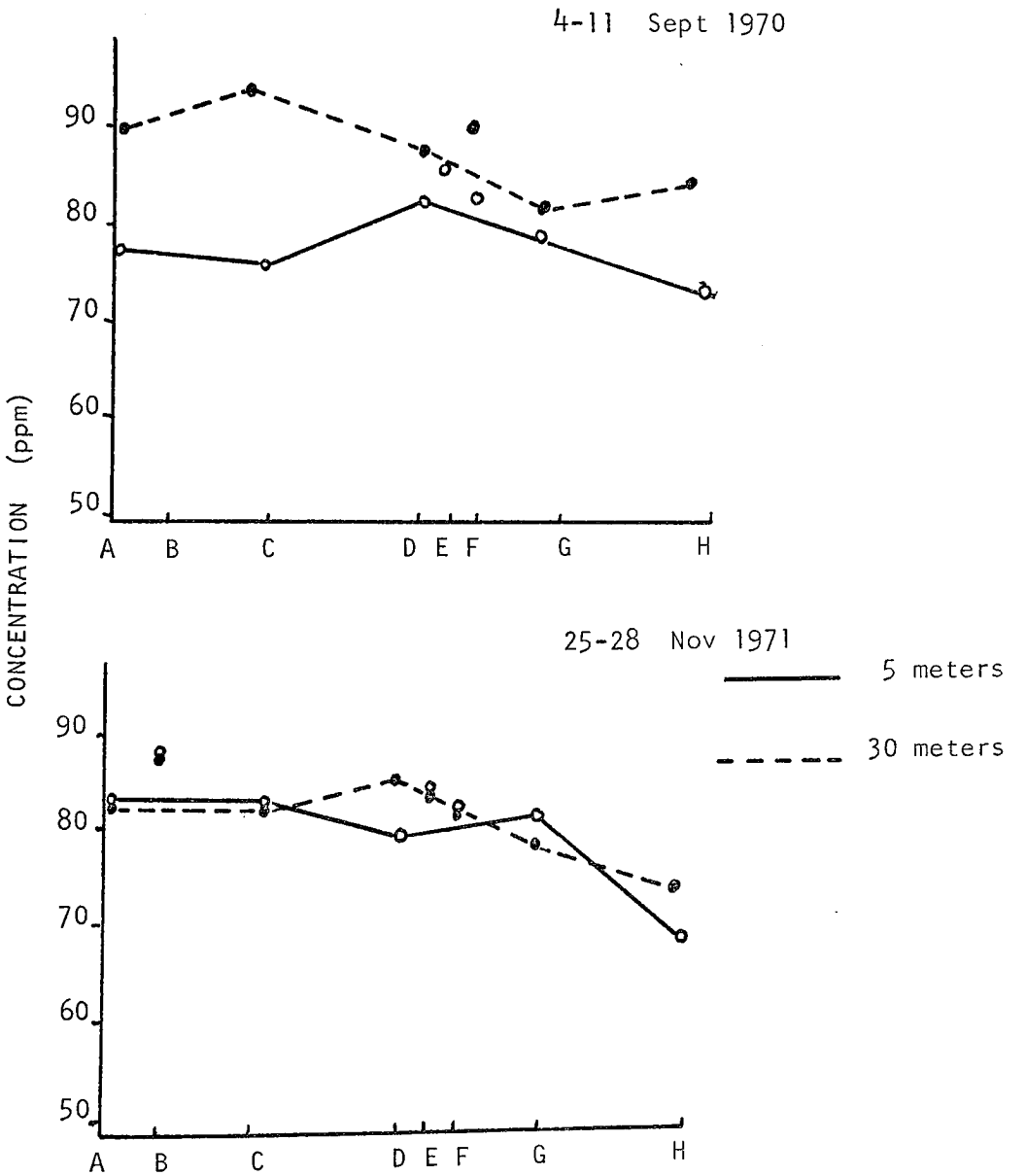


Figure 25. September and January Chloride Concentrations



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 26. September and November Calcium Concentrations

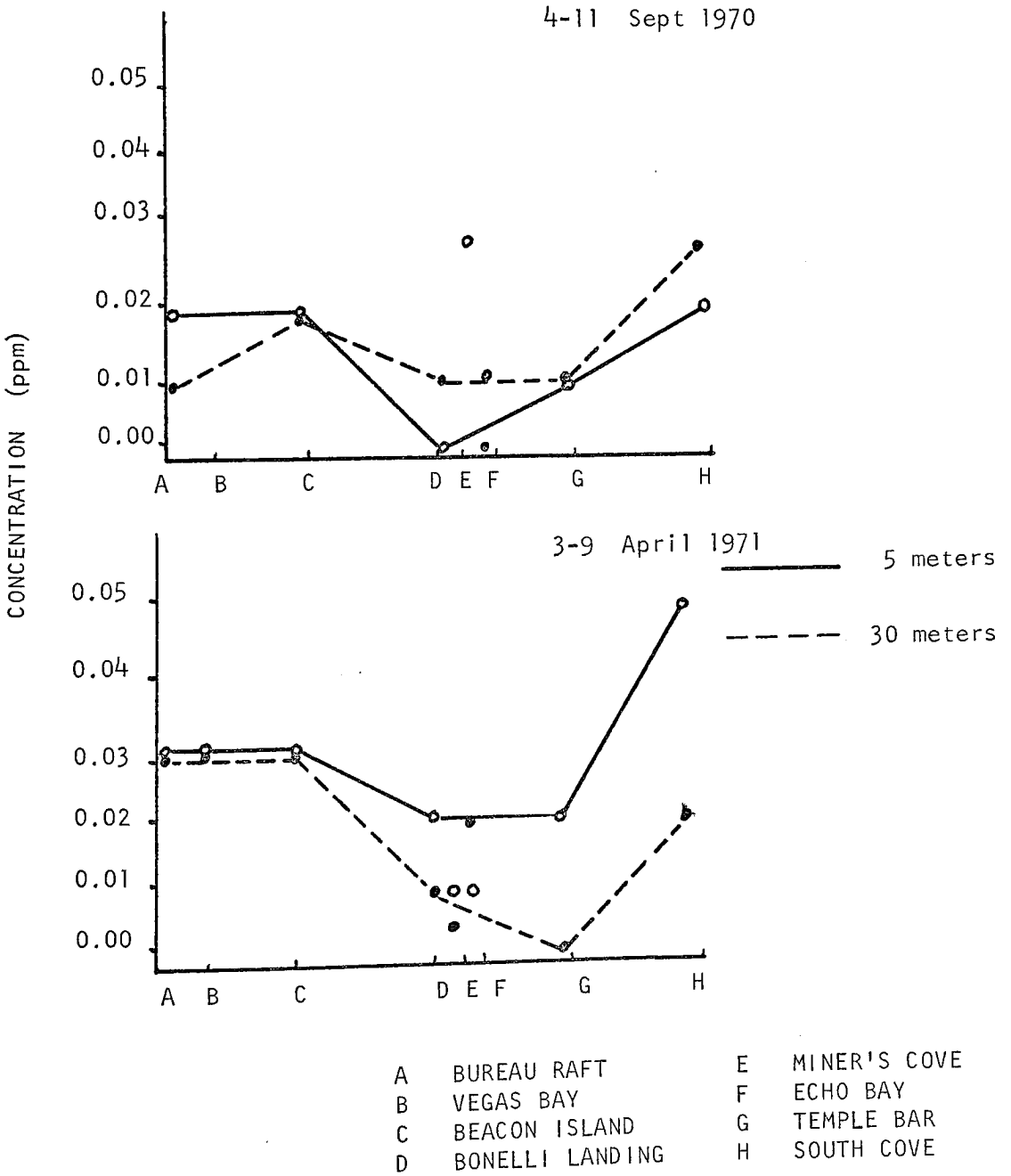
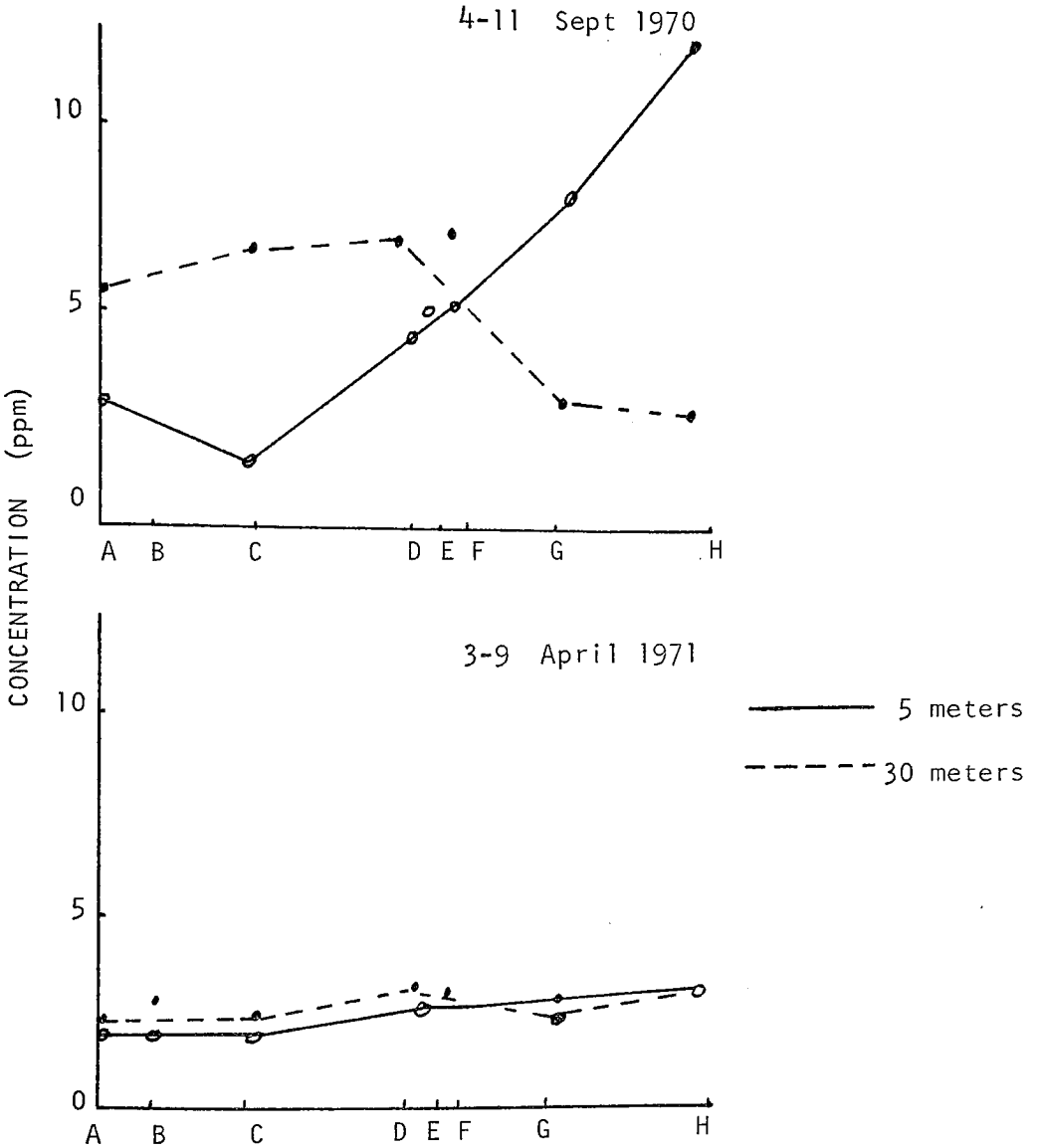


Figure 27. September and April Phosphate Levels (PO_4)



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 28. September and April Nitrate Concentrations

or greater than 0.3 ppm (Lee, 1970). Excessive nitrogen is available at all times of the year. Boulder Basin does not contribute excessive nitrate values.

Bicarbonate

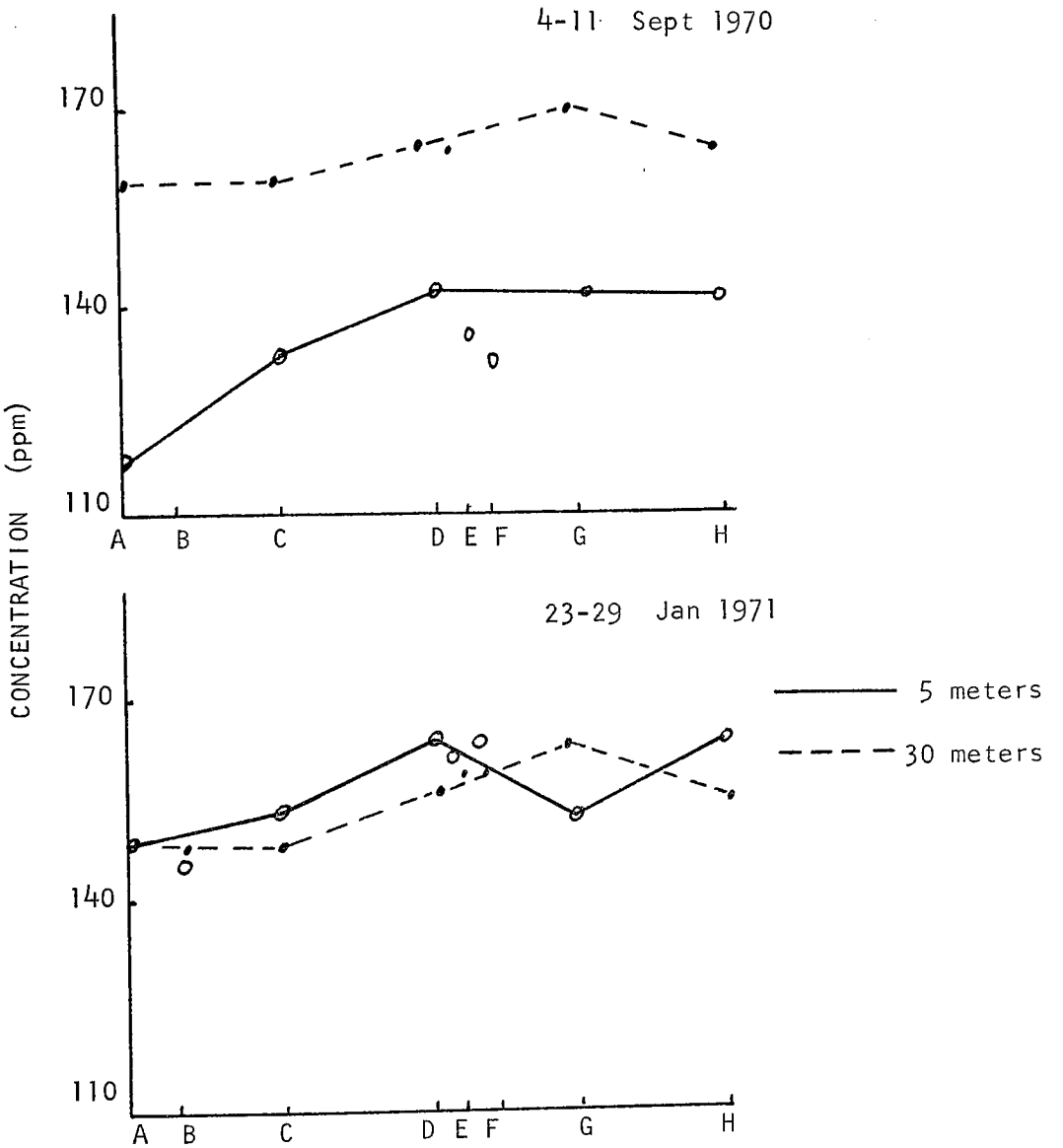
The bicarbonate (HCO_3) values show excellent response to thermal stratification in September (Figure 29). The higher values are found 30 m beneath the surface. The trend is toward reduced HCO_3 values across the Lake. The summer levels are 10-15 ppm less than the cool winter turnover values. Excessive HCO_3, based on ppm data, is available throughout the year. The carbonate levels read zero at all times of the year.

Iron, Manganese, Zinc

These elements do not show a consistent trend across the system. Manganese is available in the optimal range. The iron and zinc levels do not appear to be limiting. The highest zinc values were repeatedly recorded at Beacon Island (Figure 30). Although the levels of micronutrient requirements in not known, their presence in the ppm range is taken as evidence of their availability.

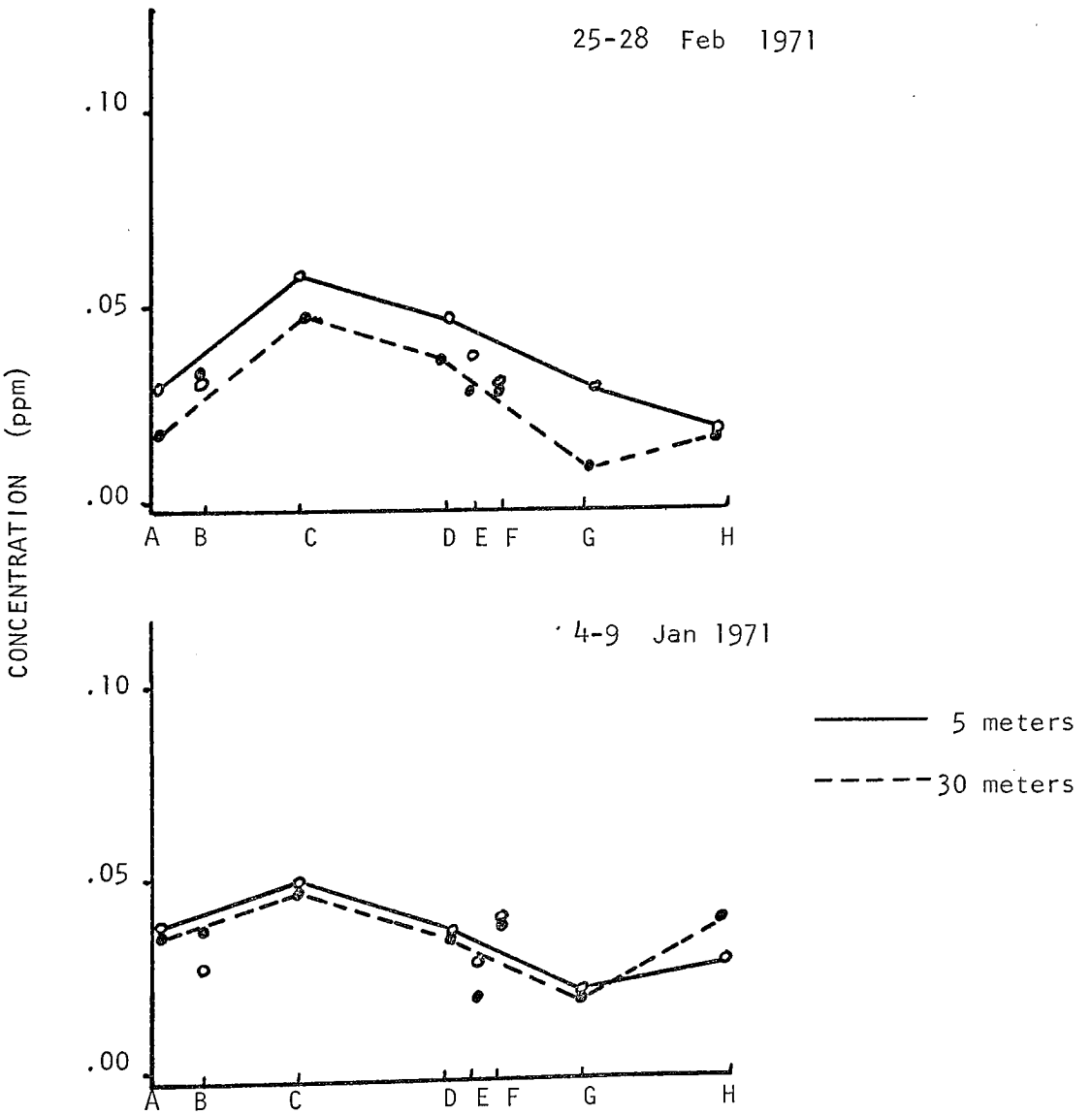
Copper

The copper levels do not appear to follow any trend (Figure 31). Generally copper is toxic to all algae at concentrations greater than 0.05 ppm (Hutchinson, 1967).



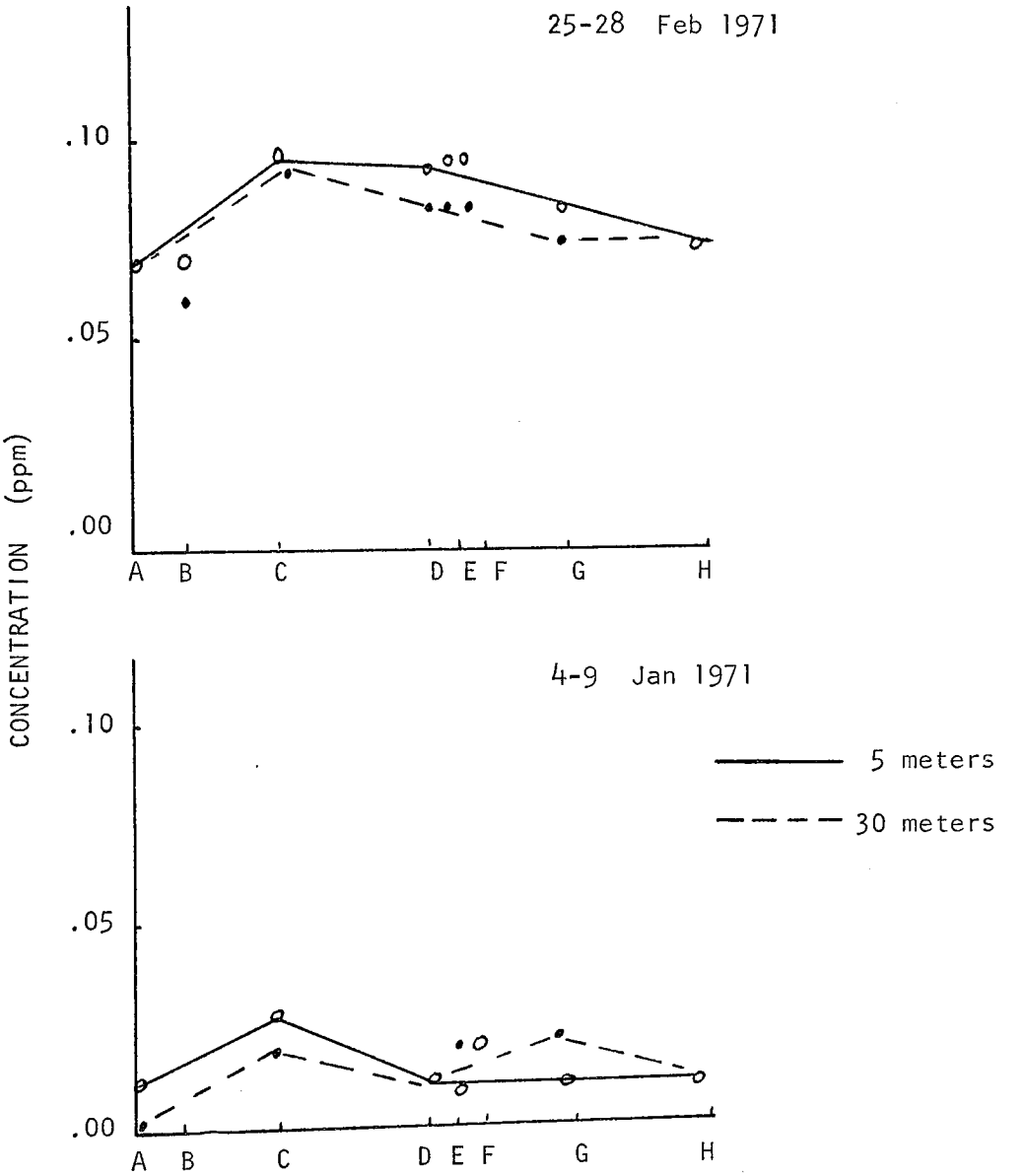
A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 29. September and January Bicarbonate Values



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 30. February and June Zinc Concentrations



A	BUREAU RAFT	E	MINER'S COVE
B	VEGAS BAY	F	ECHO BAY
C	BEACON ISLAND	G	TEMPLE BAR
D	BONELLI LANDING	H	SOUTH COVE

Figure 31. February and June Concentrations of Copper

This level is exceeded many times in Lake Mead. However, the Cu level at certain times of the year is too low to detect.

Sulphate

The sulphate levels consistently increase by more than 60 ppm across Lake Mead (Figure 32). This is a result of extensive chemical action in the reservoir. The sulphate begins to increase at South Cove. Part of the increase can be attributed to salt concentration. Part is a result of the hydrobiology. In Gregg's Basin we get high productivity resulting in a high Biochemical Oxygen Demand (BOD) in the bottom of the Basin. This creates low dissolved oxygen conditions and low electropotential (Eh). Under these conditions hydrogen sulphide (H_2S) is released and iron is precipitated out. Some of the available H_2S goes into solution as sulphates. The sulphate level in Boulder Basin is 15 times as high as it is in Lake Erie.

Light Intensity

The depth of penetration appears to increase in warm months. The one per cent level appears to be consistently deeper at Bonelli Landing and Temple Bar with the former being the clearest water in the Lake. Light penetration does not consistently improve across the system as sediment is lost. The transparency in Boulder Basin is often as poor as South Cove.

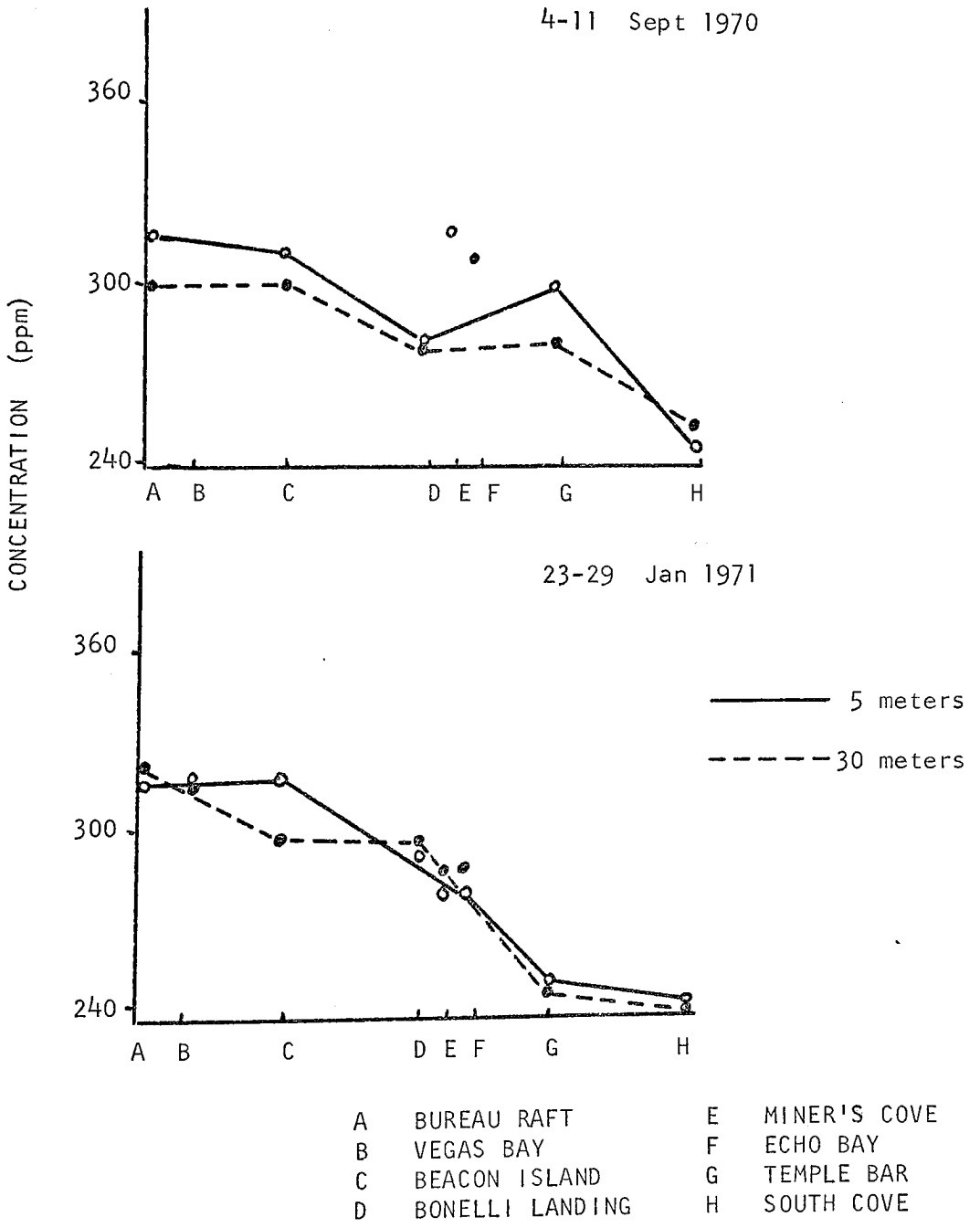


Figure 32. September and January Sulphate Concentrations

Zooplankton

The important groups generally represented in the zooplankton of lakes belong to the group of nonphotosynthetic: Protista, Rotifera, and Crustacea. In addition to members of these groups, a few coelenterates, flatworms, mites, and larval insects may be found in the plankton.

Lakes generally have three major distinct habitats: the benthic, which is the mud-water interface area; the littoral, which usually consists of the shore line habitat; and the pelagic, which is the free, open water area. The Lake Mead investigation was restricted to the pelagic area.

The thermocline in a lake is that area which, during the summer months, separates the upper warm water called the epilimnion, from the bottom colder water, referred to as the hypolimnion. When the water temperature of the epilimnion equals that of the hypolimnion, the lake turns over, i.e., the water in the epilimnion begins to circulate with the water in the hypolimnion. This condition circulates the nutrients that were trapped in the hypolimnion during the summer months and reintroduces them into the upper layer of water. This condition persists until the spring. The warming trend plus the availability of the nutrients cause what is known as the spring bloom. The phytoplankton take advantage of these conditions and begin to reproduce rapidly. This phytoplankton bloom (Figure 33)

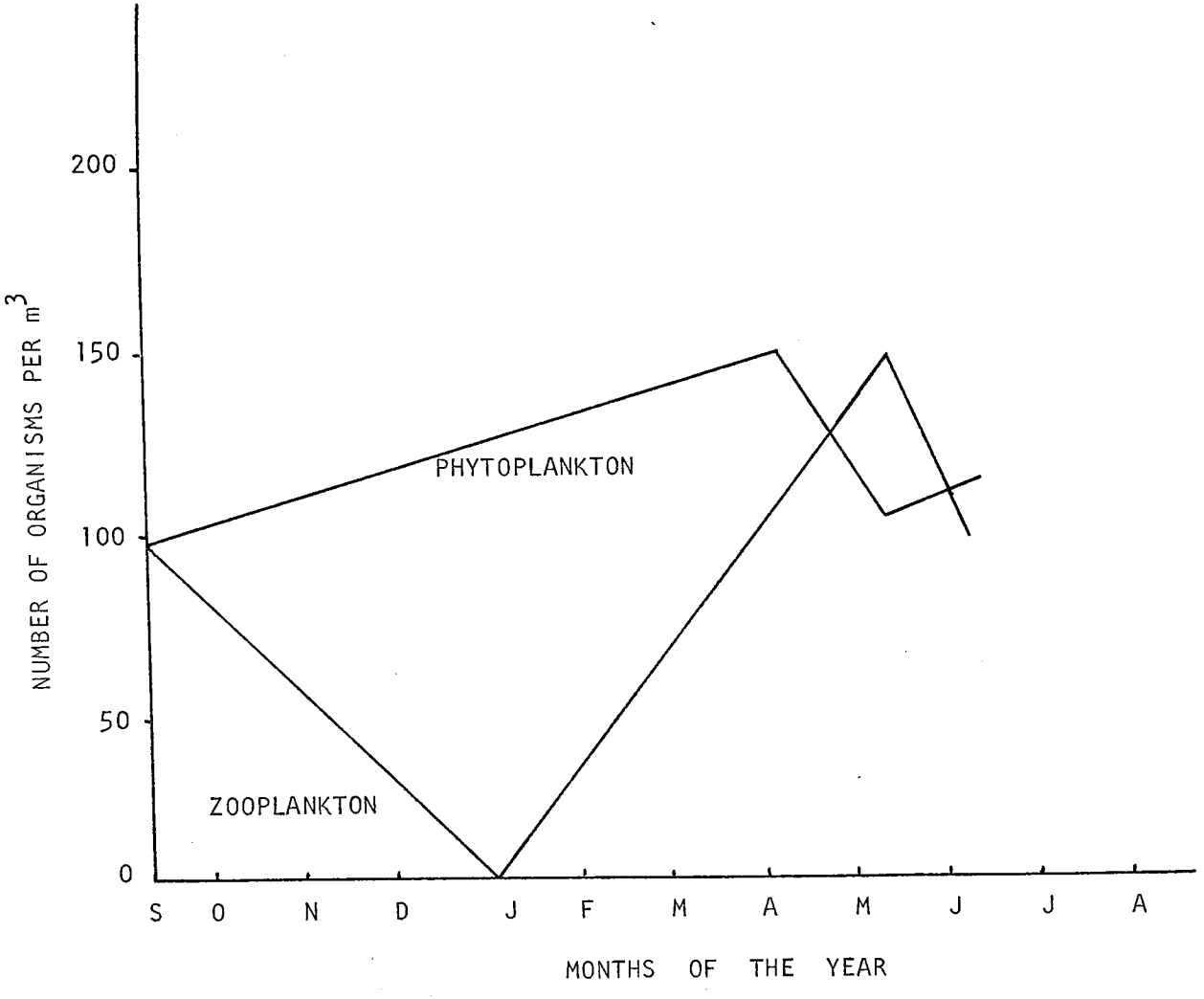


Figure 33. Phytoplankton-Zooplankton Growth Patterns -- After Riley and Bumpus (1946).

is usually soon followed by an increase in the number of zooplankton (Riley and Bumpus, 1946).

Other Zooplankton Studies on Lake Mead

Moffet (1943) stated that Ceratium in Lake Mead was the most abundant organism, followed by Calanoid, Cyclopoid, Microcystis, Daphnia, and Polyarthra (a rotifer). No quantitative data were given. Comparing this with the zooplankton of 1971 we find that Ceratium is still the most abundant organism. But that is where the similarity ends. Comparing the organisms found in 1943 we see that in 1971 the next most abundant organisms were the Cyclopoids, and a rotifer, Keratella. Since Keratella is the dominant rotifer found in Lake Mead, we assume that it now occupies the ecological niche that Polyarthra once held. In 1971, the rotifer Polyarthra was no longer present; this could mean that while Keratella was establishing itself in Lake Mead, Polyarthra found it very difficult to compete. Hutchinson (1967) states that Keratella feeds mainly on rotifers such as Polyarthra. This may explain their absence.

The next most abundant organisms were the Daphnia and the Calanoids (see Appendix A).

Zooplankters found to be present in the waters of Lake Mead are:

Phylum: ARTHROPODA
  Class: CRUSTACEA
    Order: CLADOCERA
      Family: DAPHNIDAE
        Genus: DAPHNIA
      Family: BOSMINIDAE
        Genus: BOSMINA
  Sub-Class: COPEPODA
    Order: CYCLOPOIDA
    Order: CALANOIDA
Phylum: ASCHELMINTHES
  Class: ROTIFERA (ROTATORIA)
    Order: PLOIMA
      Genus: KERATELLA

In addition, the following organisms were counted due to their obvious high numbers in the samples.

Phylum: PROTOZOA
  Order: DINOFLAGELLATA
    Genus: CERATIUM
Phylum: CHRYSOPHYTA
  Class: BACILLARIACEAE
    Genus: ASTERIONELLA

The larva stage of development in the Copepoda is called a nauplius. Because these nauplii are hard to differentiate between Cyclopoida and Calanoida, they were put into a category by themselves.

The Rotifera

The rotifers are the most important soft-bodied invertebrates in the fresh water plankton. If we were to designate a single major taxonomic category that is most characteristic of fresh waters, it could only be the class Rotifera. The rotifers are one of the few groups that have unquestionably originated in fresh waters, and it is here that they have attained their greatest abundance and

diversity. The rotifers are minute, chiefly microscopic animals. Their most characteristic feature is the ciliated area at or near the anterior end of the body, serving to bring food to the mouth. The disc-like ciliated anterior end has a resemblance to a pair of revolving wheels owing to the synchronized beating of the cilia. We have already briefly discussed the one rotifer present in Lake Mead, Keratella. This rotifer is an omnivorous animal, ingesting all organic particles of the appropriate size. They are a limnetic or open water class occurring over a wide depth range, even as deep as 100 or 200 meters.

Keratella generally have a spring maximum number with another smaller maximum in the fall. Both maximums were recorded in Lake Mead (Figure 34). The general seasonal trend of the total plankton population (Pennak, 1946) in large, deep lakes was represented on the figure. The third curve in Figure 34 shows the general trend of the total plankton population in Lake Mead with the exception of Ceratium. The fall maximum occurs when the water has cooled sufficiently to allow the thermocline to dissipate, which in turn allows the nutrients trapped below the thermocline to be re-introduced into the upper photic zone. If the weather conditions are favorable, the plankton will take advantage of the newly introduced nutrients, and will show a late summer maximum. The total ecology of any lake is very complex, especially when discussing plankton

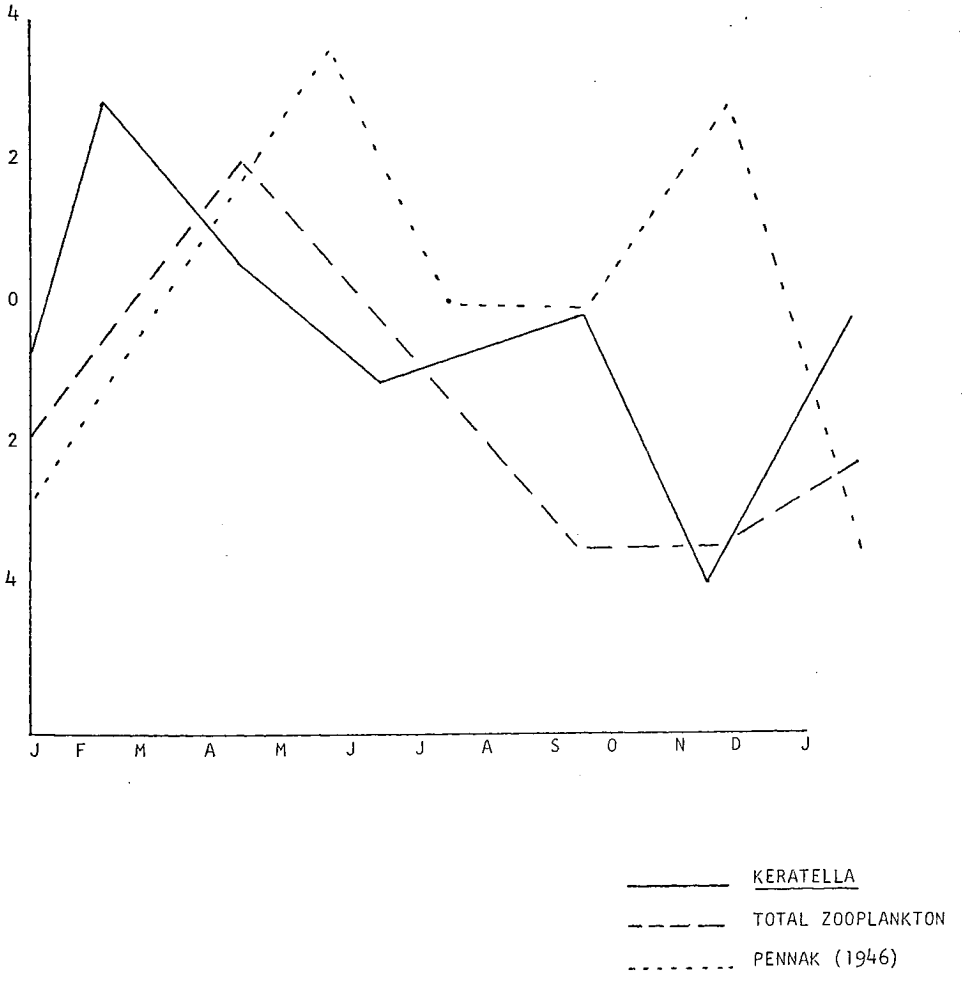


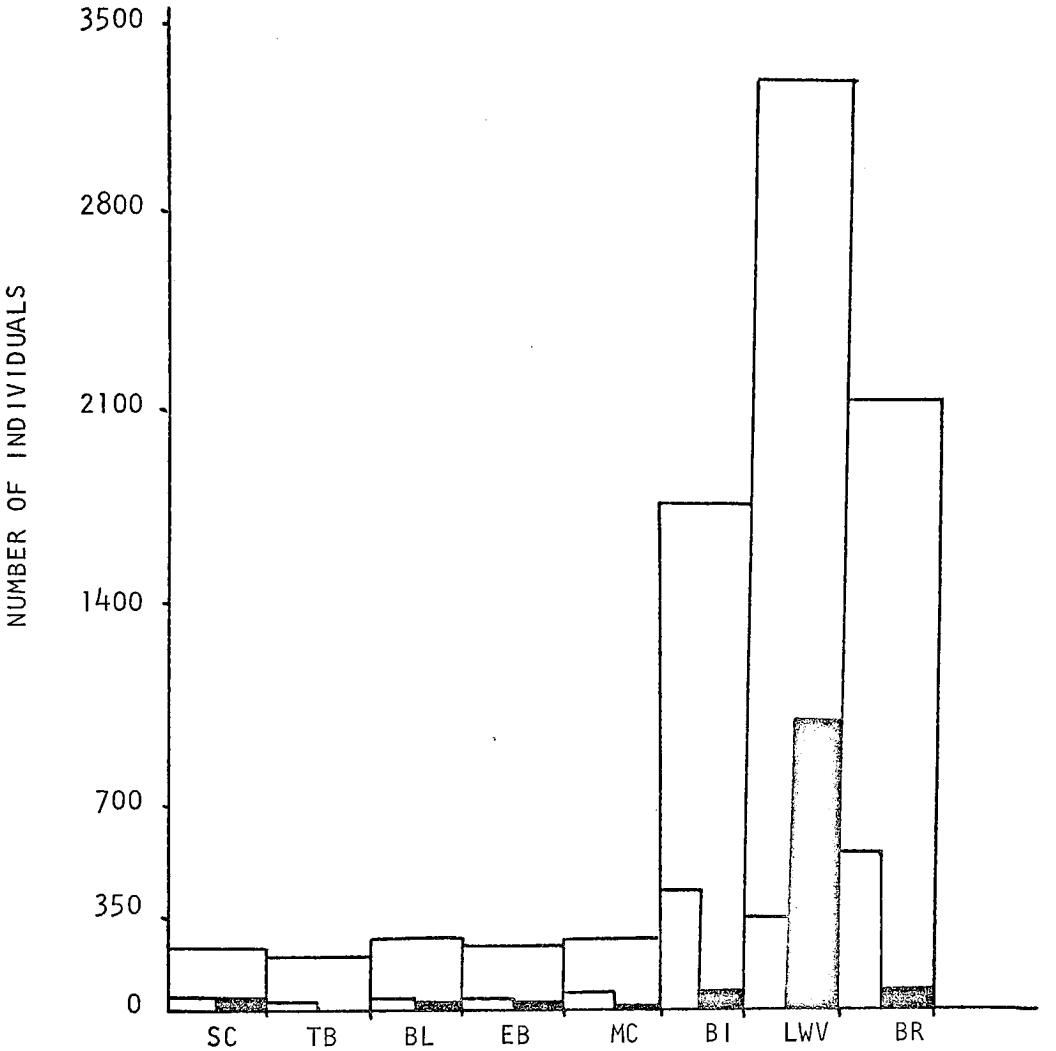
Figure 34. Seasonal Zooplankton in Lake Mead Compared to Pennak (1946)

seasonal cycles. It is difficult at present to determine why the zooplankters of Lake Mead show only one maximum. Keratella, however, shows a typical spring and late summer maximum.

In the literature, most species of Keratella are considered rather generally as species of eutrophic waters (Hutchinson, 1967). The numbers present at Las Vegas Wash (LVW) (Figure 35) are extremely high when compared with the entire Lake. In fact, the whole Basin, including Beacon Island (BI) and the Bureau of Reclamation raft (BR) show the effect LVW has on Boulder Basin. Figure 36 graphically shows the difference between LVW and an unpolluted site such as Temple Bar (TB). Here we examine the abundance of Keratella from the surface to a depth of 35 meters, covering over 90 per cent of the photic zone. These graphs may not prove that Boulder Basin is polluted but they do point out that the Basin is significantly more productive than the rest of the reservoir.

The Crustacea

The great majority of the planktonic metazoa, both in the sea and in fresh waters, belong to the Crustacea; in the fresh-water environment the planktonic Crustacea are represented mainly by species of the order Cladocera and by species of the sub-class Copepoda.



SC	SOUTH COVE	MC	MINER'S COVE
TB	TEMPLE BAR	BI	BEACON ISLAND
BL	BONELLI LANDING	LVW	LAS VEGAS WASH
EB	ECHO BAY	BR	BUREAU RAFT

Figure 35. Total Number of *Keratella* with January (▭) and June (▬) Values Shown

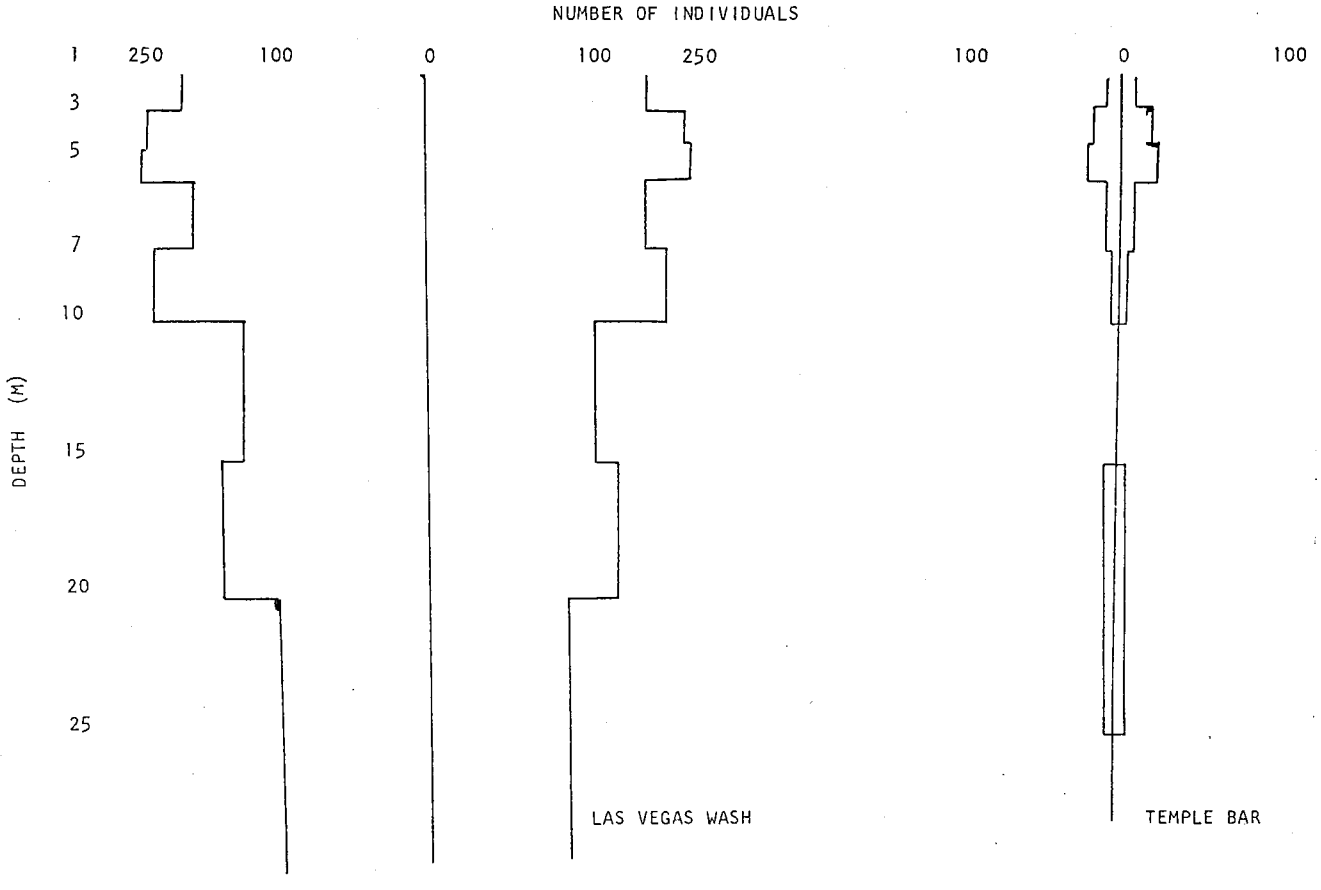


Figure 36. Total Keratella Counted at Las Vegas Wash and Temple Bar

All the species of Crustacea considered here are more nektonic than any species of phytoplankton and are also less likely to be at the mercy of turbulent water movements than the planktonic rotifers.

Cladocera

The genera Bosmina and Daphnia were the only genera found in Lake Mead. Both were monocyclic, that is, having one population maximum and both are common open water forms. Bosmina have their populations peak in April then usually alternate with another species (Hutchinson, 1967). This was found to be the case in Lake Mead (Figure 37) with the other genus being Daphnia. Hutchinson's data showed the Bosmina population being 16 per cent higher than the Daphnia maximum. In Lake Mead, Bosmina were 14 per cent higher than the Daphnia. In January, Bosmina numbered 701 while Daphnia numbered 10. In February, Bosmina again outnumbered Daphnia 4,049 to 291. In the month of June we see that the species dominance was clearly shifted in favor of Daphnia, 3,956 to 119 for Bosmina. It is interesting to note here that the total numbers for these two species greatly increase in the Boulder Basin, which includes BI, LVW, and BR (see Appendix A).

Copepoda

Cyclopoida and Calanoida are the two orders of the free-living fresh water Copepoda that we were concerned

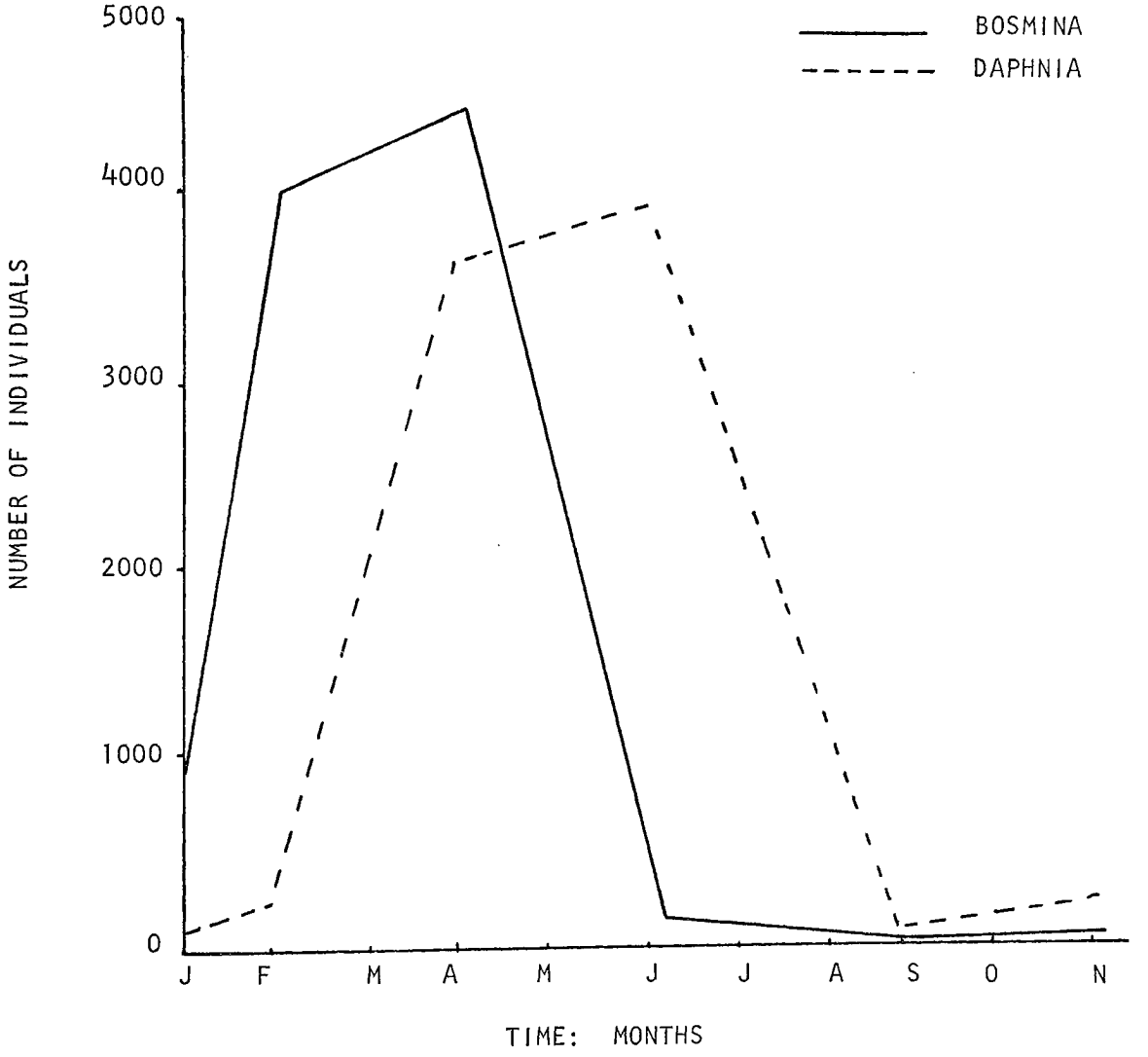


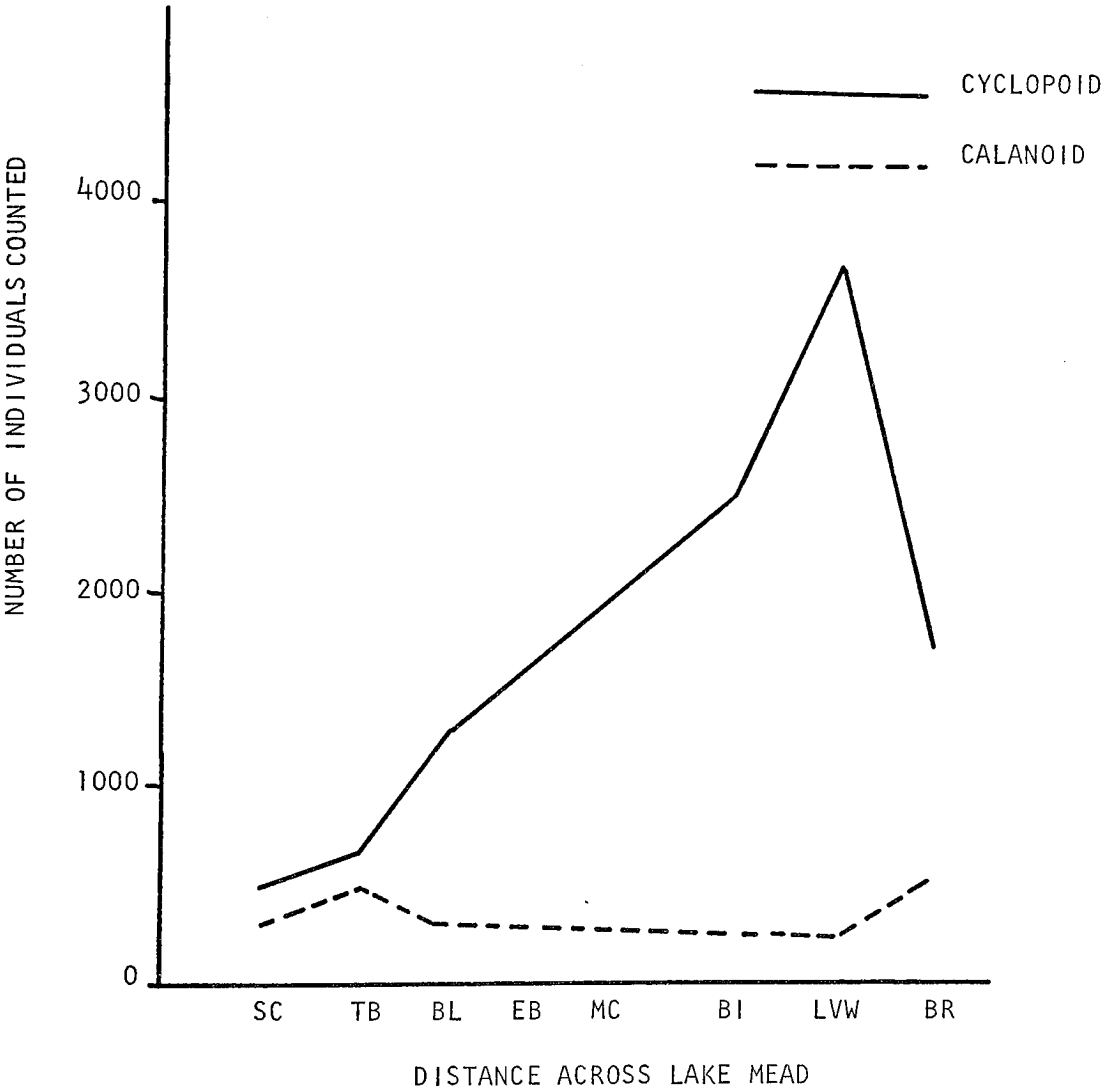
Figure 37. Seasonal Peaks of Daphnia and Bosmina

with. Generally, Cyclopoida are littoral benthic forms while Calanoida are limnetic organisms. In Lake Mead the Cyclopoid population dominate the Calanoida (Figure 38). The Cyclopoida are generally carnivorous while Calanoida are herbivorous. In LVW the Cyclopoida reach their highest numbers while the Calanoida reach their lowest. This suggests different types of environmental conditions. Figure 39 shows the relationship of Cyclopoida to the primary productivity data.

The total number of Cyclopoids in LVW are significantly higher than at any other location on the Lake. Figure 40 compares the Cyclopoida at LVW with the Cyclopoids at TB. These numbers are total counts. Copepod nauplii in LVW may outnumber the nauplii in the other locations. In TB the total number of nauplii was 1,245 compared to the more productive LVW at 4,016.

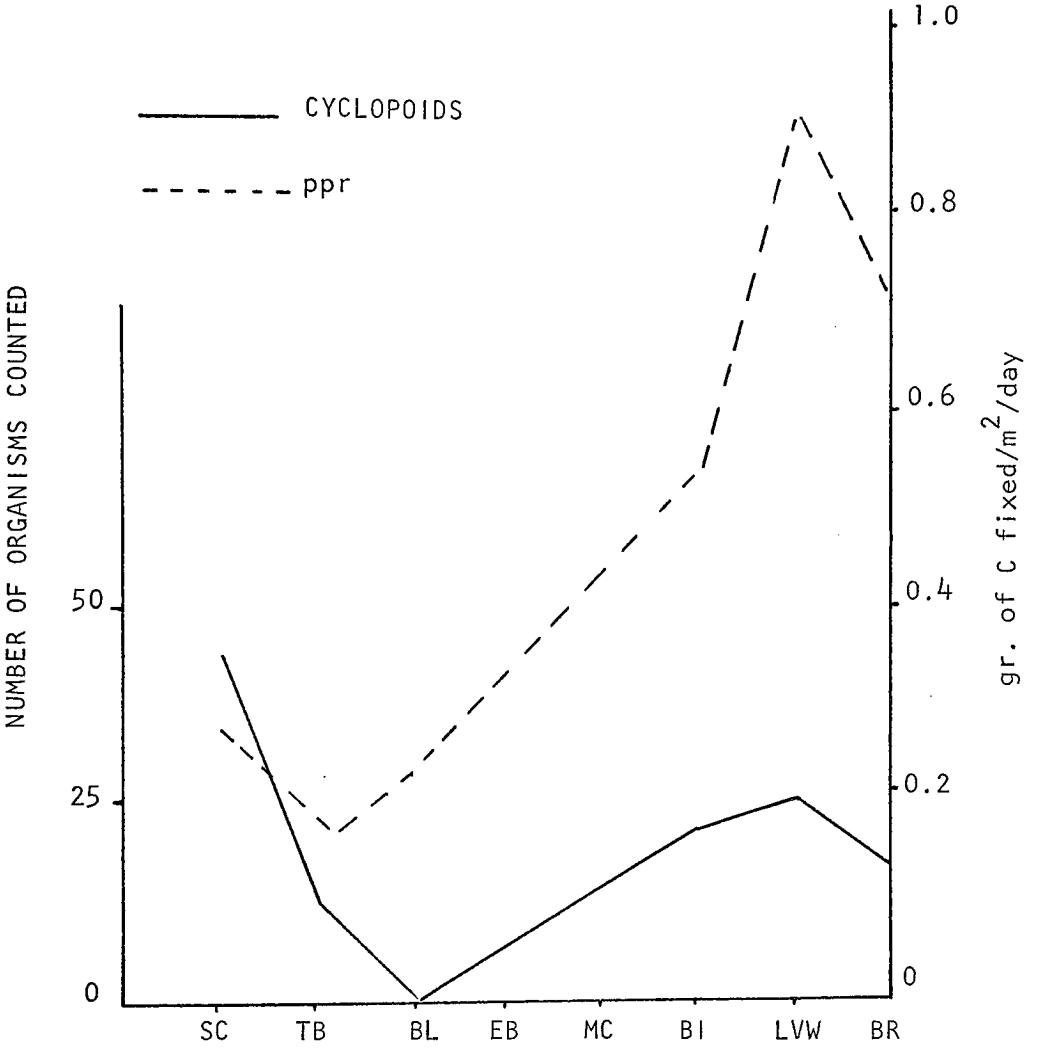
Ceratium

Of all the organisms investigated, the dinoflagellate Ceratium is the only one that shows a definite decrease in numbers at LVW (Figure 41). Hutchinson (1967) states that Ceratium is most probably characteristic of mesotrophic water, although Hutchinson places Ceratium under his heading of eutrophic dinoflagellate plankton. The general summer maximum reported for Ceratium was confirmed by our data (see Appendix A).



SC	SOUTH COVE	MC	MINER'S COVE
TB	TEMPLE BAR	BI	BEACON ISLAND
BL	BONELLI LANDING	LVW	LAS VEGAS WASH
EB	ECHO BAY	BR	BUREAU RAFT

Figure 38. Total Numbers of Calanoids and Cyclopoids



SC	SOUTH COVE	MC	MINER'S COVE
TB	TEMPLE BAR	BI	BEACON ISLAND
BL	BONELLI LANDING	LVW	LAS VEGAS WASH
EB	ECHO BAY	BR	BUREAU RAFT

Figure 39. January Values for PPR and Cyclopoids

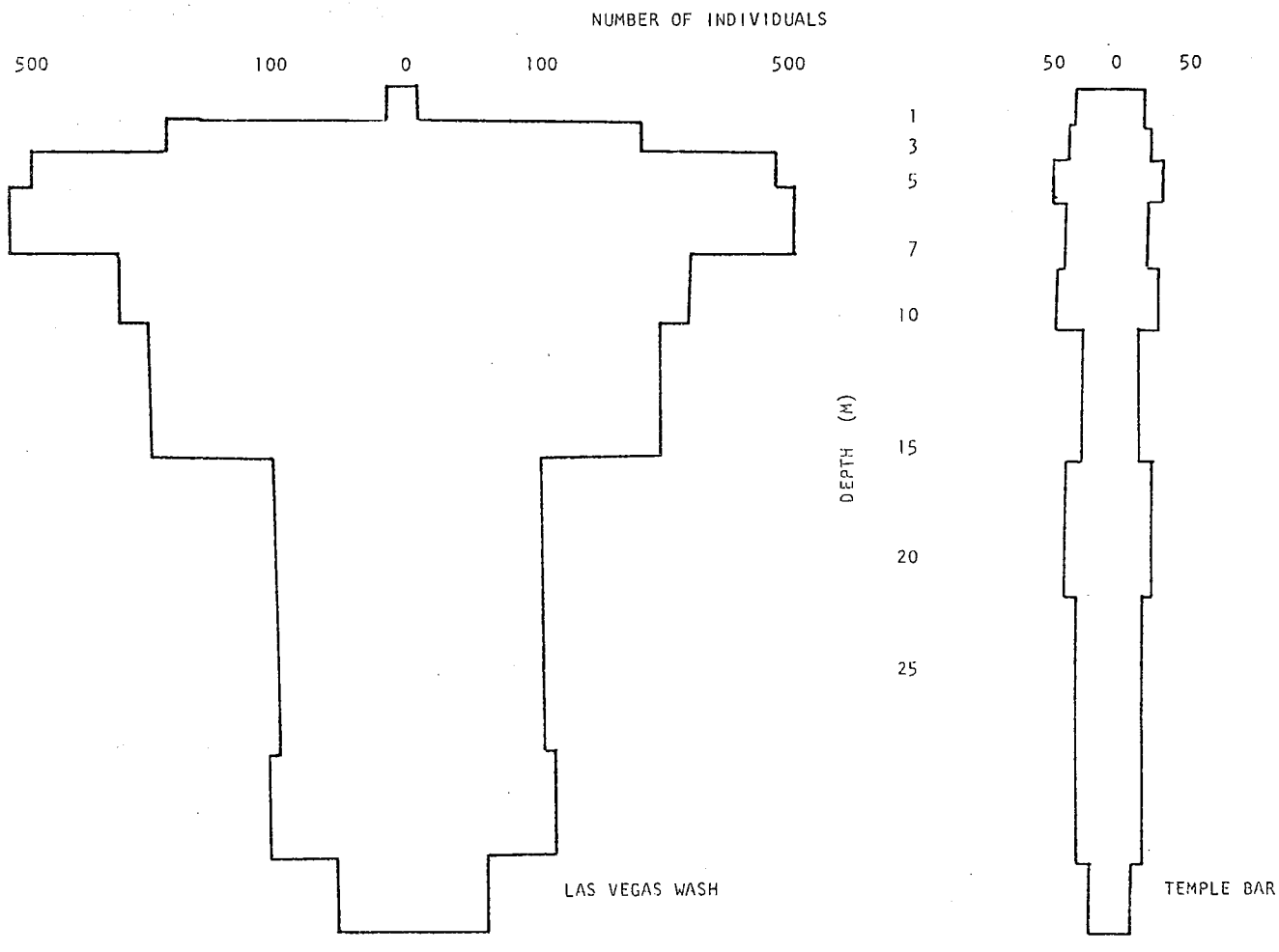


Figure 40. Number of Cyclopoids Recorded at Las Vegas Wash and Temple Bar

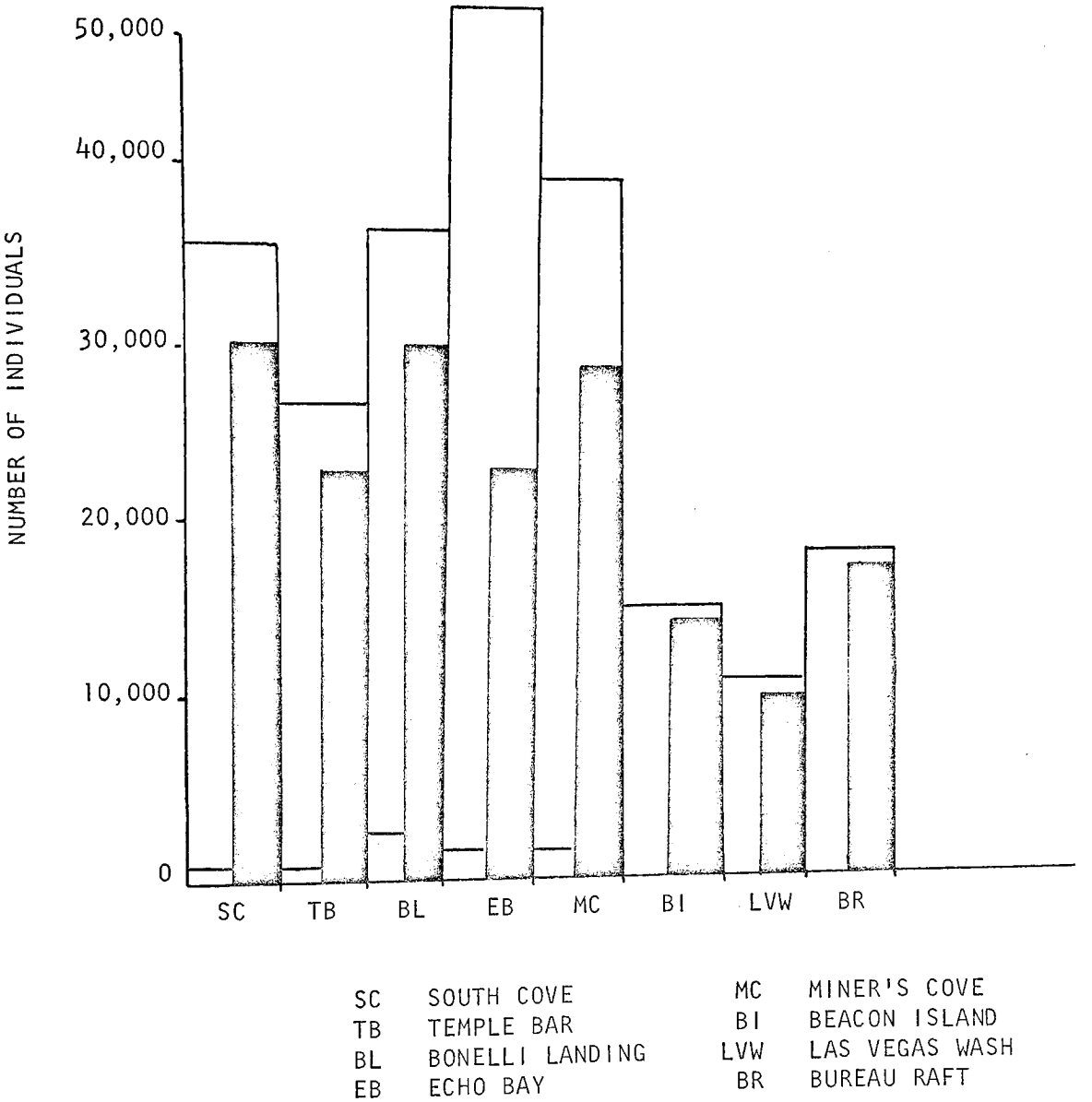


Figure 41. Total Number of *Ceratium* with January (▭) and June (▩) Values Given

Asterionella

Asterionella thrives very well in polluted waters. High numbers at South Cove tell us that Asterionella are taking full advantage of the nutrients flowing in from the Colorado River. Another population pulse at LVW is a result of the enriched waters. The diatom Asterionella usually shows a fall maxima. In Lake Mead Asterionella showed a spring and summer maxima. Hutchinson (1967) classifies Asterionella in his eutrophic diatom plankton category, stating that Asterionella may be the dominant plankter in highly productive lakes. The diatoms are one of the most important members of the fresh-water limnetic phytoplankton. They are always present in significant numbers and in many lakes they are perennial dominants.

Primary Productivity (PPR)

The rate of photosyntheses (primary productivity rate) was computed for each station. The example given (Table 7) is for Lake Mead Station 3 (Beacon Island) on the ninth of September, 1970. The light and dark bottles were inoculated and placed "in situ" at 10:30 and removed at 14:30. A total of 2.10 microcuries of ^{14}C was added. The highest ppr had occurred at 3 meters (45.218 mg of carbon/cubic meter/hour). The hourly data were then integrated over the solar day (686.00 langleys). The output was

Table 7. Primary Productivity at Beacon Island

PRIMARY PRODUCTIVITY LAKE MEAD STA 3 8/ 9/70 FROM 1030 TO 1430

COUNTER EFFICIENCY = 0.236 MICROCURIES OF C14 ADDED = 2.10

COMPENSATION DEPTH = -0.0 METERS BOTTLE SIZE = 125.00 ML AMOUNT FILTERED = 50.00 ML

LANGLEYS FOR DAY = 606.00 LANGLEYS FOR TEST PERIOD = 314.00 SECHI DEPTH = -0.00 METERS

DEPTH IN METERS	LT COUNT TIME	LT COUNTS/SEC	DK COUNT TIME	DK COUNTS/SEC	LIGHT - DARK	MG C12/LITER
0.00	6.64	12.55	20.00	2.20	10.35	21.900
1.00	2.55	32.68	20.00	2.32	30.36	21.900
3.00	1.42	58.69	20.00	1.75	56.94	22.000
5.00	1.59	52.41	20.00	1.69	50.72	22.000
7.00	2.15	36.76	20.00	0.96	37.80	23.000
10.00	4.97	16.77	20.00	0.75	16.01	24.200
15.00	20.00	3.67	20.00	0.68	2.99	22.800
20.00	20.00	1.09	20.00	0.61	0.48	23.700

DEPTH IN METERS PRIMARY PRODUCTIVITY IN MG. OF CARBON/CUBIC METER.HOUR

	LIGHT	DARK	LIGHT - DARK
0.00	9.716	1.550	8.165
1.00	25.629	1.627	24.002
3.00	46.398	1.180	45.218
5.00	41.415	1.115	40.300
7.00	31.964	0.577	31.387
10.00	14.420	0.431	13.989
15.00	2.803	0.346	2.457
20.00	0.709	0.302	0.407
TOTAL* MG PER SQUARE METER =	372.304	13.487	358.818
AVERAGE* MG PER CUBIC METER =	18.615	0.674	17.941

TOTAL PPR MG C/SQUARE METER.DAY = 3135.655
AVERAGE MG C/CUBIC METER.DAY = 156.783
TOTAL EFF. (PER CALORIE OF LIGHT)= 4.5709 X1/10000

printed in total ppr as: mg C/square meter/day = 3135.655, or as an average: mg C/cubic meter/day = 156.783.

Many authors describe primary productivity in the units of area or volume. Our data have been analyzed using both techniques. The space-time distribution of ppr was presented as an area in Figure 42.

Distributions were given for 8 stations at six different times of the year. The ppr data were subject to different weather conditions each day. The data were not corrected for weather differences, i.e., cloud cover for half a day.

We will follow the criteria for different lake types as given by Rodhe (1969). He based his classification on an area using the units: mg (mg C fixed/m^2/day) (Table 8).

The January and April runs indicate the lowest ppr values (Figure 42). However, we should note that the South Cove (SC), Temple Bar (TB), and Bonelli Landing (BL) stations behaved as an oligotrophic lake. As we look at Boulder Basin we see a jump in productivity which classifies the Basin as a natural eutrophic lake.

The June data indicate that the ppr increases as the temperature of the water and the solar radiation begin to rise. We notice that the whole of Lake Mead behaves as a natural eutrophic lake in June. South Cove and Las Vegas Wash have elevated ppr values, but in general, the January,

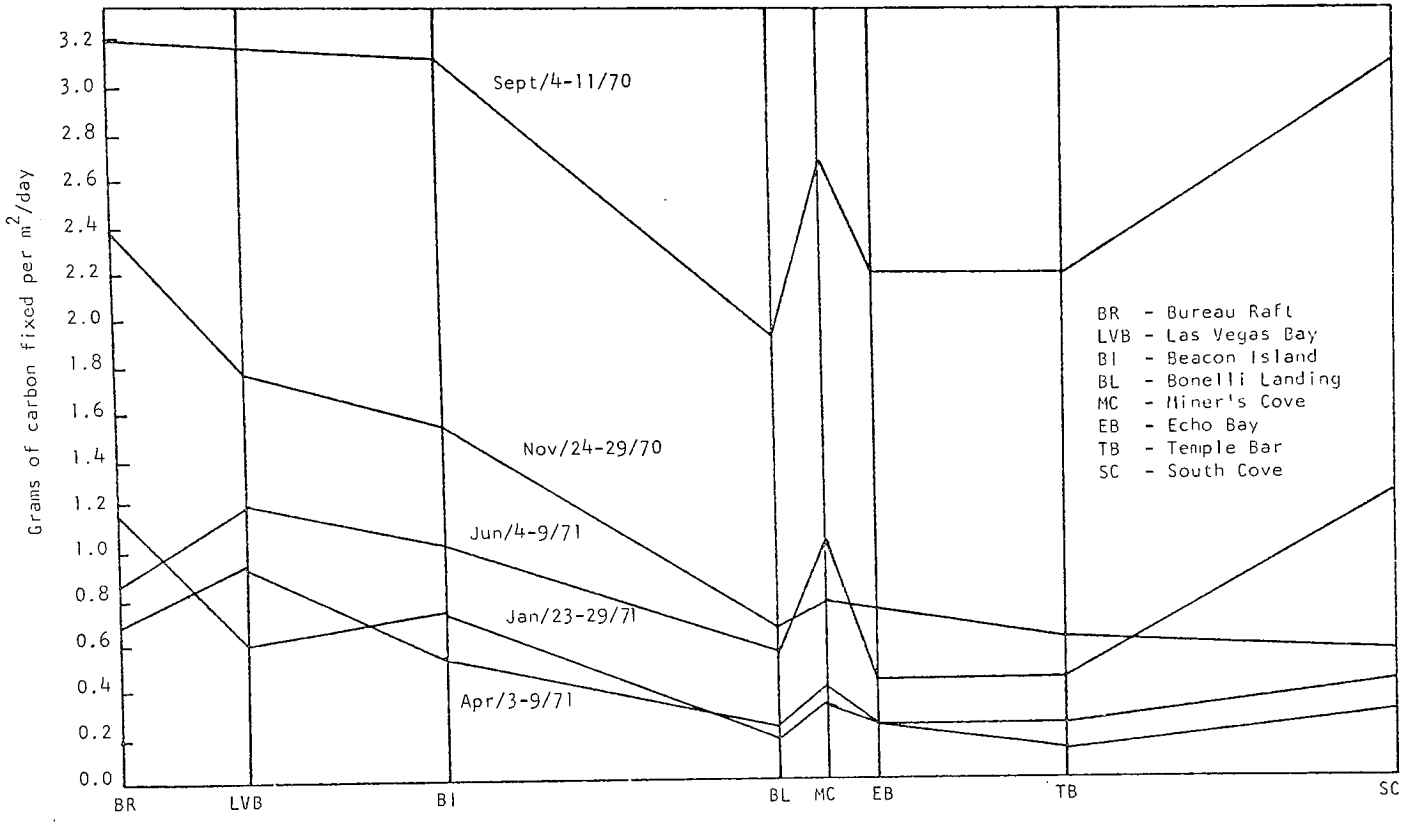


Figure 42. Space-Time Distribution of Primary Productivity

Table 8. Autotrophy (Phytoplankton) -- After Rodhe (1969).

	Oligotrophic Lakes	Eutrophic Lakes		
		Natural	Polluted	
Mean rates in growing season	30-100	300-1,000	1,500-3,000	mg of C/m^2/day
Annual rates	7-25	75-250	350-700	g of C/m^2/year

April, and June values are constant relative to each station.

In September the ppr values have moved the Lake into a polluted eutrophic state. South Cove has very high primary productivity. The ppr drops from Temple Bar to Bonelli Landing. However, the ppr values in Boulder Basin are very high, with the Bureau of Reclamation Raft station having the highest values.

By November, the thermocline is partially destroyed and mixing has begun to take place. As the solar radiation and the temperature of the water are reduced the ppr begins to lessen. Once again, we see the ppr values at the Bureau Raft are the highest in the system.

The natural flow of the system is East to West with Overton Arm providing a flow from the North. The data on each sample date indicated that Miner's Cove had a much higher ppr value than Echo Bay or Bonelli Landing. We can only conclude that there is a nutrient source at or below Echo Bay.

There is little doubt that Lake Mead is suffering from nutrient inflows at South Cove and Las Vegas Bay.

CHAPTER 6

SYSTEM ANALYSIS

Multivariate Analysis

Employed in the statistical multivariate analysis are:

1. Stepwise regression analysis.
2. Principal component analysis.

Multiple regression is used in data analysis to obtain the best fit of a set of observations of independent and dependent variables by an equation of the form:

$$y = b_o + b_1x_1 + b_2x_2 + \dots + b_nx_n \qquad (6.1)$$

where y is the dependent variable; x_1, x_2, ... are the independent variables; and b_o, b_1, ... are the coefficients to be determined.

A multiple regression solution gives the least squares "best" value of these coefficients for a particular sample of observations. The solution also gives a measure of the reliability of each of the coefficients so that inferences can be made regarding the parameters of the population from which the sample of observations was taken.

For a large number of variables, any method of regression analysis requires a large number of calculations.

Most methods of regression analysis are based on techniques particularly adaptable to a desk calculator where a minimum transcription of intermediate answers is desirable.

In the stepwise procedure, intermediate results, which are not even recorded by normal calculation methods, are used to give valuable statistical information to each step in the calculation. These intermediate answers are also used to control the method of calculation. Essentially, without adding greatly to the number of arithmetic steps, a number of intermediate regression equations are obtained, as well as the complete multiple regression equation. These equations are obtained by adding one variable at a time and thus give the following intermediate equations:

$$y = b_o + b_1x_1 \tag{6.2}$$

$$y = b'_o + b'_1x_1 + b'_2x_2 \tag{6.3}$$

$$y = b''_o + b''_1x_1 + b''_2x_2 + b''_3x_3 \tag{6.4}$$

$$\vdots$$

The variable added is that one which makes the greatest improvement in "goodness of fit." The coefficients represent the best values when the equation is fitted by the specific variables included in the equation.

An important property of the stepwise procedure is based on the facts that (1) a variable may be indicated to

be significant in any early stage and thus enter the equation, and (2) after several other variables are added to the regression equation, the initial variable may be indicated to be insignificant. The insignificant variable will be removed from the regression equation before adding an additional variable. Therefore, only significant variables are included in the final regression.

The inherent assumptions in the use of multiple regression have been described by Hahn and Shapiro (1966). Their first assumption, says that the process error, e_i for the regression equation to be used, is a normally distributed random variable with zero mean and constant variance σ_e^2 for all observations. This very general assumption is also used in our chemical, biological, and hydrodynamic parameter investigation.

The second assumption deals with the statistical independence of the observations from which the regression is developed. This assumption is violated, yet used in many ecosystem studies. The chemistry, biology, and hydrodynamics are all related in a complex fashion. It is our hope that by treating them independently we can resolve some of the complexities.

In our multivariate analysis we must also assume that the values of the independent variables are known without error. We are confident that the measured values in the field are sufficiently accurate; however, one can

never be sure of the number of recording errors in a large scale field collection program and subsequent data analysis.

The fourth assumption relates that the correct form of the model has been chosen. This is a difficult assumption since we have no standard to relate to other than nature. We know that nature does not operate in a linear fashion; however, we are willing to trade off some reality in anticipation of developing a first-approximation model that has in turn, utility.

The last assumption deals with the typical nature of the data to be sampled. Although the data were not random samples, we feel that each basin was sampled "in situ," resulting in a natural association of variables that were typical of the situation that we wished to generalize.

The principal component analysis is used to examine the dependence structure of multivariate data and reduce its dimensionality (i.e., eliminate redundant parameters). The original observation variables are transformed into a smaller number of component variables, which are linear functions of the observation variables. The objective is to explain as much of the variance in the original observations as possible with a minimum number of components.

Multivariate analysis tends to agitate most researchers who have had field experience in biological studies. The two main reasons are:

1. That a certain amount of knowledge exists about the system and should be used.
2. That linear relationships in biological systems are poor.

However, all field investigators must recognize the following problems:

1. The inability to measure all variables.
2. The inability to measure any variable continuously in time and space.
3. The high level of uncertainty in many sampling techniques.
4. The lack of full understanding of the phenomena governing water quality (Moore, 1972).
5. The state-of-the-art in chemical species interaction.

If we can accept the ignorance that exists today in hydro-biological studies with an open mind, we can surely accept the multivariate approach as a first approximation. I personally have mixed emotions about the linear approach. Much of the interpretation has physical meaning which is very reassuring. However, some relationships cannot be physically explained.

The multivariate approach used is very encouraging; however, much work is needed to build confidence in the output. The statistical approach is used to provide some

functional information in those areas where knowledge is uncertain.

Several multivariate approaches were used to relate the mass of data collected. Since each state had been defined chemically, biologically and physically, the simplest step was to linearly relate the variables. This approach implies two assumptions:

1. That the events are linearly related.
2. That there is no phase lag.

Both of these assumptions are intolerable in a biological system, but they are a natural starting point. Many writers feel that the scope of the eutrophication problem precludes deterministic or analytic modeling at the present time. We agree that the level of sophistication in deterministic eutrophication is in the infant stage. It is therefore reasonable to presume that in the investigation of reservoirs where the time and expense required to evaluate all the parameters for analytical models is not feasible, we could try a first approach at quantifying the phenomenon. While not the ultimate answer, such models can provide direction and background for further studies and models can simultaneously provide in turn, predictive tools needed in water quality management.

Stepwise Regression Analysis

A Numerical Analysis Laboratory program (University of Arizona, Computer Center) Stepwise Regression Analysis was used. Each of the thirty measured parameters were assigned a variable number as shown in Table 9.

The program was set up to use the 30th parameter as the dependent variable. This left the other 29 parameters as independent variables explaining the value of the dependent variable. The second run uses the 29th variable as the dependent variable and the 30th variable takes the place of the 29th variable as one of the 29 independent variables. This procedure continued until all 30 variables had been defined in terms of the other 29 variables.

An example of the computer printout is given in Appendix B. The equation is of the form:

$$y = b_o'' + b_1''x_1 + b_2''x_2 + b_3''x_3 + b_4''x_4 + b_5''x_5 + b_6''x_6 \qquad (6.5)$$

where: y = ppr

b_o'' = constant

b_1'', b_2'', etc. = coefficient

x_1, x_2, x_3, etc. = variables

The dependent parameter for this run is ppr. Step No. 6 indicates that we are looking at the sixth parameter

Table 9. Parameter Index Table

Variable	Index Number	Variable	Index Number
temperature	01	Fe	16
dissolved oxygen	02	Mn	17
light intensity	03	Zn	18
soluble salts	04	Ca	19
electro-conductivity	05	B	20
CO_3	06	Nauplii	21
NO_3	07	*Daphnia*	22
HCO_3	08	*Bosmina*	23
SO_4	09	*Calanoid*	24
Cl	10	*Cyclopod*	25
Mg	11	*Keratella*	26
Ca	12	*A sterionella*	27
Na	13	*Ceratium*	28
PO_4	14	primary productivity (14_C)	29
pH	15	alkalinity	30

recognized as being a major factor in ppr. Each parameter 1, 8, 9, 14, 23, 25 has been independently investigated by the computer and by a stepwise fashion has moved to the next most significant independent parameter contributing to ppr. The program was set up to go through the 29 independent variables or steps printing out the decreasing contribution of each of the steps.

The F level in Appendix B was 4.1. At this step (No. 6) we choose to analyze the output. The R-squared value 82.2 per cent showed that we had explained the variance in ppr very well at the 95 per cent confidence level for the parameters used.

The six variables were:

1	Temperature
8	HCO_3
9	SO_4
14	PO_4
23	Bosmina
25	Cyclopod

Using the constant and coefficient given in step No. 6, the equation relating the variables to ppr was:

$$ppr = 117 + (.527)(Temp) - (.593)(HCO_3) - (.090)(SO_4) + (235)(PO_4) - (.035)(Bosmina) - (.014)(Cyclopod) \quad (6.6)$$

The equation for ppr shows that the independent variables are a function of one constant plus or minus six quantities. It is curious to note that the computer assigned priority values to a physical parameter (temp) then chemical parameters and finally grazing zooplankton.

The positive effect of temperature has been widely confirmed. As the temperature increases, the ppr will increase. However, the HCO_3 has a negative effect. The inhibitory effect of SO_4 is very curious since SO_4 increases considerably across the system. The strong argument about PO_4 as a controlling nutrient gains some support from the equation. The grazing effect of Bosmina may reduce the phytoplankton present resulting in the lower ppr. Cyclopods which may eat plant or animal material, negatively act on the ppr.

To confirm that the equation for ppr does exist for the available data, we chose the results at Temple Bar on September 10, 1970. The parameter values at that time were:

Temperature	26.6°C
HCO_3	142 ppm
SO_4	300 ppm
PO_4	.01 ppm
Bosmina	0
Cyclopod	1

applying equation (6.6):

$$ppr = 117 + (.527)(26.6) - (.593)(142) - (.090)(300) + (235)(.01) - (.035)(0) - (.014)(1) = 22.2 \text{ mg C fixed/m}^3\text{/day} \quad (6.7)$$

The actual measured ppr on that date, at that location with those variables was 18.7 mg C fixed/m^3/day. These results confirm the excellent predictive ability of the equation for the given data.

To prove that the equation held not only in the summer but also in the winter months, a January run was analyzed. The Beacon Island sample on the 27th of January, 1971, was recorded as having:

Temperature	11.6
HCO_3	156
SO_4	320
PO_4	.02
Bosmina	0
Cyclopods	0

The equation for ppr was:

$$ppr = 117 + (.527)(11.6) - (.593)(156) - (.090)(320) + (235)(.02) - (.035)(0) - (.014)(0) = 6.3 \text{ mg C fixed/m}^3\text{/day} \quad (6.8)$$

The actual ppr value recorded on the 27th of January at Beacon Island was 6.109 mg C fixed/m^3/day.

The examples indicated that the equation held for different stations at different times of the year with different parameter values.

Principal Component Analysis

Since one of our objectives was to functionally relate all of our variables we decided that a Principal Component Analysis would tell us which variables were accounting for the biological response. Only the 5th and 30 meter data were analyzed because complete chemistry studies were done at these levels.

The computer program referenced the 31 variables (including depth) and normalized the data to a zero mean and unit variance (Table 10). A large 31 x 31 correlation matrix was set up (Table 11). From the correlation matrix solution the eigenvalues were found and their per cent contribution was recorded (Table 12). The eigenvector showing the best correlation accounted for only 20 per cent of the variance on the data. The plot of the first eigenvector was given in Figure 43.

Generally the plot indicates that at larger depths, both the dissolved oxygen and the light extinction were low. Under these conditions soluble salts and electrical conductivity were below normal. This was supported by Na, Cl, and SO_4 being low. The zooplankton response to this

Table 10. Principal Component Analysis -- Lake Mead Data-- 5 and 30 Meters (31 Variables).

Index	Mean	Standard Deviation	Variable
1	17.50000	12.50000	Depth
2	14.38043	4.76099	Temperature
3	8.94674	2.36517	Dissolved Oxygen
4	12.92717	17.64602	Light Extinction
5	768.18478	39.63884	Soluble Salts
6	1.12402	0.06873	Electrical Conductivity
7	1.23913	6.03499	CO_3
8	3.45543	1.99931	NO_3
9	153.63043	13.09391	HCO_3
10	301.06522	60.59036	SO_4
11	98.18478	6.57884	Cl
12	32.02174	5.33442	Mg
13	80.85870	9.88035	Ca
14	103.56522	7.32670	Na
15	0.01098	0.01153	PO_4
16	4.93185	3.95796	pH
17	0.08543	0.04340	Fe
18	0.04043	0.03025	Mn
19	0.03913	0.02648	Zn
20	0.07620	0.06437	Cu
21	0.41250	0.22305	B
22	38.32609	63.16922	Nauplii
23	20.93478	55.66804	*Daphnia*
24	21.69565	44.53473	*Bosmina*
25	9.06522	18.63651	*Calanoid*
26	32.68478	80.61300	*Cyclopod*
27	20.90217	35.88389	*Keratella*
28	9.77174	29.82015	*Asterionella*
29	563.91304	1619.59859	*Ceratium*
30	4.57282	8.77074	ppr
31	13.41196	16.20294	Alkalinity

Table 11. Correlation Matrix

CORRELATION MATRIX

		1 DEPTH	2 TEMP	3 DO	4 LF	5 SS	6 FC	7 CO3	8 MO3	9 HCO3	10 SO4
1	DEPTH	1.000	-.179	-.333	-.362	.017	-.033	.032	-.002	.105	.057
2	TEMP	-.179	1.000	-.451	.078	.032	-.058	-.136	.466	-.558	.057
3	DO	-.333	-.451	1.000	-.079	-.073	-.121	.113	-.393	-.028	.036
4	LF	-.362	.078	-.079	1.000	.278	-.011	.073	-.104	-.248	.372
5	SS	.017	.032	-.073	.278	1.000	.552	.127	-.156	-.208	.479
6	FC	-.033	-.058	-.121	-.011	.552	1.000	.367	-.020	-.112	.294
7	CO3	.032	-.136	.113	.073	.127	.367	1.000	-.135	-.047	.023
8	MO3	-.002	.466	-.393	-.104	-.156	-.020	-.135	1.000	-.064	-.155
9	HCO3	.105	-.558	-.028	-.248	-.208	-.112	-.047	-.064	1.000	-.242
10	SO4	.057	.057	.036	.372	.479	.294	.023	-.155	-.242	1.000
11	CL	.015	.012	-.001	.039	.612	.713	.208	-.037	-.250	.354
12	NO3	-.114	.155	-.123	-.092	.254	.379	.074	.191	-.079	.115
13	CA	.217	-.179	-.143	-.045	.303	.144	.055	-.039	.021	.151
14	MG	.030	-.114	-.087	.131	.607	.594	.117	-.011	-.197	.241
15	NA	-.067	-.053	-.068	-.111	.070	.454	.307	.043	.060	-.147
16	K	-.072	.123	.260	.179	-.307	-.215	.064	.278	-.063	-.244
17	FE	.049	-.060	-.055	-.356	-.091	-.123	-.232	.103	.152	-.237
18	MN	-.022	.413	-.272	-.233	-.202	.002	-.071	.443	-.162	-.142
19	ZN	.025	.513	-.518	.310	.106	.079	-.149	.345	-.183	.013
20	CU	-.033	.202	-.242	-.414	-.206	.073	-.147	.580	.048	-.248
21	PB	-.015	-.042	.649	-.341	.308	.170	.136	-.050	.090	.150
22	CD	-.105	-.021	.329	.055	.179	.361	.353	-.232	-.060	.134
23	HG	-.121	.027	.157	.317	.317	.137	.120	-.233	-.150	.155
24	AS	.043	-.241	.136	-.107	.155	.352	.431	-.294	.075	-.026
25	CHL	-.153	-.003	.278	-.092	.209	-.023	.031	-.237	-.021	.140
26	CN	-.018	-.041	.191	-.067	.235	.231	.318	-.260	-.231	.203
27	[illegible]	-.135	.054	.139	-.062	.274	.235	.021	-.263	-.177	.038
28	[illegible]	-.055	-.056	.097	.016	-.130	-.101	.053	-.132	.211	-.050
29	C	-.177	.103	.224	.016	.240	-.214	-.068	-.149	-.139	.187
30	BOD	-.382	.493	-.110	.175	-.170	.071	-.052	.441	-.693	.020
31	[illegible]	.119	-.358	.262	-.041	.190	-.288	-.010	-.351	.620	.065

Table 11.--Continued Correlation Matrix

CORRELATION MATRIX

		11 CL	12 MG	13 CA	14 NA	15 PO4	16 PH	17 FE	18 MN	19 ZN	20 CU
1	DEPTH	.015	-.114	.217	.039	-.067	-.073	.040	-.022	.025	-.029
2	TEMP	.002	.145	-.179	-.114	-.053	.120	-.030	.415	.513	.042
3	DO	-.031	-.123	-.141	-.007	-.048	.240	-.050	-.272	-.519	-.242
4	LS	.339	-.052	-.045	.111	-.111	.072	-.356	-.233	.210	-.414
5	SS	.012	.254	.383	.607	.070	-.307	-.001	-.282	.106	-.236
6	EC	.713	.370	.164	.594	.454	-.215	-.123	.008	.079	.073
7	COD	.223	.074	.065	.117	.307	.064	-.292	-.071	-.148	-.147
8	[illegible]	-.037	.121	-.039	-.011	.043	.273	.100	.649	.365	.530
9	[illegible]	-.156	-.079	.021	-.197	.060	-.063	.152	-.162	-.194	.045
10	NO3	.254	.115	.101	.261	-.147	-.274	-.237	-.142	.013	-.258
11	CL	1.000	.231	.137	.574	.359	-.141	.014	.056	-.046	.144
12	MG	.231	1.000	-.402	.709	.237	-.071	.057	.094	.310	.218
13	CA	.137	-.402	1.000	.141	.022	-.050	-.042	-.060	-.139	-.093
14	NA	.574	.709	.141	1.000	.249	-.252	.041	-.156	.041	-.242
15	PO4	.359	.237	.022	.249	1.000	-.045	-.153	-.052	.028	-.132
16	PH	-.141	-.071	-.050	-.252	-.045	1.000	.251	.003	.203	.212
17	FE	.014	.057	-.042	.041	-.150	.251	1.000	-.016	.170	.464
18	MN	.056	.094	-.060	-.156	-.052	.089	-.018	1.000	-.002	.014
19	ZN	-.046	.310	-.139	.041	.028	.203	.170	-.002	1.000	.060
20	CU	.144	.218	-.093	-.242	-.132	.212	.464	.014	.060	1.000
21	[illegible]	.088	-.115	.169	.303	.067	-.325	-.073	-.744	-.615	-.531
22	[illegible]	.263	.033	.149	.113	.314	.260	-.306	-.224	-.236	-.255
23	[illegible]	.165	-.013	.142	.088	-.045	.194	-.342	-.124	-.135	-.304
24	[illegible]	.251	.063	.110	.174	.439	.222	-.009	-.282	-.205	-.177
25	[illegible]	-.030	-.084	.119	.006	-.211	.057	-.147	-.190	-.170	-.271
26	[illegible]	.175	.025	.157	.131	.108	.286	-.333	-.157	-.150	-.263
27	[illegible]	.387	.255	-.033	.342	.277	.252	.144	-.300	.153	-.139
28	[illegible]	-.115	-.195	-.016	-.165	.307	.030	-.347	-.126	-.170	-.256
29	[illegible]	-.154	-.042	.087	-.029	-.267	-.001	-.364	-.088	-.090	-.321
30	[illegible]	.239	.264	-.017	-.103	.146	.293	.491	.210	.499	.309
31	[illegible]	-.374	-.284	.124	-.004	-.308	-.126	-.576	-.311	-.604	-.471

Table 11.--Continued Correlation Matrix

CORRELATION MATRIX

		21 B	22 N	23 DR	24 MOS	25 CAL	26 CY	27 K	28 A	29 C	30 PPR	31 ALK
1	DEPTH	-.015	-.105	-.121	.043	-.153	-.085	-.125	-.065	-.177	-.382	.119
2	TEMP	-.682	-.283	.027	-.241	-.303	-.041	.054	-.054	.103	.493	-.358
3	DO	.549	.229	.157	.135	.278	.191	.133	.007	.254	-.110	.262
4	LE	-.241	.256	.017	-.107	-.202	-.007	-.062	.016	.015	.175	-.041
5	[illegible]	.308	.179	.317	.155	.209	.285	.274	-.130	.240	-.170	.140
6	[illegible]	.179	.301	.137	.352	-.123	.231	.285	-.101	-.214	.071	-.288
7	[illegible]	.136	.358	.129	.431	.131	.312	.021	.063	-.063	-.042	-.019
8	[illegible]	-.303	-.272	-.038	-.054	-.237	-.263	-.243	-.139	-.149	.241	-.331
9	[illegible]	.021	-.300	-.150	.075	-.121	-.231	-.177	.211	-.139	-.493	.023
10	[illegible]	.130	.134	.165	-.220	.140	.203	.068	-.040	.187	.020	.155
11	[illegible]	.328	.245	.155	.251	-.039	.175	.327	-.015	-.154	.229	-.374
12	[illegible]	-.115	.010	-.018	.063	-.084	.025	.285	-.155	-.052	.238	-.244
13	[illegible]	.153	.149	.142	.110	.119	.157	-.033	-.015	.037	-.217	.124
14	[illegible]	.240	.113	.086	.174	.006	.131	.252	-.165	-.029	-.103	[illegible]
15	[illegible]	.037	.014	-.045	.439	-.211	.104	.277	.307	-.267	.146	[illegible]
16	[illegible]	-.305	.251	.194	.222	.057	.256	.252	.030	-.001	.222	-.126
17	[illegible]	-.373	-.305	-.349	-.069	-.147	-.363	.144	-.307	-.305	.491	-.376
18	[illegible]	-.746	-.224	-.124	-.232	-.100	-.157	-.300	-.126	-.025	.210	-.311
19	[illegible]	-.215	-.236	-.135	-.205	-.170	-.160	.153	-.178	-.090	.499	[illegible]
20	[illegible]	-.331	-.205	-.304	-.177	-.171	-.253	-.139	-.256	-.321	.309	[illegible]
21	B	1.000	.293	.197	.347	.179	.215	.149	.047	.047	-.305	[illegible]
22	N	.293	1.000	.437	.557	.145	.679	.337	.295	.114	-.152	[illegible]
23	DR	.197	.437	1.000	.192	.150	.579	.086	.214	.456	-.127	.182
24	MOS	.347	.557	.192	1.000	.043	.372	.417	.107	-.112	-.116	[illegible]
25	CAL	.179	.145	.150	.043	1.000	.224	-.050	.214	.570	-.174	.432
26	CY	.215	.679	.579	.372	.224	1.000	.313	.176	.206	-.070	.286
27	K	.149	.337	.086	.417	-.050	.313	1.000	.001	-.110	.228	-.343
28	A	.047	.295	.214	.107	.214	.176	.001	1.000	.102	-.124	.115
29	C	.047	.114	.456	-.112	.570	.206	-.110	.102	1.000	-.072	.412
30	PPR	-.305	-.152	-.127	-.116	-.174	-.070	.228	-.124	-.072	1.000	-.513
31	ALK	.305	.133	.182	-.010	.432	.286	-.233	.145	.412	-.513	[illegible]

Table 12. Per Cent of Variance Explained by Each Eigenvalue

	Eigenvalues	Per Cent Variance	Cumulative Per Cent
1	6.00110	.19358	.19358
2	4.91945	.14579	.33937
3	3.94840	.12737	.46674
4	2.52296	.08139	.54813
5	2.08846	.06737	.61550
6	1.84646	.05956	.67506
7	1.25015	.04033	.71539
8	1.21887	.03932	.75470

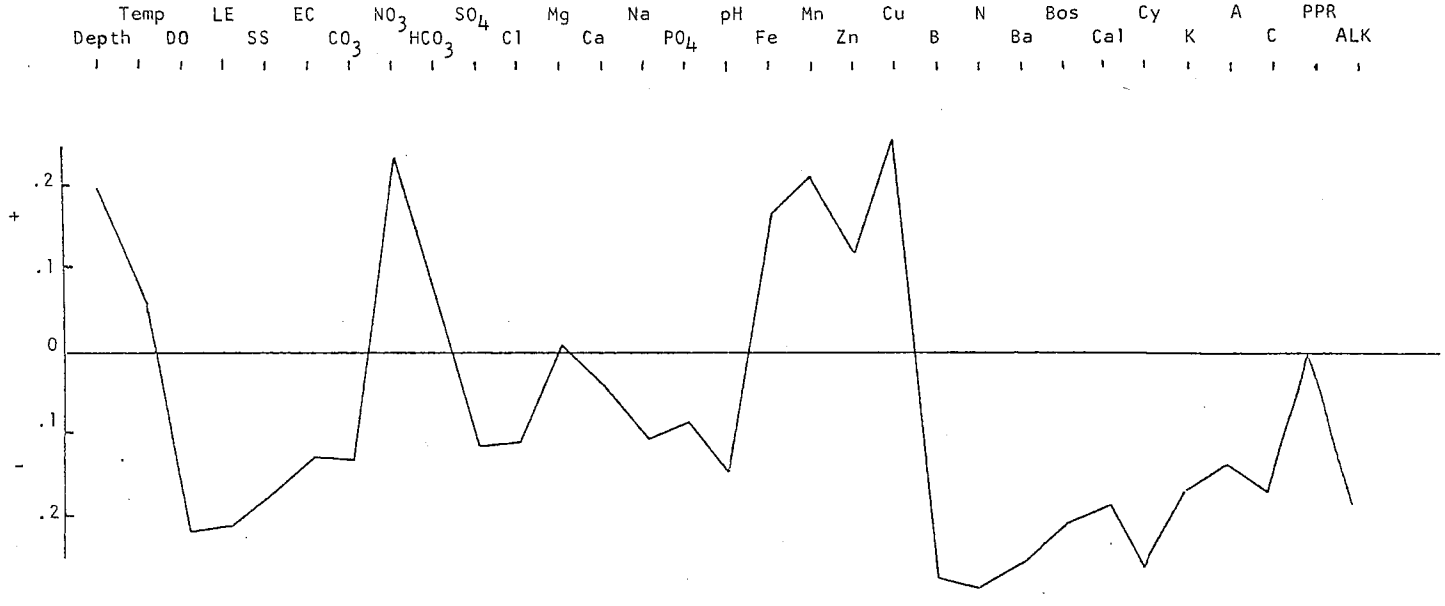


Figure 43. Dominant Eigenvector of the 31 Variables

deep water was a considerable reduction in the numbers of all the species.

The second eigenvector accounts for about 15 per cent of the variance in the data. The plot in Figure 44 shows that close to the surface of the water the temperature was above normal. The light extinction was very high. The zooplankton were above normal in numbers with the ppr being very high.

As we looked at the next 3 eigenvectors we realized that the data were separating out according to depth, season, and location.

Since the best eigenvector could only explain 20 per cent of the data relationships we decided the Principal Component Analysis was a poor predictive tool when dealing with seasonal data from different stations.

Testing the Model

Since the multiple regression model accounted for 82 per cent of the variance in the ppr values, we decided to test the six variables used. The Bureau of Reclamation Raft on the 7th of September, 1970 was eliminated from the data. The Stepwise Regression was forced to look only at the six variables of equation (6.6). The resulting equation was of the form:

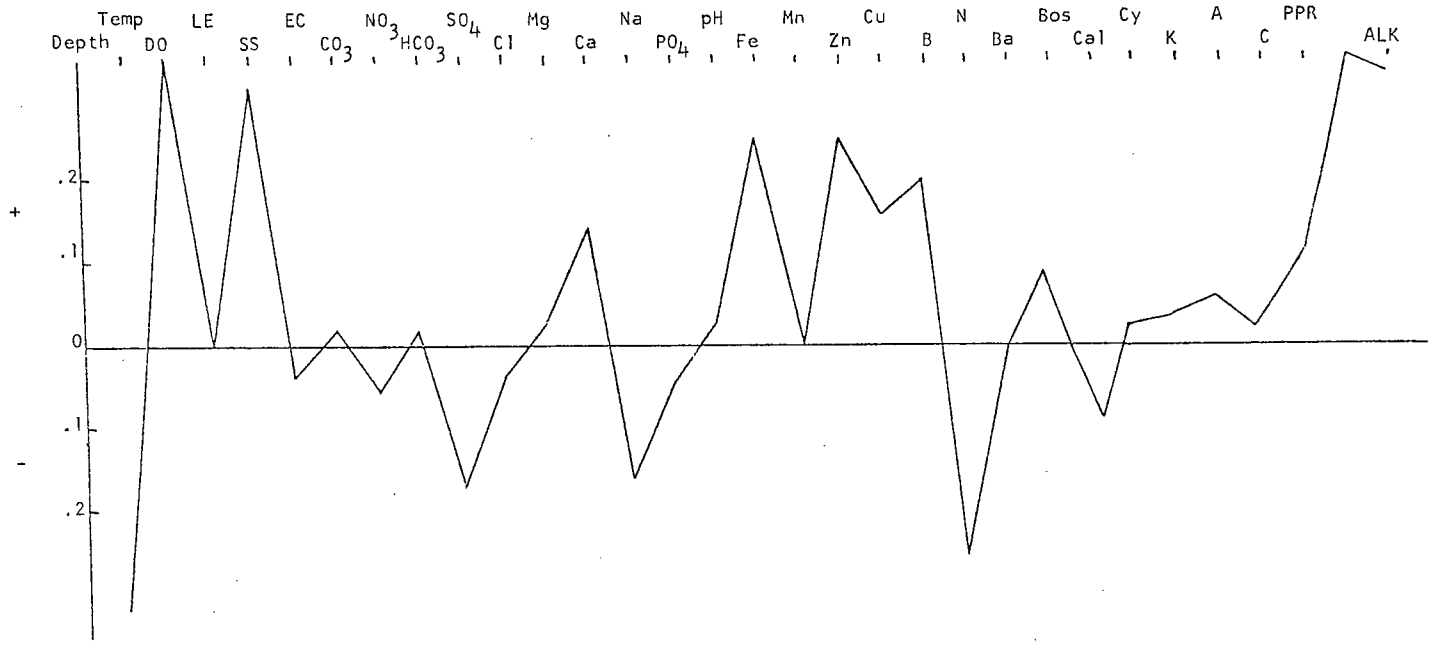


Figure 44. Minor Eigenvector of the 31 Variables

$$ppr = 116.5 + (.529)(Temp) - (.589)(HCO_3) - (.090)(SO_4) + 234\ (PO_4) - (.035)(Bosmina) - (.014)(Cyclopoda) \quad (6.9)$$

The variables measured on the 7th of September, 1970 at the Raft included:

Temperature	26.4°C
HCO_3	117 ppm
SO_4	320 ppm
PO_4	.02 ppm
Bosmina	0
Cyclopoda	0

Substituting into equation (6.9):

$$ppr = 116.5 + (.529)(26.4) - (.589)(117) - (.090)(320) + (234)(.02) - (.035)(0) - (.014)(0)$$

$$= 41.0 \text{ mg C fixed/m}^3\text{/day} \quad (6.10)$$

The actual ppr measured at the Raft was 37.8 mg C fixed/ mg^3/day. Since equation (6.9) was derived independent of the data measured on the 7th of September, 1970 we are optimistic about the excellent predictability of the regression equation.

CHAPTER 7

CONCLUSIONS

Discussion

The ex post appreciation of the sample design in any field study should be evaluated not only to qualify the ex ante design but also to provide desperately needed insight into future field surveys. The Lake Mead investigation has shown that repetitive winter investigations do not provide further insight into the ppr causal relationships. We conclude from the chemical and biological data that the February run was of no added value. Rather, we suggest that more sampling should have been done during times of greatest change, i.e., August to November. The temporal sampling design in any ppr investigation should be based, ex ante, upon the knowledge of thermal stratification in the subject water system so as to insure the sampling of highest pollution potential.

The horizontal spatial distribution of ppr did not vary in wave number with temporal sampling. This led us to believe that we had adequately described the spatial changes in ppr across the reservoir. We were very interested to note that the relative ppr at each station did not change with time. This suggests that if the inputs to the

system do not change, the water temperature is a dominant factor in ppr.

The vertical distribution of ppr at each location was described very well. The intensive sampling at depths of 0, 1, 3, 5, 7, and 10 meters quantified the areas of highest algal photosynthesis. The samples taken at 15 and 20 meters described the reduction of ppr with depth. The ppr below 20 meters was negligible at all sample dates and locations.

The assumption of chemical homogeneity above and below the thermocline is too gross an approximation for pollution investigations. The cost of chemical analyses was such that samples could be taken at 5 and 30 meter depths. We would rather have seen more chemical sampling in the high ppr areas. Future investigations should include in-depth sampling to develop some appreciation of reservoir effects upon chemical distributions.

Temporal and spatial changes in chemical and biological properties of the river-reservoir system have been established. The ppr data in Figure 45 show how Lake Mead behaves as an oligotrophic lake in the winter months and as an eutrophic lake in the summer months. The sensitive ppr technique indicated how the algal growth rates accelerated from June to September. The EPA (1967) Report on Pollution in Las Vegas Wash was conducted in May, 1966. Using the poor index of 2,000 algae/ml, EPA was attempting

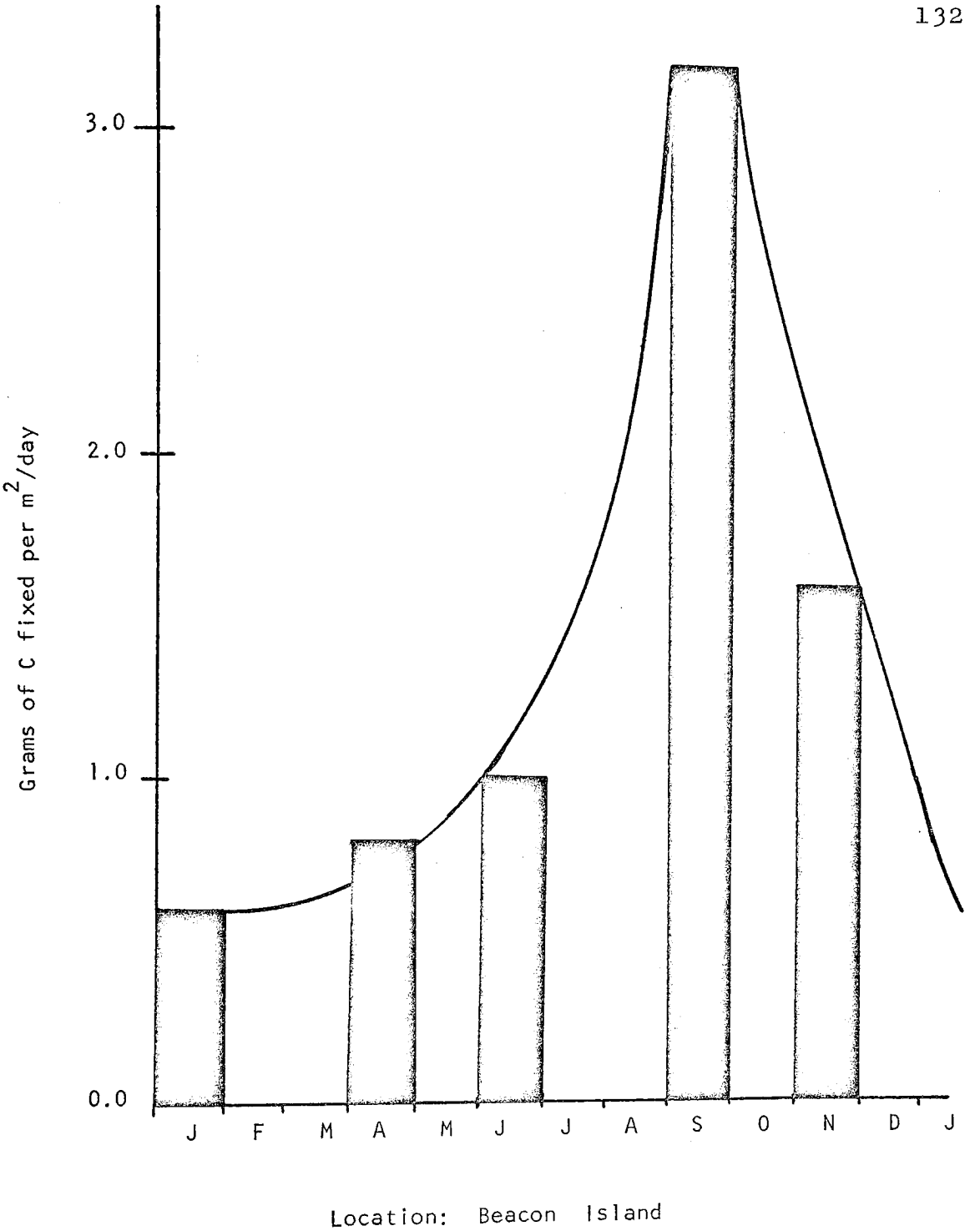


Figure 45. Temporal Changes in Algal Growth Rates

to set some water quality standards. Our data show how the September values are considerably higher than the May-June values. Consequently, any standard set for May values would naturally be broken in September. The Bureau of Reclamation (1970) report used data taken in May and November, completely missing the high September values. The Bureau of Reclamation (1971) report used March, May, August, and November sampling dates but showed that highest chlorophyll values occurred in May, not August. The May temperature profile showed the Lake was still in winter conditions with no thermal stratification. The EPA (1968a) report used data taken in April. We can only conclude that when pollution parameters are being investigated they should at least be measured during their highest temporal values.

The spatial changes in chemical and biological properties of the system provided considerable insight to the effect of inputs to Lake Mead. Las Vegas Wash, the Muddy and Virgin Rivers, and the Colorado River all contribute different concentrations of chemical species. The effect of this changing chemistry could only be measured by using a number of sampling sites. The input and output (South Cove and Bureau Raft) often acted very much alike. However, the changes through the system described variabilities that partially explained the problem in Lake Mead (Figure 42).

Primary productivity rates (ppr) and plankton population counts were conducted at several sampling locations in Lake Mead. Two major sources of pollution were concluded from the ppr data (Figure 46). Las Vegas Wash was the major source of pollution to Lake Mead. The three locations in Boulder Basin indicated that the pollution source at Las Vegas Wash had affected the whole Basin. In fact, the Bureau Raft, which is the station closest to Hoover Dam, shows ppr rates higher than Las Vegas Bay. The higher values at Beacon Island which is upstream from Las Vegas Bay, indicates that the hydrodynamics are circulating the pollutants throughout the Basin.

The minor source of pollution occurs at South Cove. Since there are no sewage treatment facilities at South Cove, we could assume that there is some contribution from "campers." However, earlier works by the EPA (1968a) indicate that the highest nutrient levels are recorded above Gregg's Basin. We conclude that there is a nutrient source in the Grand Canyon. The source may be natural or the result of human wastes. Regardless of the source, the need exists to determine where and how nutrients are entering South Cove.

The zooplankton analysis at each of the stations has resulted in useful diagnostic data. The total number of the rotifer Keratella (Figure 35) indicates that Boulder Basin acts completely independent of the whole of Lake Mead

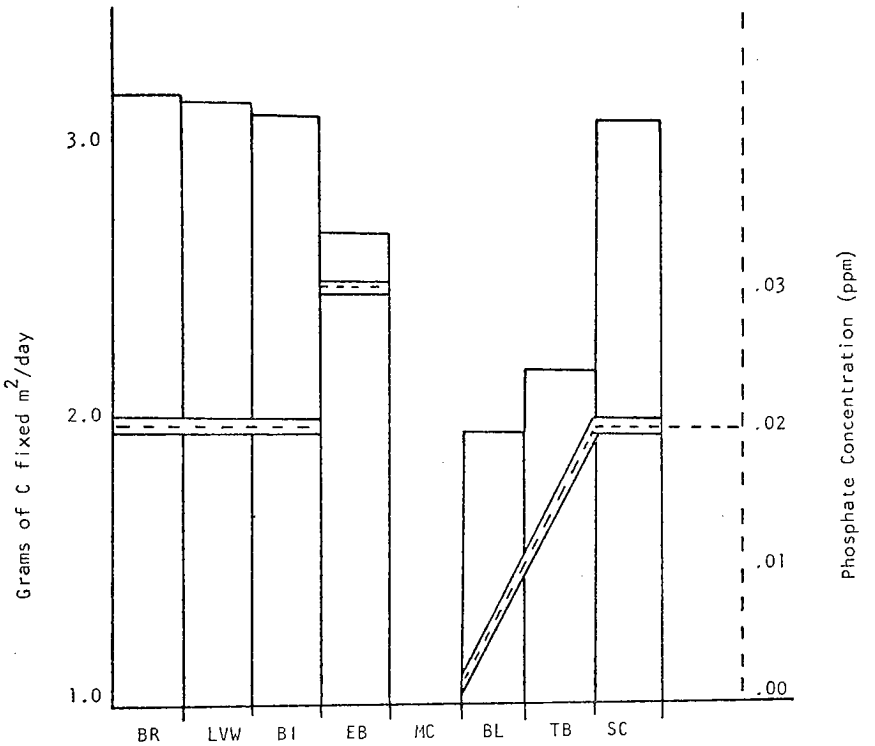


Figure 46. Spatial Distribution of PPR and Phosphate (September, 1970)

with respect to Keratella. South Cove and Echo Bay have high ppr; however, the total number of Keratella at these two locations is not different from the low ppr areas at Bonelli Landing and Temple Bar. Keratella is an indicator of the poor water quality in Boulder Basin. The increase in this organism outside of Boulder Basin would indicate a spreading of the water problem.

Ceratium was one of the phytoplankton that were analyzed. Hutchinson (1967) places Ceratium in his eutrophic plankton category but states that Ceratium is most probably an indicator of mesotrophic water, i.e., between oligotrophic and eutrophic types. Our phytoplankton data confirm Hutchinson's theory. All of our data have shown that Boulder Basin is highly polluted and the rest of the Lake is in an oligotrophic state. The total number of Ceratium (Figure 41) shows that Ceratium is low in numbers in Boulder Basin indicating that it can exist in eutrophic waters. However, the majority of the Ceratium was found upstream of Boulder Basin in the oligotrophic or mesotrophic waters.

The macro and micro nutrient concentrations at each sampling location were determined. The concentration of micro-nutrients was not low enough to reduce the ppr rates. There is strong evidence that the HCO_3, SO_4, and PO_4 levels are the major elements controlling the ppr. This assumes

that the other nutrients, i.e., nitrates, are available in sufficient supply.

The two dimensional distribution of the nutrients has shown that Las Vegas Wash, Echo Bay, and South Cove are receiving high nutrient levels. The vertical distribution of nutrient shows that Mg, K, Mn, Z, Cu, and SO_4 do not change with thermal stratification, while Cl, Na, Ca, and HCO_3 show a noticeable difference in their 5 and 30 meter data during summer stratification.

The last objective of the study was to relate ppr to physical and chemical changes in the system. The sampling dates (Table 6) were chosen to maximize the number of state sets. The surveys were designed to measure the state sets as thermal stratification began and ended. State sets were also measured during stratification and winter turnover. The locations were chosen across the Lake to represent the largest variety of conditions. In effect, we tried to vary all the parameters over their natural range in Lake Mead and relate them to ppr. The four classes of state sets are given in Figure 17. Class I included the highest number of variables and was used to develop our regression model. All of the variables included in this study are represented in Class I. The number of state sets in Class II is four times as many as Class I, but only 14 variables were investigated. Classes III and

IV have progressively higher numbers of state sets, but the number of variables are reduced to two.

The Class I data were used to develop the stepwise regression analysis. The resulting equation was:

$$ppr = 117 + (.527)(Temp) - (.593)(HCO_3) - (.090)(SO_4) + (235)(PO_4) - (.035)(Bosmina) - (.014)(Cyclopoda) \quad (7.1)$$

The computer selected physical, chemical, and biological parameters in their respective order. The units to be used in equation (7.1) are:

ppr	= Mg C fixed/m^2/day
Temperature	= °C
HCO_3	= ppm or mg/liter
SO_4	= ppm or mg/liter
PO_4	= ppm or mg/liter
<u>Bosmina</u>	= number in 6 liters
<u>Cyclopoda</u>	= number in 6 liters

The equation accounts for 82 per cent of the variability in the ppr data. The level of confidence in these six parameters was set at 95 per cent. The works of Cole (1967), Chen (1970), and DiToro et al. (1970) describe algal growth rate (ppr) as a function of temperature, chemistries, and grazing zooplankton. The major difference in our approach is the lack of a solar energy source. We

have shown that in Lake Mead light penetration improvement has not resulted in higher productivity. In fact, as the light penetration improves from South Cove to Bonelli Landing, the ppr rates decrease considerably.

The equation (7.1) was tested by removing one station from the data and computing a new stepwise regression equation (6.9). The new equation was very close to the original equation which included all of the data. This would indicate that the pattern across Lake Mead had been very well defined. The result of the test was very close to the actual ppr value. We conclude from the test that the state sets measured included the ranges of the variables in the test station. We are confident that we have measured the majority of the state sets in Lake Mead and can predict the ppr at most locations at any time of the year. Using the criteria established by Rodhe in Table 8, the regression model is a first approximation for realistic prediction and is of management utility.

Future State Set Analysis

We have shown that equation (7.1) holds for the eight stations in Lake Mead at 5 meter depths. However, the utility of the equation can be improved considerably by increasing the number of state sets in Class I. To increase the number of state sets we would maintain the same number of variables and increase the number of

different locations. To accomplish this, we could take the study into Lake Mohave, Lake Havasu, and Imperial Reservoir. At each of these locations several sets of states will be obtained.

The validity of the existing model should be tested with a complete set of independent data. The test data will serve not only to validate the model, but also to increase its predictive range.

APPENDIX A

ZOOPLANKTON DISTRIBUTION

Organism	Bureau Raft	Las Vegas Wash	Beacon Island	Miner's Cove	Echo Bay	Bonelli Landing	Temple Bar	South Cove	(Mon)
Nauplius	74	29	77	97	118	69	44	219	Jan
	779	786	437	493	578	290	225	178	Feb
	1502	2078	1768	1033	1113	2032	740	567	Apr
	260	867	292	226	228	161	220	750	Jun
	365		208	96	182	134	86	176	Sep
	194	256	71	42	69	47	16	85	Nov
Daphnia	0	0	0	0	6	0	0	4	Jan
	5	16	4	19	191	9	28	19	Feb
	255	858	507	436	572	647	228	187	Apr
	1475	674	315	361	384	191	321	235	Jun
	0		0	0	2	0	0	0	Sep
	0	0	0	0	12	0	0	2	Nov
Bosmina	70	332	50	17	21	4	74	133	Jan
	726	1835	343	293	319	226	184	123	Feb
	153	1749	1338	248	152	406	185	185	Apr
	8	60	4	4	8	4	9	22	Jun
	4		8	34	2	2	4	6	Sep
	15	25	19	23	133	77	28	29	Nov
Calanoida	0	8	8	0	17	9	6	21	Jan
	162	54	51	385	285	32	25	15	Feb
	152	104	71	261	310	253	137	129	Apr
	215	86	209	264	386	72	272	219	Jun
	0		0	8	0	0	2	0	Sep
	0	0	11	12	31	10	14	5	Nov

Organism	Bureau Raft	Las Vegas Wash	Beacon Island	Miner's Cove	Echo Bay	Bonelli Landing	Temple Bar	South Cove	(Mon)
Cyclopoida	15	28	21	25	6	0	15	42	Jan
	180	221	67	220	485	85	66	45	Feb
	972	1985	1830	476	780	906	208	256	Apr
	690	1801	705	550	257	366	296	172	Jun
	48		44	78	18	6	50	70	Sep
	63	79	41	17	48	13	3	24	Nov
Keratella	426	277	397	143	69	79	23	27	Jan
	970	1274	656	55	85	52	25	70	Feb
	564	750	623	39	32	118	143	128	Apr
	75	991	40	9	43	17	0	29	Jun
	470		842	1342	14	342	320	216	Sep
	84	47	88	8	0	31	1	0	Nov
Asterionella	0	0	0	0	0	0	0	0	Jan
	5	3	48	0	0	6	3	27	Feb
	121	813	17	251	232	328	812	1849	Apr
	130	0	18	34	76	4	76	426	Jun
	0		0	0	0	0	0	0	Sep
	1	0	1	0	0	0	0	0	Nov
Ceratium	0	0	0	197	219	370	42	144	Jan
	3	2	15	651	1577	374	178	203	Feb
	46	118	41	8705	24286	6054	1073	2093	Apr
	18195	10640	15695	29972	23293	30840	25821	32746	Jun
	22		2	0	2	4	0	6	Sep
	0	0	0	12	9	10	0	3	Nov

APPENDIX B

STEPWISE REGRESSION PRINTOUT

Step No. 6
Variable Entering 23
F Level = 4.100
Standard Error of Y = 4.838441E + 00
R-Squared = 8.228338E - 01
Constant = 1.171260E + 02

Variable	Coefficient	Std Error of Coef	T Value
1	5.276966E-01	1.823218E-01	2.894313E+00
8	-5.930301E-01	9.331045E-02	-6.355452E+00
9	-9.029366E-02	2.874343E-02	-3.141367E+00
14	2.348079E+02	7.444931E+01	3.153929E+00
23	-3.543582E-02	1.750104E-02	-2.024784E+00
25	-1.429743E-02	8.392991E-03	-1.703496E+00

Analysis of Variance

Source of Variation	df	Sum of Squares	Mean Square	F-Ratio
Regression	6	4.240400E+03	7.067333E+02	30.189
Residual	39	9.130101E+02	2.341052E+01	
Total	45	5.153410E+03		

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