NUTRIENT MANAGEMENT WITH

HYDROELECTRIC DAMS ON THE COLORADO

RIVER SYSTEM[1]

Larry J. Paulson[2]

Lake Mead Limnological Research Center
Department of Biological Sciences
University of Nevada, Las Vegas
Technical Report No. 8

February 1981

1) A version of this report is being submitted to the Journal of the American Society of Limnology and Oceanography.

2) Director, Lake Mead Limnological Research Center

ABSTRACT

Phytoplankton growth in lakes and reservoirs can usually be controlled by diverting or chemically treating (AWT) wastewater inflows. However, needs to conserve and reuse wastewaters and high costs for AWT have limited implementation of these nutrient management techniques. In reservoirs with high flushing rates, the outflow represents a major nutrient loss which can vary with the operation of dams. Biological processes create vertical nutrient gradients in Lake Mead from which water of varying fertility can be drawn for discharge. The present-day operation of Hoover Dam from a deep-water discharge results in annual nutrient losses of 6273×10^3 kg N and 169×10^3 kg P. This effectively protects the reservoir from nutrient buildup and eutrophication by wastewater discharge into Las Vegas Bay. Long-term operation of the dam from the deep discharge (hypolimnion) has contributed to a decrease in reservoir fertility since Lake Powell was formed upstream in 1963. Reservoir productivity has decreased accordingly and may be the cause for a serious decline in the largemouth bass fishery. Operation of Hoover Dam from a surface discharge (epilimnion) would decrease nutrient losses from Lake Mead and thus serve to increase reservoir fertility. Selective nutrient withdrawal at dams appears to be an effective method for managing reservoir nutrient status in multi-reservoir systems like the Colorado River.

INTRODUCTION

Phytoplankton growth in lakes and reservoirs can usually be controlled by manipulating flow rates (sewage diversions) or nutrient concentrations (advanced wastewater treatment) of wastewater inflows. These techniques have been reasonably effective in reducing or averting eutrophication, but their implementation has been limited by recent needs to conserve and reuse wastewaters or by the high treatment costs for advanced wastewater treatment (AWT). The contemporary approaches to nutrient management have evolved from nutrient loading models developed in studies of natural lakes (Vollenweider 1968). These lakes have long retention times, and nutrient losses in the outflow are minimal (Dillon 1975). In lakes and reservoirs with high flushing rates, the outflow can strongly influence ambient nutrient concentrations (Dillon 1975). Nutrient losses from reservoirs can further vary depending on how the operating criteria of hydroelectric dams or other impoundment structures interact with vertical nutrient gradients in the reservoir (Wright 1967; Soltero, Wright and Horpestad 1973; Martin and Arneson 1978; Paulson, Baker and Deacon 1979).

Selective withdrawal has long been recognized as a means of using natural thermal or dissolved oxygen gradients in reservoirs to manage water quality of tailwaters (Stroud and Martin 1973). Biological processes commonly alter the vertical and seasonal distribution of nutrients in thermally stratified reservoirs (Hannan 1979). This provides natural nutrient gradients from which water of varying fertility can be drawn for discharge. In this paper, I describe how the operation of Hoover Dam currently influences annual nutrient losses from Lake Mead, and how it may have influenced the nutrient and trophic status of the reservoir in the past. Nutrient models are presented to illustrate how Lake Mead would respond to different operating criteria at Hoover Dam, and the implications of this are discussed relative to reservoir nutrient management.

Description of Lake Mead

Lake Mead is a large interstate reservoir located in the Mojave Desert of southeastern Nevada and northwestern Arizona. It was formed in 1935 by construction of Hoover Dam and is one of a series of multipurpose reservoirs on the Colorado River. Lake Mead extends 183 km from the mouth of Grand Canyon to Black Canyon, the site of Hoover Dam (Fig. 1). It is separated into two large basins by Boulder Canyon located midway through the reservoir. The area above Boulder Canyon is collectively referred to as the Upper Basin, and that below as the Lower Basin. Lake Mead has a surface area of 660 km^2 and a volume of 36×10^9 m^3 at the maximum operating level of 374 m (Lara and Sanders 1970). Hoover Dam is equipped with intake gates at 320 m and 272 m elevations. The dam has been operated from the lower intake gates since 1954.

The Colorado River via discharges from Lake Powell provides 98% of the annual inflow to Lake Mead. The remainder is derived from the Virgin and Muddy Rivers, which discharge into the Overton Arm, and Las Vegas Wash which discharges secondary-treated sewage effluents into Las Vegas Bay (Fig. 1). The Colorado River provides 85% of the

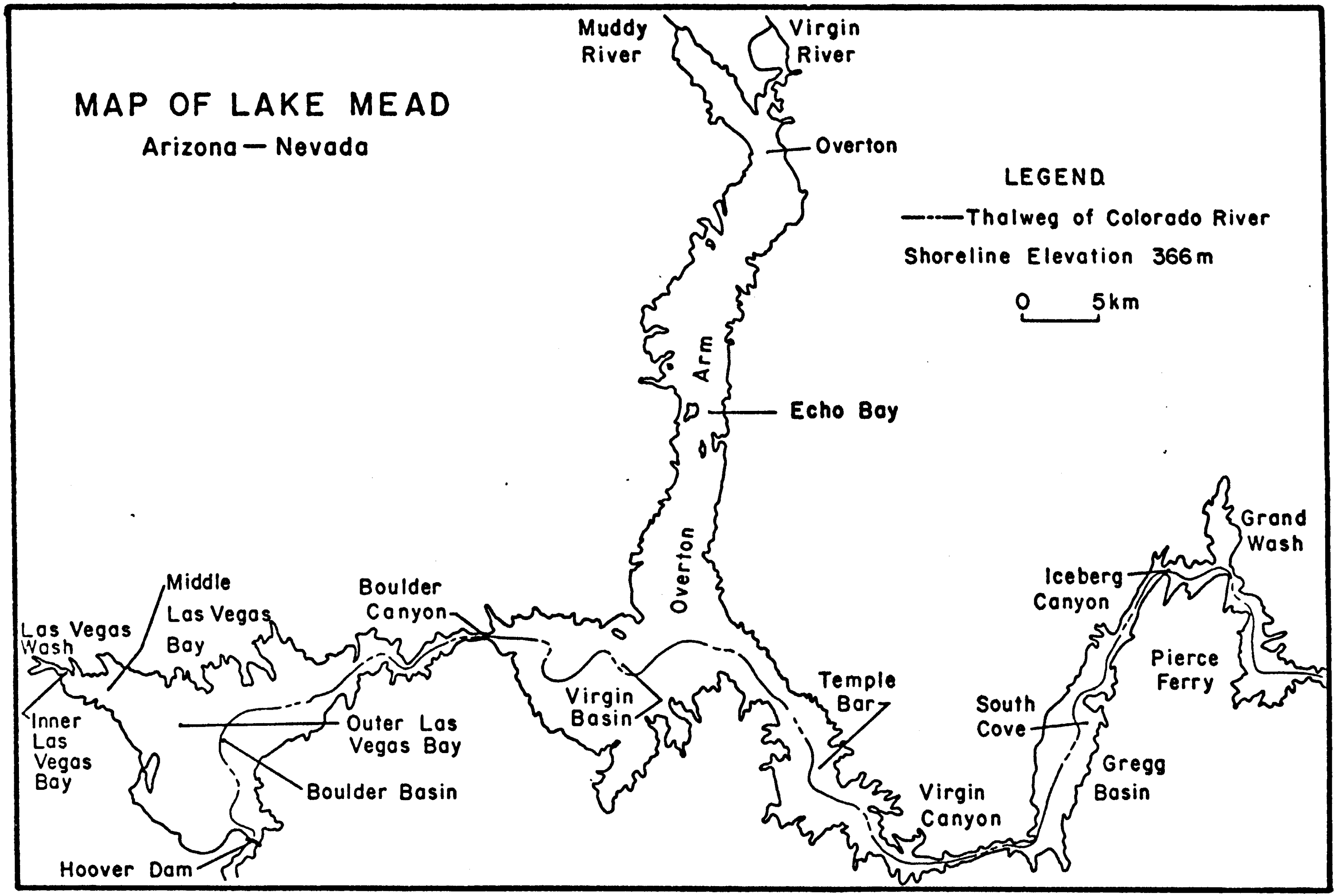

Fig. 1. Map of Lake Mead.

annual inorganic nitrogen, while Las Vegas Wash contributes 60% of the phosphorus input to the reservoir (Baker and Paulson 1981). The Upper Basin is phosphorus limited and most of the Lower Basin nitrogen limited during the summer months (Paulson and Baker 1981, Kellar and Paulson 1981). On the basis of chlorophyll-*a* concentrations the Upper Basin is oligotrophic, and most of the Lower Basin is oligotrophic-mesotrophic (Paulson, Baker and Deacon 1980). The inner portion of Las Vegas Bay, near the sewage outflow, is mesotrophic-eutrophic.

Lake Mead is monomictic and is usually completely mixed by January. Surface temperatures range from 10-12°C in the winter to 28-30°C in the summer. Thermal stratification develops at a depth of 10-15 m in late May and persists through October (Paulson et al. 1980). A metalimnetic oxygen minimum develops at the thermocline during the summer, and concentrations often decrease to less than 4 mg l^{-1}. Hypolimnetic oxygen concentrations usually exceed 6 mg l^{-1}. The waters are alkaline (pH 7.5-8.6) and high in salinity (750-800 mg l^{-1}).

METHODS

Historical nutrient data presented in this paper were derived from several sources. The U.S. Geological Survey (USGS) has monitored nitrate concentrations, monthly, in Grand Canyon, Lake Mead and below Hoover Dam ever since the reservoir was formed in 1935. These water quality records are published in "Quality of Surface Waters for the United States. Part 9. Colorado River Basin", through 1967 and in "Water Resources Data for Arizona" from 1968-present. Annual nitrate loading to Lake Mead from the Grand Canyon and loss rates at Hoover Dam were computed by multiplying mean annual nitrate concentrations (time weighted) by annual discharge rates. Discharge data for the Colorado River are published in: "Surface Waters of the United States. Part 9. Colorado River Basin"; U.S. Geological Survey Water Supply Papers until 1967, and in "Water Resources Data for Arizona" after 1967. Mean nitrate concentrations in Lake Mead were determined from USGS data collected monthly at the Hoover Dam intake towers (Fig. 1).

The nutrient profiles presented for Boulder Basin and chlorophyll-*a* concentrations for Las Vegas Bay during the period from 1972-1977 were derived from the Lake Mead Monitoring Program (Deacon and Tew 1973;

Deacon 1975, 1976, 1977). Chemical analyses for this program were performed by the U.S. Environmental Protection Agency, Las Vegas, Nevada, using methods described by Mullins, Snelling, Moden and Seals (1975). In 1972, chlorophyll-a concentrations were determined by 16 h acetone extractions (90%) of membrane filtered samples (Strickland and Parsons 1968). Chlorophyll-a has since been determined by grinding GFC filtered samples and 4 h extractions in 90% acetone (Golterman 1969). The equations of Strickland and Parsons (1972) were used to calculate total chlorophyll-a concentrations. Nutrient data presented since October 1977 have been collected on our recent investigations in Lake Mead using the following methods summarized from Kellar, Paulson and Paulson (1980).

Water samples were collected monthly from the epilimnion (0-5 m) and hypolimnion (70 m) near the Hoover Dam intake towers (Fig. 1) from October 1977-September 1978. Water samples were frozen, filtered (GFC) and analyzed for nitrate (Kamphake, Hannah and Cohen 1967) and phosphate (Strickland and Parsons 1972). From July 1979-July 1980, water samples were collected in Boulder Basin (Fig. 1) monthly during the winter, bimonthly during spring and fall, and weekly during the summer. Nitrate and phosphate analyses were performed as previously described. Samples were also analyzed for ammonia (Liddicoat, Tibbits and Butler 1975), total nitrogen (D'Elia, Stendler and Corwin 1977) and total phosphorus (Goldman 1974). Monthly nutrient loss rates from Hoover Dam were determined by multiplying epilimnion and hypolimnion nutrient concentrations by the respective monthly discharges from the dam.

RESULTS AND DISCUSSION

Inorganic Nutrient Distribution and Loss Rates

A consistent trend has been observed in the vertical distribution of nutrients in the Lower Basin of Lake Mead since monitoring began in 1972. Phytoplankton deplete nitrate, and to a lesser degree phosphate, from the epilimnion during the summer (Fig. 2). Nutrient concentrations remain high in the metalimnion and hypolimnion due to light limitation and sinking and remineralization of phytoplankton cells. The nutrient profiles shown in Fig. 2 develop in early summer and persist through

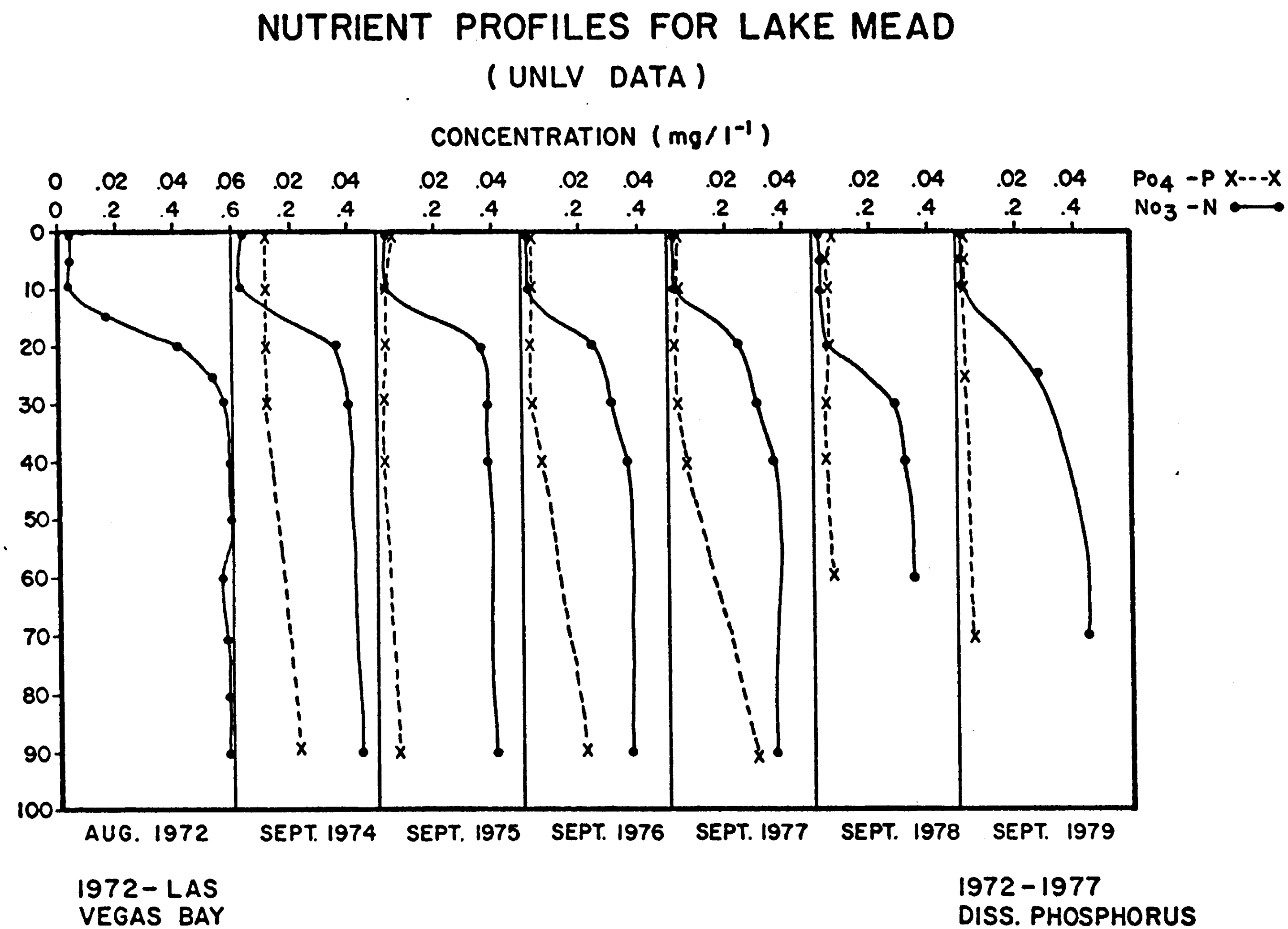

Fig. 2. Inorganic nutrient profiles for the Lower Basin, Lake Mead. Data for 1972 collected in Outer Las Vegas Bay and since then in Boulder Basin.

October when the reservoir begins to destratify. Epilimnetic nutrient concentrations progressively increase through the fall, and vertical nutrient gradients are reduced by mixing during isothermal periods of winter and early spring. These patterns in nutrient distribution are perhaps common to most stratified lakes and reservoirs, but they have added significance in Lake Mead due to the present-day operation of Hoover Dam.

Hoover Dam is currently operated from a hypolimnion discharge (90 m at 1977-78 lake elevations) and seasonal discharges are regulated to generate power and provide irrigation water. During the period from October 1977-September 1978, this resulted in annual losses of 2896 x 10^3 kg NO_3-N and 91 x 10^3 kg PO_4-P. Nitrate losses were greatest during summer when hypolimnion concentrations were high and discharges were elevated for power generation (Fig. 3). Phosphate losses were highest in the spring and early summer when loading from Las Vegas Wash increased hypolimnetic phosphorus concentrations in Boulder Basin (Baker and Paulson 1981). The present-day operations of Hoover Dam result in an enormous loss of inorganic nutrients from the reservoir, but this would decrease significantly if the dam were operated from an epilimnion discharge.

Annual nitrate loss would decrease to 750 x 10^3 kg N and phosphate to 49 x 10^3 kg P with an epilimnion discharge. These values are 74.1% and 46.2% lower than corresponding loss rates from the hypolimnion discharge. Phosphate losses would become fairly constant over the year due to less seasonal variation in epilimnetic concentrations (Fig. 3). Nitrate losses would be greatly reduced during summer when phytoplankton deplete epilimnetic nitrate concentrations. Inorganic nutrient losses from an epilimnion discharge would be similar to those from a hypolimnion discharge during winter when the reservoir is isothermal and completely mixed.

Even though inorganic nutrient losses from Hoover Dam would be significantly reduced with an epilimnion discharge, entrainment of phytoplankton, zooplankton, and other organic materials might simply alter the chemical form, and not the total amount, of nutrients lost in the discharge. In order to evaluate this possibility, we computed inorganic, organic and total nutrient loss rates from Hoover Dam during

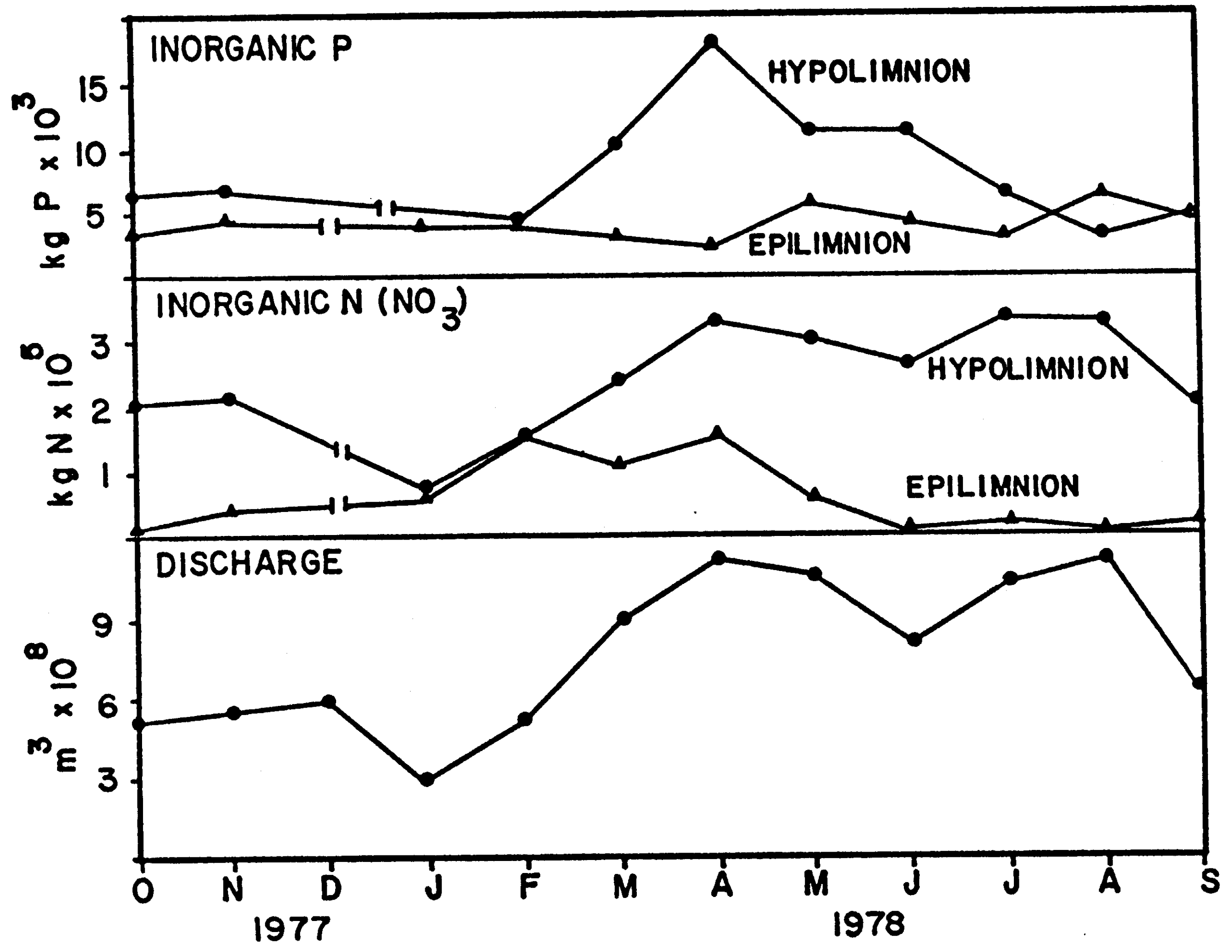

Fig. 3. Inorganic nutrient loss and discharge from Lake Mead from October 1977-September 1978.

July 1979-July 1980. The same seasonal trends were again evident in losses of inorganic nutrients (Fig. 4). Annual losses of inorganic nitrogen and phosphorus from the hypolimnion discharge exceeded those from the epilimnion discharge by 2535 x 10^3 kg N and 71 x 10^3 kg P (Table 1). Organic nitrogen and phosphorus losses were indeed slightly higher (381 x 10^3 kg N and 3 x 10^3 kg P) from the epilimnion than hypolimnion discharge, but the differences were low by comparison to those for inorganic nutrients (Table 1). Total nitrogen and total phosphorus losses would still be 2154 x 10^3 kg N and 68 x 10^3 kg P higher from the hypolimnion discharge. This indicates that rates of nutrient displacement into, and discharges from, the hypolimnion would still exceed rates of nutrient entrainment in discharges from the epilimnion. Alterations of discharge depth on Hoover Dam would, therefore, have a significant influence on losses of total, as well as inorganic, nutrients from Lake Mead.

Long-Term Effects of Reservoir Operation

The previous results clearly indicate that inorganic and total nutrient loss rates from Lake Mead will vary in relation to the depth of discharge at Hoover Dam. However, little is known about how this will influence reservoir nutrient concentrations over a long-term period. Wright (1967) hypothesized that deep-discharge reservoirs would progressively decline in fertility due to withdrawal of nutrient-rich hypolimnion water. He further maintained that shallow-discharge reservoirs would operate like natural lakes and increase in fertility. Wright's (1967) hypotheses have since been supported by comparative limnological studies in reservoirs on the Madison River (Martin and Arneson 1978), and the Colorado River (Paulson, Baker and Deacon 1979) systems.

In the Colorado River system, the formation of Lake Powell in 1963 resulted in a significant initial reduction in nitrate loading to Lake Mead (Fig. 5a). This was due primarily to low discharges from Glen Canyon Dam during the 1963 and 1964 water years. Annual discharges were increased again in 1965 and have since remained fairly constant (Paulson and Baker 1981). Nitrate loading, however, continued to increase through 1970 which we suspect was caused by a transient loss of nitrogen from the Lake Powell sediments when the reservoir was

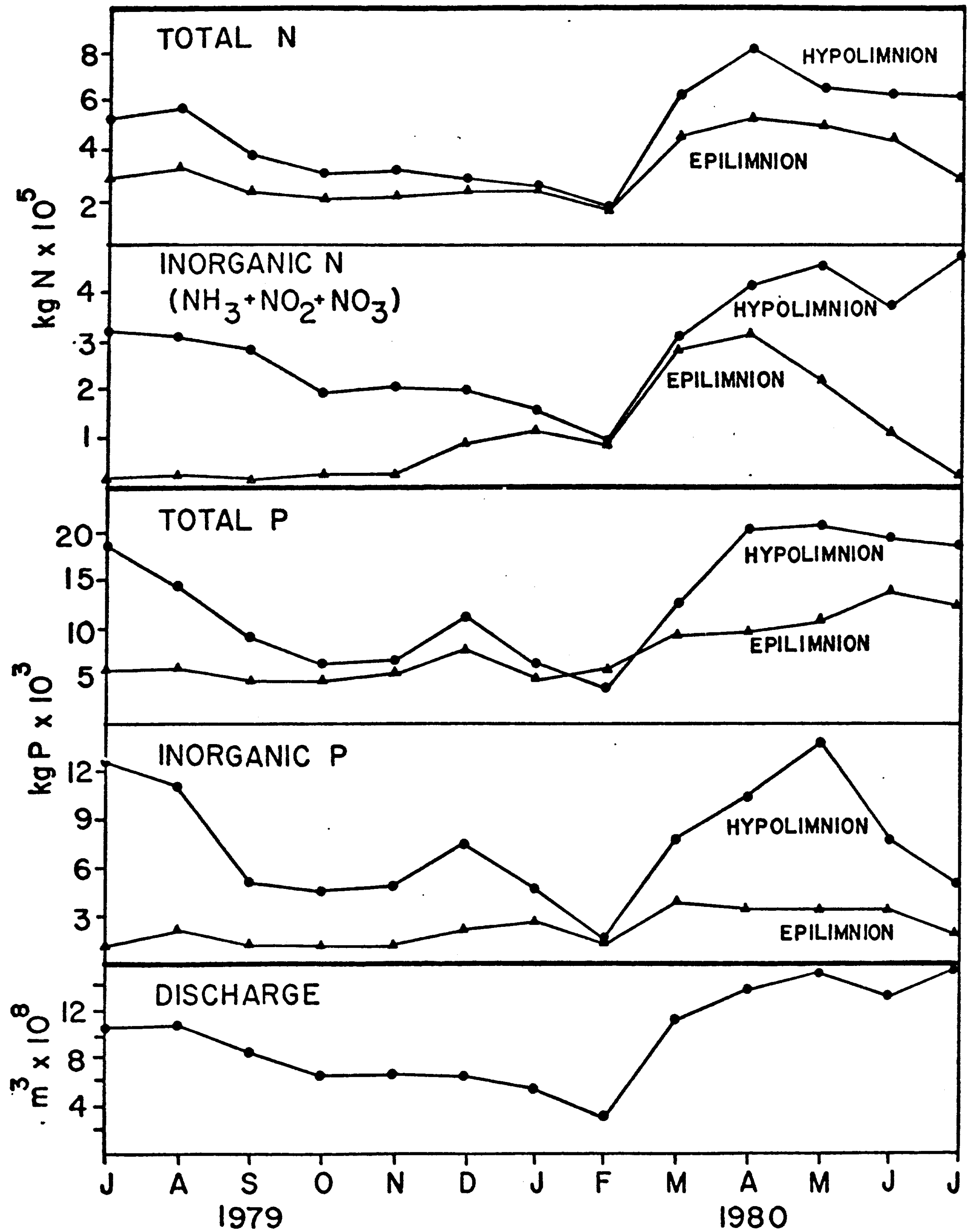

Fig. 4. Inorganic and total nutrient loss and discharge from Lake Mead July 1979-July 1980.

Table 1. Nutrient losses from Hoover Dam for an epilimnion and hypolimnion discharge during July 1979 to July 1980.

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

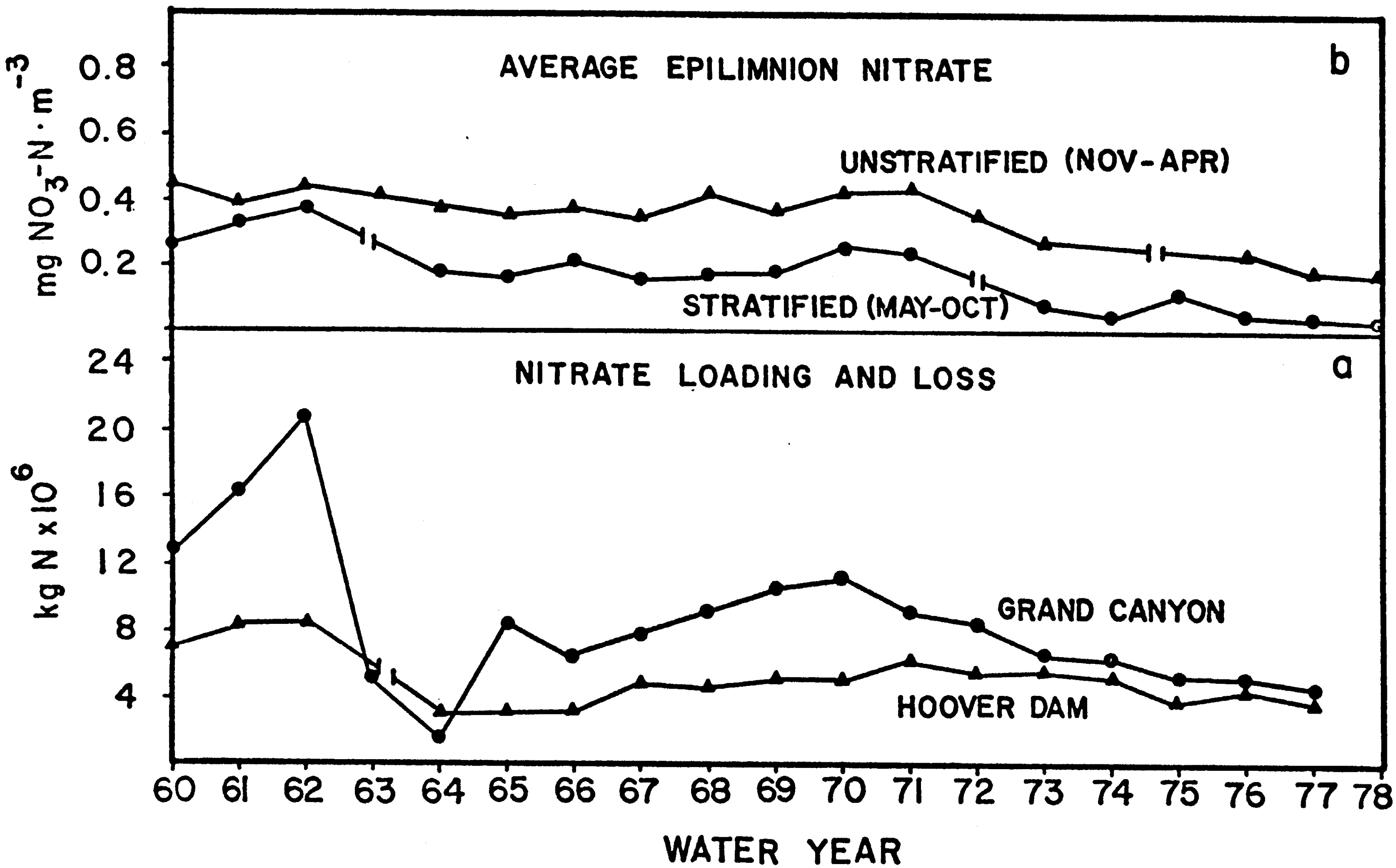

Fig. 5. Historical nitrate loading from Colorado River and loss at Hoover Dam and average epilimnion nitrate concentrations at the Hoover Dam intake towers. (USGS data).

filling (Paulson and Baker 1981). Nitrate loading decreased after 1970 and now appears to be approaching steady-state. These changes in loading were also accompanied by changes in nitrate concentrations in Lake Mead (Fig. 5b). Average epilimnetic nitrate concentrations have decreased from historic (1960-1962) levels of 300 mg m^{-3} to current levels of 50 mg m^{-3} during the thermally stratified period. Similarly, during unstratified periods, concentrations have declined from 400 mg m^{-3} to 150 mg m^{-3}. The greatest decreases occurred when nitrate loading was reduced in the Colorado River after 1970 (Fig. 5a). However, it appears that this was accelerated by high phosphorus loading from Las Vegas Wash that allowed phytoplankton to utilize more nitrate and subsequently increased nitrate losses from Hoover Dam and nitrogen sedimentation in the Lower Basin.

The Colorado River has historically been the principal nutrient source for Lake Mead (Paulson and Baker 1981). The river still provides nearly 85% of the annual nitrogen loading (Baker and Paulson 1981), but phosphorus loading was markedly reduced after Glen Canyon Dam was constructed in 1963 (Prentki, Paulson and Baker 1981). Lake Powell now retains 70% of the dissolved phosphorus inputs (Gloss, Mayer and Kidd 1980) and 80% of the suspended sediment loads (Paulson and Baker 1981) that once flowed into the Upper Basin of Lake Mead. Phosphorus desorption from suspended sediments in the Colorado River is an important mechanism for sustaining the dissolved phosphorus in Lake Powell (Mayer and Gloss 1980), and presumably such was also the case when turbid flows entered Lake Mead. Retention of suspended sediments and dissolved phosphorus in Lake Powell has thus reduced loading to Lake Mead and caused the reservoir to become more phosphorus limited after 1963.

Sewage effluent discharges from Las Vegas Wash, however, rose steadily over this period, and the effluents now contribute 15% of the annual nitrogen and 60% of the annual phosphorus input to the reservoir (Baker and Paulson 1981). The phosphorus-rich inflow is confined to the Lower Basin and historically has elevated phosphorus concentrations and phytoplankton productivity in the basin (Paulson and Baker 1981). High phosphorus loading in the late 1960's and early 1970's enabled phytoplankton to assimilate more inorganic nitrogen and contributed to the decline in nitrate concentrations that occurred after 1970 (Fig. 5b). Increased nitrate uptake and higher productivity also increased displacement of nitrogen to the sediments (Prentki et al. 1981). Nitrogen sedimentation in the Lower Basin increased from an average of 484 metric ton yr^{-1} in the pre-Lake Powell period to 636 metric ton yr^{-1} in the post period. Remineralization of sedimenting organic materials in the hypolimnion apparently also increased since there was a slight, but consistent, increase in nitrate losses from Hoover Dam during 1967-1971 (Fig. 5a). The combined losses of nitrogen (sediments and discharge) resulted in progressive depletions of nitrate in the Lower Basin during the early 1970s (Fig. 5b). High nitrate losses from Hoover Dam have since kept nitrate concentrations at low levels during stratified periods and caused further reductions in nitrate concentrations during the unstratified period (Fig. 5b).

The hypolimnion discharge at Hoover Dam has, therefore, had a major influence on historical nitrate concentrations in Lake Mead. In years of relatively high loading, the discharge effectively prevented nitrate accumulation in the reservoir. However, once loading from the Colorado River decreased in 1970, Hoover Dam rapidly stripped nitrate and accelerated the decline in reservoir nitrate concentrations. Lake Mead now appears to be approaching a steady-state, and nitrate concentrations will probably remain at current levels, so long as loading does not change.

Consequences on Reservoir Productivity

In a recent paper (Paulson and Baker 1981), we described how productivity in Lake Mead might have changed in response to changes in nutrient loading caused by the formation of Lake Powell. We concluded that reservoir-wide productivity must have decreased due to development of phosphorus deficiencies in the Upper Basin and nitrogen deficiencies in the Lower Basin. We recently completed a sediment survey in Lake Mead, and chemical analyses indicate that reservoir-wide productivity has decreased by as much as 55% of pre-Lake Powell levels (Prentki et al. 1981). The most severe reductions have occurred in the Upper Basin, but even near the sewage outflow in Las Vegas Bay, it appears that the formation of Lake Powell had an effect on productivity.

Chlorophyll-a concentrations have decreased considerably in the inner Las Vegas Bay since the first measurements were made in 1968 (Fig. 6). The most significant reduction has occurred during the spring, which is reflected by a decrease in maximum chlorophyll-a concentrations. The spring bloom began to diminish after 1972 and has since been reduced to about half the historic levels. Weekly phytoplankton counts made during the bloom in 1972 revealed that it was composed primarily of dinoflagellates (Glenodinium and Hemnidinium) and the green alga, Carteria (Fig. 7). There was a close relationship between the abundance of Hemnidinium and chlorophyll-a concentrations during the bloom period. This bloom tainted the waters of Las Vegas Bay red, and dinoflagellates may have been the cause for numerous local complaints regarding water quality in the bay during the late 1960s. These conditions ultimately led to the decision to construct a 53 million dollar AWT plant (90 mgd) in Las Vegas to remove phosphorus from effluents discharged into the bay. This decision has recently come under severe criticism, and the future operation of the plant will be determined through litigation.

This controversy, in part, stems from the apparent improvement in water quality of the bay (Fig. 6). Although phytoplankton counts have been done sporadically since 1972, data collected in the spring of 1975 and 1976 revealed that Hemnidinium was absent from the community, and the other species were greatly reduced in abundance (Table 2). Dinoflagellates generally require high nutrient concentrations, especially nitrate (Harrison 1973). Such nutrient conditions existed in Las Vegas Bay in the late 1960s and early 1970s (Hoffman, Tramutt and Heller 1971) when nitrate loading from the Colorado River was high and phosphorus loading from Las Vegas Wash was on the increase. Nitrate concentrations have since decreased throughout the reservoir due to reduced loading from the Colorado River and increased losses to the sediments and the Hoover Dam discharge. Las Vegas Wash only contributes 15% of the inorganic nitrogen to Lake Mead (Baker and Paulson 1981), and this does not appear to be sufficient to maintain nitrogen concentrations at levels required for spring dinoflagellate blooms. The present-day operation of

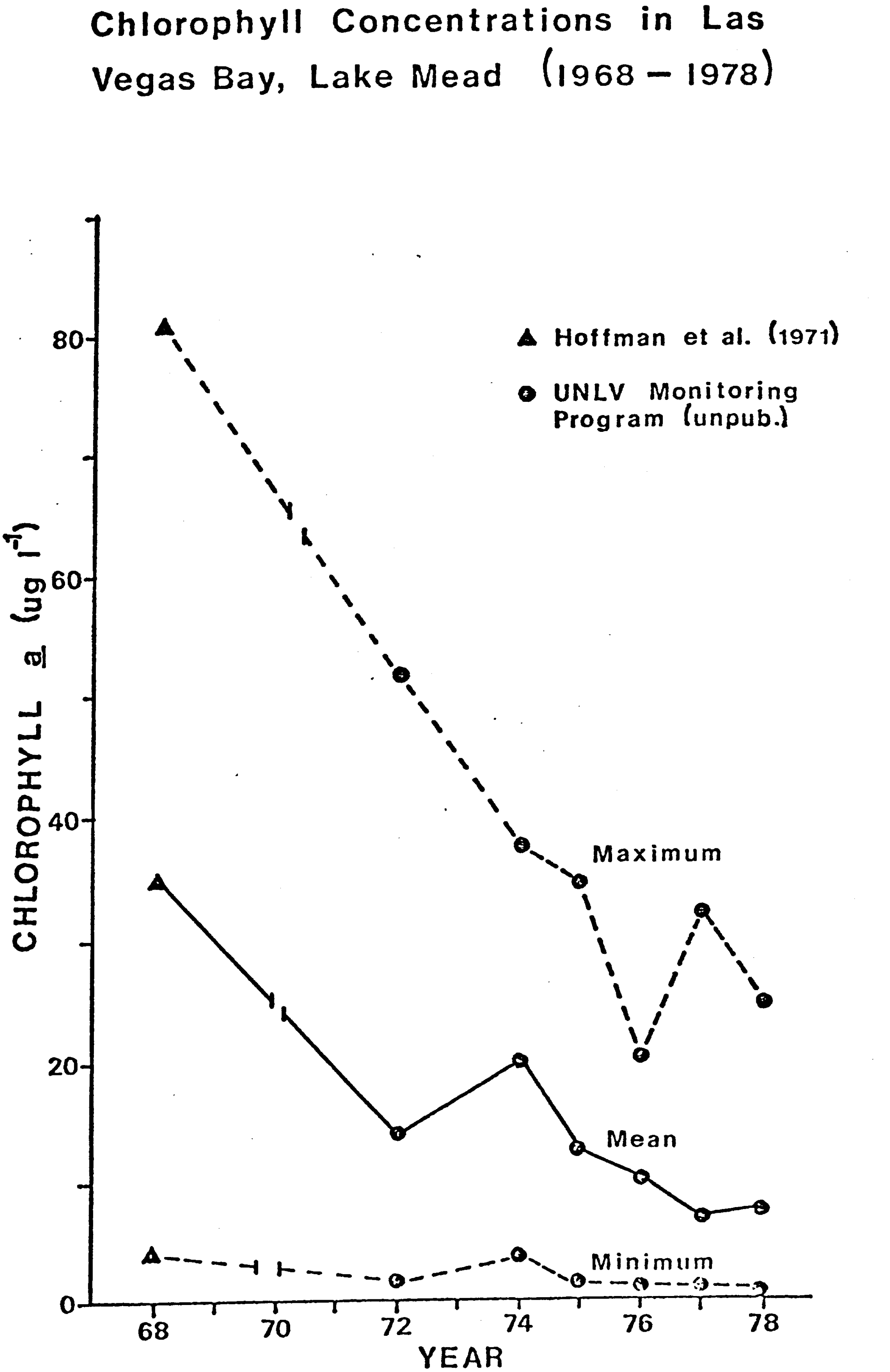

Fig. 6. Historical chlorophyll-a concentrations in the Inner Las Vegas Bay, LaKe Mead.

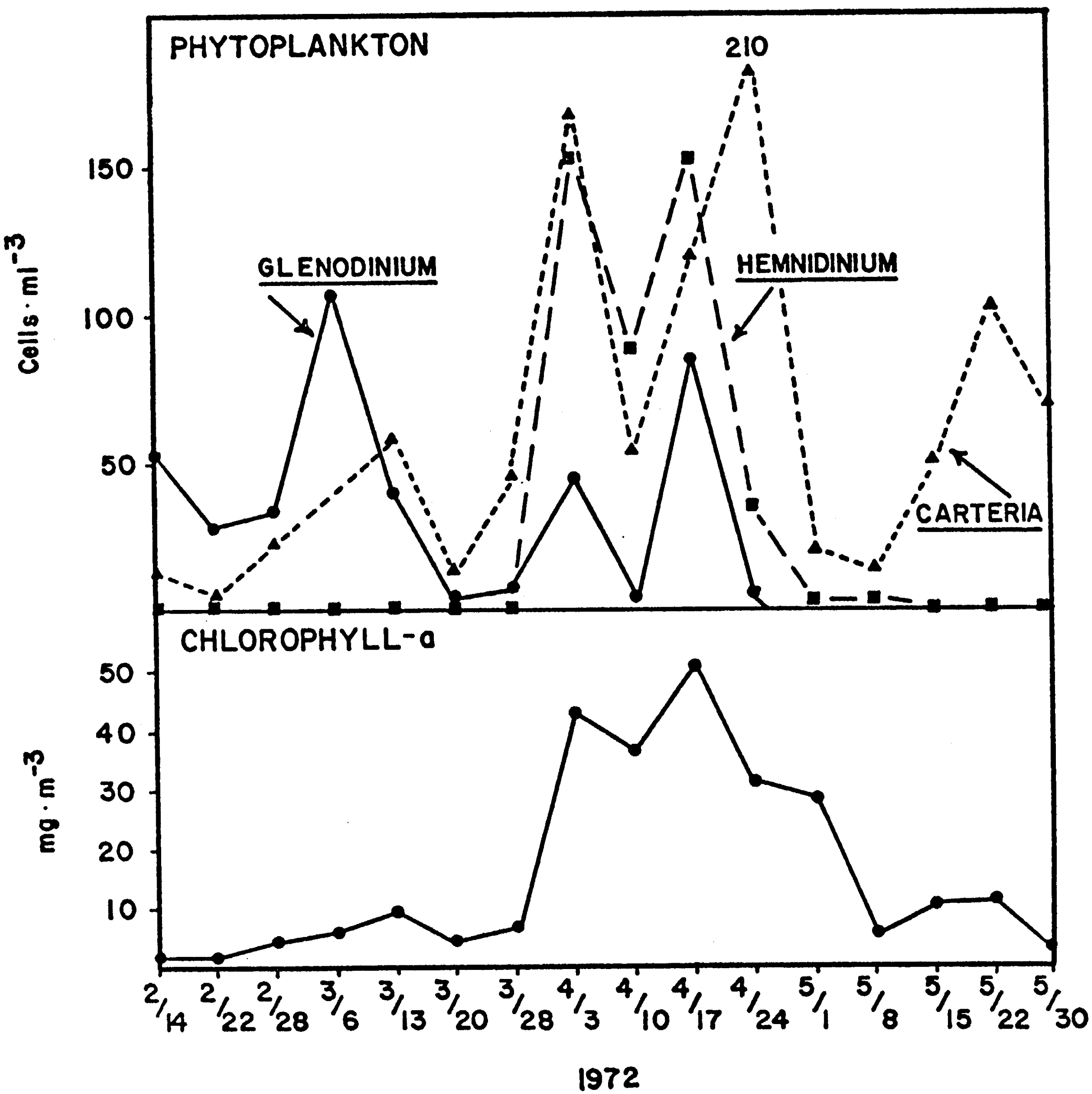

Fig. 7. Relationship of chlorophyll-a and phytoplankton in the Inner Las Vegas Bay during 1972.

Table 2. Abundance of dinoflagellates and *Carteria* in Las Vegas Bay during the spring of 1975 and 1976 ($cell \cdot ml^{-1}$).

Date	Glenodinium	Hemnidinium	Carteria
4/28/75	74.0	-	107
5/16/75	-	-	28
5/28/75	-	-	46
1/19/76	-	-	59
2/19/76	-	-	13
3/29/76	6.6	-	113
5/27/76	13.0	-	616

estimates of how nitrate concentrations would have differed with an epilimnion discharge from Hoover Dam.

Initially, nitrate losses at Hoover Dam would have been much lower from an epilimnion discharge (Fig. 8a), thus allowing reservoir nitrate concentrations to increase (Fig. 8b). Nitrate losses would have increased as nitrate accumulated in the reservoir and eventually have reached levels similar to those from the hypolimnion discharge. However, steady-state reservoir concentrations during the unstratified period would have been about 650 mg m^{-3}, or roughly three times current levels.

In applying the model to an epilimnion discharge, the same model parameters were used as for the hypolimnion discharge (Table 3). Most of these apply directly to either case, but there is some uncertainty regarding how phytoplankton would have responded to increased nitrate concentrations. As the historical data have already shown, the displacement and retention coefficient parameters are sensitive to changes in phytoplankton productivity. Increased phosphorus loading from Las Vegas Wash during the late 1960s and early 1970s increased rates of nitrogen displacement and retention in the Lower Basin. Long-term data are not available to develop a similar model for phosphorus, but results of our studies during 1977-1980 clearly demonstrate that more phosphorus would be retained in Lake Mead if Hoover Dam were operated from an epilimnion discharge. It is difficult to predict how much this would have increased phosphorus concentrations, but it is possible to obtain an estimate if we assume phosphorus would have increased proportional to nitrate concentrations. Nitrate and phosphate concentrations averaged 194 and 4 mg m^{-3} during the unstratified period of 1979-1980. Based on model predictions steady-state nitrate concentrations in this period would have been 650 mg m^{-3}, or 3.4 times current levels. Phosphate concentrations would therefore have been 13.6 mg m^{-3}.

It is, of course, impossible to quantitatively validate the nitrate model or predictions regarding phosphate concentrations. Nonetheless, my purpose here was not so much to predict actual reservoir nutrient concentrations, as it was to evaluate how different operating criteria of Hoover Dam would influence the long-term nutrient status of the reservoir. In this regard, the model serves a useful purpose and, when combined with the historical data, permits a more refined description of Wright's (1967) hypothesis.

In reservoirs that develop vertical nutrient gradients, an epilimnion discharge will initially result in low rates of inorganic nutrient loss (Fig. 9a). Loss rates will increase as nutrients accumulate in the reservoir (Fig. 9b), but a steady-state will be reached when combined losses (discharge and sedimentation) balance nutrient inputs. The time required to reach steady-state will vary directly with reservoir flushing time. Entrainment of autochthonously-produced organic materials in an epilimnion discharge could offset increased retention of inorganic nutrients in reservoirs where flushing rates exceed nutrient displacement rates into the hypolimnion. In this case, alterations in discharge depth would simply change the chemical form, not the total amount, of nutrients discharged from the reservoir.

Reservoirs operated from a hypolimnion discharge will exhibit reverse patterns of nutrient loss (Fig. 9a). Nutrient loss rates will be high initially but then decrease rapidly, in direct proportion to hypolimnion flushing times. The chemical form of nutrients discharged from the reservoir will vary in relation to the depth and flushing times of the hypolimnion. Remineralization of displaced organic materials will result in greater losses of inorganic than organic nutrients from deep reservoirs like Lake Mead. Sedimentation will also result in significant retention of nutrient inputs in reservoirs with low flushing times. Shallow reservoirs with high flushing rates will have higher losses of organic than inorganic nutrients in the discharge and nutrient retention will be low due to rapid flushing of organic materials. Regardless of reservoir depth or flushing times, steady-state conditions will again occur when combined losses balance inputs. However reservoir nutrient concentrations will be roughly half as high as those in reservoirs with an epilimnion discharge (Fig. 9b). Neel (1963) maintained that a hypolimnion discharge would cause enrichment of downstream reservoirs, and vice versa, for an epilimnion discharge. Initially, this would be true, but nutrient losses would eventually converge (Fig. 9a)

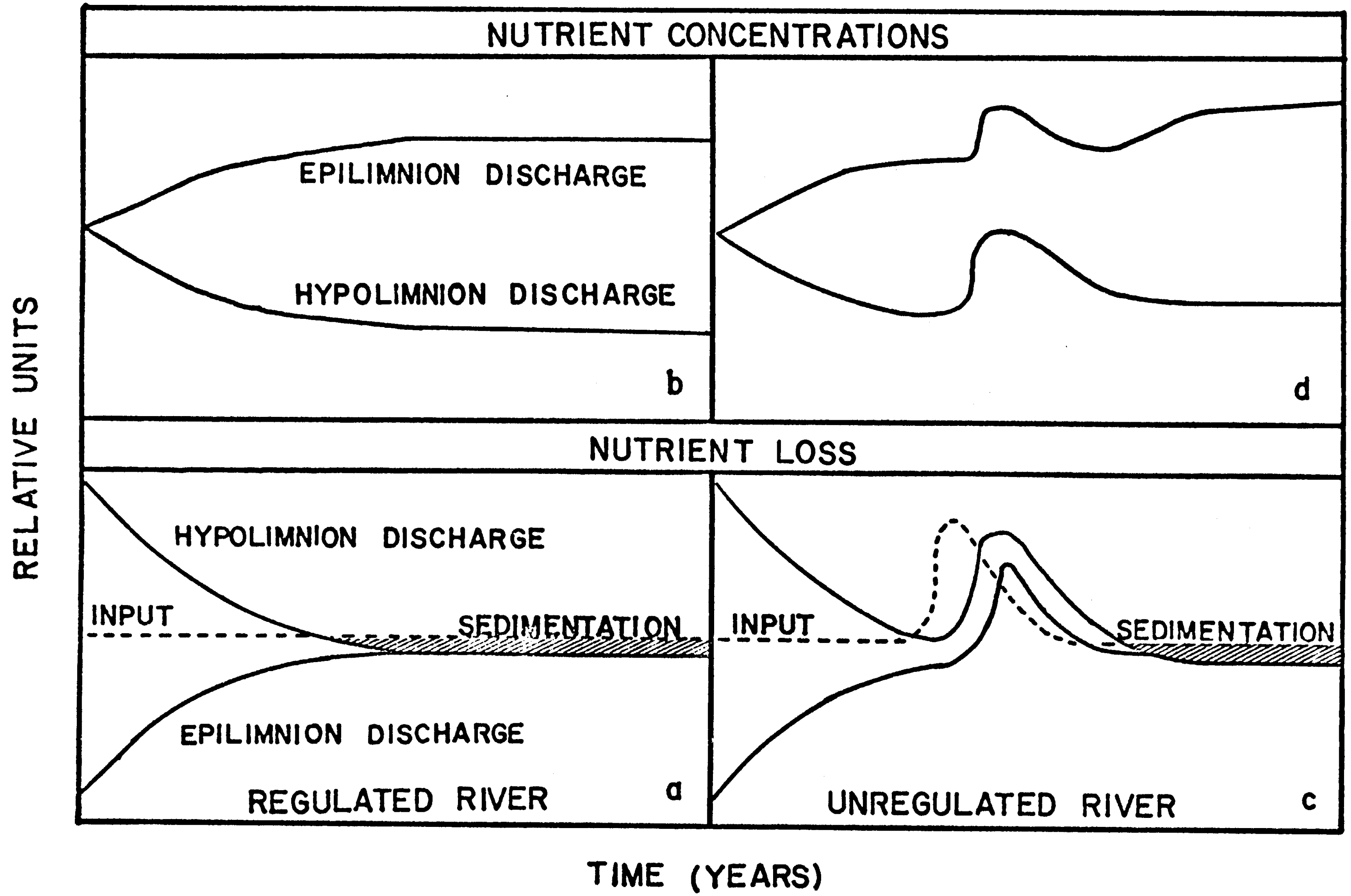

Fig. 9. Effects of different operating criteria of dams on nutrient studies in reservoirs.

on the same rate, and loading to downstream reservoirs will be similar from either discharge depth.

These conclusions would best apply to multi-reservoir systems, like the Colorado River, where annual inflows and nutrient inputs are regulated by discharges from an upstream reservoir. In reservoirs receiving unregulated inflows, nutrient loading could vary considerably in relation to annual variations in runoff. Nutrient loss rates and reservoir concentrations would then follow cyclic patterns like those shown in Fig. 9c, 9d. The patterns shown for a deep-discharge reservoir have been repeated several times during the early history of Lake Mead (Paulson et al. 1979). Spring flooding in the Colorado River periodically resulted in extremely high nitrate loading that elevated concentrations in Lake Mead. However, loss rates at Hoover Dam also increased which rapidly reduced nitrate concentrations in the reservoir.

The generalizations drawn here are based largely on results of our studies on the Colorado River system. However, the conclusions should generally apply to most reservoirs, and are in fact consistent with results of Martin and Arneson's (1978) limnological comparison of a surface-discharge lake and deep-discharge reservoir on the Madison River. The patterns of nutrient loss depicted for an epilimnion and hypolimnion discharge are also supported by experimental studies in Kortowskie Lake (Mientki and Mlynska 1977). Annual nitrogen and phosphorus retention in Kortowskie Lake were 36.2% and 65.9%, respectively, with an epilimnion discharge. Nitrogen retention decreased to 28% and phosphorus to -10% when a pipe was installed in the lake to withdraw hypolimnion waters. The hypolimnion discharge is currently being used to restore water quality of the lake and protect it against excessive eutrophication in the future (Sikorowa 1977).

Implications for Reservoir Management

The historical changes in nutrient and trophic status of Lake Mead illustrate a number of important points regarding nutrient management in reservoirs. These first demonstrate the profound impact that construction of upstream reservoirs can have on nutrient loading downstream. Regulated discharges from upstream dams will stabilize annual nutrient loading, but nutrients retained in one reservoir will reduce loading to downstream reservoirs. If these are limiting nutrients, as nitrogen or phosphorus usually are, the trophic state of downstream reservoirs will decrease accordingly. This could have a detrimental effect on reservoir sport fisheries which comprise a valuable beneficial use in most reservoirs. In multi-reservoir systems like the Colorado River, operation of hydroelectric dams or other impoundment structures from an epilimnion discharge might be effective in sustaining reservoir fertility. Initially, this would reduce loading to downstream reservoirs, but as reservoir concentrations increased, so would loss rates. Eventually, nutrient losses from an epilimnion discharge would be similar to those from a hypolimnion discharge, but concentrations in the reservoir would be much higher.

This strategy might not be desirable in reservoirs receiving unregulated flows. Nutrient loading in unregulated rivers will be highly unstable due to annual variations in runoff. Flooding appears to be an effective mechanism for replenishing reservoir nutrient concentrations. In this situation, operation of dams from a hypolimnion discharge would insure that fertility did not increase to levels that impair recreational or municipal uses of the reservoir. The same strategy should probably be employed in reservoirs that receive high nutrient loading from wastewater discharges.

Phosphorus loading to the Lower Basin of Lake Mead was 2.9 g P m^{-2} $year^{-1}$ from October 1977-September 1978. The basin should be "dangerously" eutrophic on the basis of Vollenweider's (1968) model. Except for areas of the inner Las Vegas Bay, the basin is currently oligotrophic-mesotrophic (Paulson et al. 1980; Baker and Paulson 1981). One of the main reasons for the discrepancy between measured and predicted trophic status of the reservoir is the present-day operation of Hoover Dam. Approximately 70% of the annual phosphorus input to the basin is lost in the hypolimnion discharge (Baker and Paulson 1981). This would decrease to 40% if the dam were presently operated from an epilimnion discharge, and sewage treatment would have to be increased accordingly to maintain the trophic state at current levels. The nutrient and trophic status of Lake Mead, and Las Vegas Bay in particular, would have been higher if Hoover Dam had been operated from an epilimnion discharge during the post-Lake Powell period. Operation of the AWT plant in Las Vegas would perhaps have been crucial for protecting water quality in the bay. This is in sharp contrast to current water quality conditions that have led to litigation over the AWT plant and an evolving philosophy that wastewater discharges may be desirable for maintaining fertility at levels which improve, or at least prevent further declines in the largemouth bass fishery (Paulson et al. 1979). In reservoirs where water quality problems do exist, it seems that alterations in the operations of dams can be used to achieve what has occurred purely by accident in Lake Mead..

The operating criteria of most dams, Hoover Dam included, are usually established independent of considerations for the impact on reservoir nutrient status. Many reservoirs are operated from an epilimnion discharge to avoid releasing waters that are low in dissolved oxygen or high in potentially toxic compounds (NH_3, H_2S). However, this mode of dam operations may in fact contribute to development of these conditions. Surface-discharge reservoirs will retain more nutrients that in turn will stimulate higher productivity. Hypolimnetic oxygen deficits bear a direct relationship to nutrient loading and productivity (Smith 1979), and could probably best be avoided by operating dams from a deep discharge. Conversely, many reservoirs are operated from a hypolimnion discharge to satisfy temperature requirements for cold-water trout fisheries in the tailwaters. This obviously is an effective strategy since most reservoir tailwaters support good trout fisheries. However, this may be achieved at the expense of the warm-water fisheries in the upstream reservoir. High nutrient losses in the hypolimnion discharge will reduce concentrations in the reservoir. Unless these nutrients are replenished, this will result in a decrease in reservoir productivity that could adversely influence warm-water fish production in the reservoir.

Establishment of operating criteria for dams or other impoundment structures must therefore include a careful analysis of their impact on reservoir nutrient and trophic status. These factors are extremely important because they influence and are influenced by virtually every use of reservoirs. The apparent benefits achieved in one use, or in one segment of river, may be offset by detrimental impacts elsewhere. "Trade-offs" are inevitable to some extent, but can probably be minimized if managers are aware of the consequences associated with different operating criteria of dams.

REFERENCES

Baker, J.R. and L.J. Paulson. 1981. Influence of Las Vegas Wash density current on nutrient availability and phytoplankton growth in Lake Mead, (in press). In Symposium on surface water impoundments. June 2-5, 1980. Minneapolis, MN.

Deacon, J.E. 1975. Lake Mead Monitoring Program. Univ. Nev. Las Vegas, final report to Clark County Sanitation Dist. 1. 297 p. (mimeo).

Deacon, J.E. 1976. Lake Mead Monitoring Program. Univ. Nev. Las Vegas, final report to Clark County Sanitation Dist. 1. 182 p. (mimeo).

Deacon, J.E. 1977. Lake Mead Monitoring Program. Univ. Nev. Las Vegas, final report to Clark County Sanitation Dist. 1. 55 p. (mimeo).

Deacon, J.E. and R.W. Tew. 1973. Interrelationship between chemical, physical and biological conditions of the waters of Las Vegas Bay of Lake Mead. Univ. Nev. Las Vegas, final report to the Las Vegas Valley Water Dist. 186 p. (mimeo).

D'Elia, C.F., P.A. Steudler, and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnol. Oceanogr. 22:760-764.

Dillon, P.J. 1975. The phosphorus budget of Cameron Lake, Ontario: The importance of flushing rate to the degree of eutrophy of lakes. Limnol. Oceanogr. 20:28-39.

Gloss, S.P., L.M. Mayer and D.E. Kidd. 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnol. Oceanogr. 25:219-228.

Goldman, C.R. 1974. Eutrophication of Lake Tahoe emphasizing water quality. EPA - 660/3-74-034. U.S. Govt. Printing Office, Washington D.C. 408 p.

Golterman, H.L. 1969. Method for chemical analysis of fresh waters. IBP Handbook 8. Blackwell Scient. Publ. 166 p.

Hannon, H.H. 1979. Chemical modifications in reservoir-regulated streams, p. 75-93. In J.V. Ward and J.A. Stanford (eds.) The ecology of regulated streams. Plenum Publ. Corp. 397 p.

Harrison, W.G. 1973. Nitrate reductase activity during a dinoflagellate bloom. Limnol. Oceanogr. 18:457-465.

Hoffman, D.A. and A.R. Jonez. 1973. Lake Mead, a case history, p. 220-233. In W.C. Ackerman, G.F. White and E.B. Worthington (eds.), Man-Made lakes: their problems and environmental effects. Geophys. Monogr. Ser. No. 17. 847 p.

Hoffman, D.A., P.R. Tramutt and F.C. Heller. 1967. The effect of Las Vegas Wash effluent upon the water quality of Lake Mead. U.S. Bur. Rec. Rept. No. REC-ERC-71-11. 25 p.

Kamphake, L.J., S.A. Hannah and J.M. Cohen. 1967. Automated analysis for nitrate by hydrazine reduction. Water Research. 1:205-216.

Kellar, P.E., S.A. Paulson and L.J. Paulson. 1980. Methods for biological, chemical and physical analyses in reservoirs. Tech. Rept. #5. Lake Mead Limnological Research Center. Univ. Nev. Las Vegas. 234 p.

Kellar, P.E. and L.J. Paulson. 1981. Alkaline phosphatase activity as an indicator of nutrient deficiency in Lake Mead. Limnol. Oceanogr. (manuscript submitted).

Lara, J.M. and J.I. Sanders. 1970. The 1963-64 Lake Mead Survey. U.S. Bur. Rec. Rept. No. REC-OCE-20-21. 169 p.

Liddicoat, M.I., S. Tibbits and E.I. Butler. 1975. The determination of ammonia in sea water. Limnol. and Oceanogr. 20:131-132.

Martin, D.B. and R.D. Arneson. 1978. Comparative limnology of a deep-discharge reservoir and a shallow-discharge lake on the Madison River, Montana. Fresh. Biol. 8:33-42.

Mayer, L.M. and S.P. Gloss. 1980. Buffering of silica and phosphate in a turbid river. Limnol. Oceanogr. 25:12-22.

Mientki, C. and I. Mlynska. 1977. Balance of nutrients in Kortowskie Lake waters during the experiment on its restoration. Pol. Arch. Hydrobiol. 24:49-59.

Mullins, J.W., R.N. Snelling, D.D. Moden and R.G. Seals. 1975. National eutrophication survey, data acquisition and laboratory analysis of stream and lake samples. EPA-600/4-75-015. U.S. EPA Las Vegas, Nev. 21 p.

Neel, J.K. 1963. Impact of reservoirs, p. 573-593. In D.G. Frey, (ed). Limnology of North America. Univ. Wisconsin Press, Madison. 734 p.

Paulson, L.J. and J.R. Baker. 1981. Nutrient interactions among reservoirs on the Colorado River, (in press). In Symposium on surface water impoundments. June 2-5, 1980. Minneapolis, Minn.

Paulson, L.J., J.R. Baker and J.E. Deacon. 1979. Potential use of hydroelectric facilities for manipulating the fertility of Lake Mead, p. 269-300. In G.A. Swanson (Tech. Coord.) The mitigation symposium: a national workshop in mitigating losses of fish and wildlife habitats. July 16-20, 1979. Fort Collins, Colo. Gen. Tech. Rept. No. RM-65. Rocky Mt. Forest and Range Exp. Sta. 696 p.

Paulson, L.J., J.R. Baker, and J.E. Deacon. 1980. The limnological status of Lake Mead and Lake Mohave under present and future powerplant operations of Hoover Dam. Tech. Rept. #1, Lake Mead Limnological Research Center, Univ. Nev. Las Vegas. 229 p.

Prentki, R.T., L.J. Paulson and J.R. Baker. 1980. Chemical and biological structure of Lake Mead sediments. Tech. Rept. No. 6. Lake Mead Limnological Research Center, Univ. Nev., Las Vegas. (in press).

Sikorowa, A. 1977. Possibilities of protection against excessive eutrophication of lakes using the method of the removal of hypolimnion waters. Pol. Arch. Hydrobiol. 24:123-135.

Smith, V. 1979. Nutrient dependence of primary productivity in lakes. Limnol. Oceanogr. 24:1051-1064.

Soltero, R.A., J.C. Wright, and A.A. Horpestad. 1973. Effects of impoundment on the water quality of the Bigham River. Water Res. 7:343-354.

Strickland, J.D.H. and T.R. Parsons. 1968. A practical handbook of seawater analysis. 1st ed., Bull. Fish. Res. Bd. Canada. No. 167. Ottawa. 311 p.

Strickland, J.D.H. and T.R. Parsons. 1972. A practical handbook of seawater analysis. 2nd ed., Bull. Fish. Res. Bd. Canada. No. 167. Ottawa. 311 p.

Stroud, R.H. and R.G. Martin. 1973. Influence of reservoir discharge location on water quality, biology and sport fisheries of reservoirs and tailwaters, p. 540-548. In W.C. Ackermann, G.F. White and E.B. Worthington (eds.) Man-made lakes: their problems and environmental effects. Geophy. Managr. Ser. 17. 847 p.

Vollenweider, R.A. 1968. Water Management Research. OECD Paris. DAS/CSI/68.27. 183 p. (mimeo).

Wright, J.C. 1967. Effect of impoundments on productivity, water chemistry and heat budgets of rivers, p. 188-199. In C.E. Lane (ed.), Reservoir fisheries resources. Symp. Amer. Fish. Soc. Spec. Publ. No. 6. 569 p.