Historical patterns of phytoplankton productivity in Lake Mead

Richard T. Prentki
University of Nevada, Las Vegas

Larry J. Paulson
University of Nevada, Las Vegas

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INTRODUCTION

Lake Mead was impounded in 1935 by the construction of Hoover Dam. The Colorado River was unregulated prior to then and therefore was subjected to extreme variations in flows and suspended sediment loads. Hoover Dam stabilized flows and reduced suspended sediment loads downstream [1], but Lake Mead still received silt-laden inflows from the upper Colorado River Basin. The Colorado River contributed 97% of the suspended sediment inputs to Lake Mead, and up to 140 x $10^6$ metric tons (t) entered the reservoir in years of high runoff [2]. Most of the sediments were deposited in the river channel and formed an extensive delta in upper Lake Mead [3,4]. However, sediments were also transported into the Virgin Basin and Overton Arm by the overflow that occurred during spring runoff [5]. The limnology of Lake Mead is thought to have been strongly influenced by this turbid overflow until Glen Canyon Dam was constructed 450 km upstream in 1963.

The construction of Glen Canyon Dam and formation of Lake Powell drastically altered the characteristics of the Colorado River inflow to Lake Mead [2]. The operation of Glen Canyon Dam stabilized flows, reduced river temperatures and cut the suspended sediment loads by 70-80% [2]. Nitrate loads decreased initially during 1963 and 1964, then increased through 1970, but have since decreased again to a lower steady state [6]. Phosphorus loads were decreased due to reductions in suspended sediment inputs [2]. Lake Powell now retains 70% of the dissolved phosphorus [1] and 96% of the total phosphorus [7] inputs that once flowed into Lake Mead. The Colorado River still provides 85% of the inorganic nitrogen to Lake Mead, but Las Vegas Wash now contributes 60% of the phosphorus inputs [2].

Wastewater discharges from Las Vegas Wash into Las Vegas Bay increased steadily during the post-Lake Powell
period. The morphometry and hydrodynamics of Lake Mead are such that the Las Vegas Wash inflow is confined to the Lower Basin where historically it has elevated phytoplankton productivity. However, high phosphorus loading and productivity have resulted in decreases in nitrate concentrations, and the Las Vegas Bay and parts of Boulder Basin have become nitrogen limited since 1972 [6]. A unique situation has therefore developed in Lake Mead in that the Upper Basin has become more phosphorus limited and the Lower Basin more nitrogen limited since the formation of Lake Powell. Paulson and Baker [2] theorized that these changes in nutrient loading and limitation must also have been accompanied by decreases in reservoir-wide productivity.

There is some evidence for this hypothesis in apparent improvements in water quality of Las Vegas Bay since 1968 [6]. Chlorophyll-a concentrations in the inner Las Vegas Bay have decreased considerably since the first measurements were made in 1968 [8] and during the period of the Lake Mead Monitoring Program [9-12]. Improvements in water quality of the bay have confounded efforts to establish water quality standards on effluent discharges and are contrary to predictions made in the early 1970s that water quality would continue to degrade with increased phosphorus loading [13]. The decline in the largemouth bass fishery documented by the Nevada Department of Wildlife [14] could also be a symptom of lower productivity in Lake Mead.

In this paper, the hypothesis that algal productivity has declined in Lake Mead as a result of impoundment of Lake Powell is evaluated. The chemical status of six stations in the Upper and Lower Basins of Lake Mead is analysed and current and past rates of organic carbon and phosphorus sedimentation are calculated. The relationship between algal productivity and accretion of organic carbon in sediment is determined, and this is used to construct a historical record of algal productivity for Lake Mead.

**METHODS**

**Sampling Locations**

The productivity and siltation patterns in Lake Mead are extremely heterogeneous due to the irregular reservoir morphometry and variable influence of nutrient loading from Las Vegas Wash and the Colorado River [15]. In order to ensure that this heterogeneity was adequately represented in the survey, multiple sediment cores were collected from several locations in the reservoir. The location of drilling sites are shown in Figure 1, and site characteristics are listed in Table I. Station locations were surveyed with an echo-sounder and the final sites were selected to provide a reasonably flat, unweeded possibility to place possible sediment density current. Stati embayment of the sewage inflow from placed in the Lower (Station 3). Two st channel in the Uppe Bay (5) stations. T

![Figure 1. Map of Lake Mead](image)

**Table I. Physical Characteristics of Stations**

<table>
<thead>
<tr>
<th>Station</th>
<th>Water Dept (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>80-95</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
</tr>
<tr>
<td>6**</td>
<td>75</td>
</tr>
</tbody>
</table>

* This station was
d** Fine sediment was
are the Lower productivity, and consistently has been a nitrogen and loading increases apparent in 1968. Vegas Bay represents Lake Mead quality of quality, which predicts subidence [13]. The symptom activity of Lake stations in and the current algal sedimentation is

Lake Mead reservoirs from to intended from drilling, ics are provide a

reasonably flat, undisturbed sediment surface. The stations were purposely placed outside the old river channel to avoid possible sediment disturbances from the Colorado River density current. Station 1 was a shallow-water site in a small embayment of the inner Las Vegas Bay, near the point of the sewage inflow from Las Vegas Wash. Stations 2 and 3 were placed in the Lower Basin; one of these in Boulder Basin (Station 3). Two stations were also placed off the old river channel in the Upper Basin: the Virgin Basin (4) and Bonelli Bay (5) stations. The sixth station was located in the Overton Arm, near Echo Bay.

![Map of Lake Mead Sediment Coring Stations](image)

**Figure 1. Map of Lake Mead Sediment Coring Stations.**

**Table I. Physical Characteristics at Sediment Coring Stations in Lake Mead.**

<table>
<thead>
<tr>
<th>Station</th>
<th>Water Depth (meters)</th>
<th>Number of cores</th>
<th>Date of submersion (month-year)</th>
<th>Relict material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>14</td>
<td>8</td>
<td>6-38</td>
<td>gravel</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>11</td>
<td>7-35</td>
<td>gravel</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>6</td>
<td>7-35</td>
<td>gravel</td>
</tr>
<tr>
<td>4</td>
<td>80-95</td>
<td>10</td>
<td>7-35</td>
<td>soil</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>11</td>
<td>7-35</td>
<td>sand</td>
</tr>
<tr>
<td>6**</td>
<td>75</td>
<td>8</td>
<td>7-35</td>
<td>sand</td>
</tr>
</tbody>
</table>

* This station was dry in low water years
** Fine sediment was not deposited above sand until 3-40

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Sediment Coring

The sediment coring was conducted by an oceanographic drilling company (Ocean/Seismic/Survey Inc., Norwood, NJ). A hydraulically-operated vibra-corer was used to obtain undisturbed sediment cores of 8.6 cm effective diameter. Coring rates were monitored with a penetration recorder. Coring was terminated when coring rates indicated that contact had been made with the old reservoir floor. The corer was retrieved and the core was immediately inspected through the Lexan liner for signs of marbling or other disturbance. Undisturbed cores were capped and stored upright. They were transferred to a walk-in freezer on the University of Nevada, Las Vegas campus within 10 hours of collection. Six to eleven cores were collected from each station. The coring was conducted over a ten-day period during mid-October, 1979.

Sediment Analyses

A detailed description of procedures used for analysis of sediments is given in Kellar et al. [16] and will only be discussed briefly here. Frozen cores were sectioned in 1.3-cm intervals from the top down. Outside surfaces of the core sections were scraped to eliminate any surface contamination. Corresponding sections of the several cores from each station were pooled.

Organic carbon content of sediment was determined with an elemental analyzer (Perkin Elmer Model 240B). Sediments were first treated with 1N HCl and heated at 105°C to drive off carbonates. Duplicate, 20-60 mg subsamples were then combusted in the elemental analyzer at 950°C. Total phosphorus was analyzed by the phosphomolybdate method following ignition of 0.5 g samples at 550°C and subsequent extraction of phosphorus from the residue into 1N H$_2$SO$_4$. Sediment bulk density and calcium carbonate content measurements were necessary in order to calculate the organic carbon sedimentation rates but are not reported here. These data and description of their analytical methodology are described by Prentki et al. [17].

The Cesium-137 counting of 500-1000 g samples was performed by Controls for Environmental Pollution Inc. (CEP), a commercial laboratory in Santa Fe, NM. The required sample size necessitated pooling two to three adjoining 1.3-cm sediment sections. A few samples were also counted by the U.S. Environmental Protection Agency, Office of Radiation Programs, Las Vegas, NV, and by the Southern Plains Watershed and Water Quality Laboratory, Durant, OK, for quality assurance purposes.
RESULTS AND DISCUSSION

Sediment Core Dating

Cesium-137 radioactivity from atmospheric bomb fallout has been widely used to date reservoir sediments [18]. Cesium-137 is strongly adsorbed by fine soil particles and, if eroded from the watershed, will be deposited in reservoir sediments. The first occurrence of Cs-137 activity in the bottom of a sediment profile indicates that the layer was deposited after the first testing in 1954. The most intensive period of fallout was caused by Russian testing during 1962-64; fallout has decreased steadily since 1964. Peak fallout, therefore, occurred during the period when Lake Powell was formed, providing an excellent sediment marker in Lake Mead.

The Cs-137 concentrations in Lake Mead sediments were generally low and differed somewhat between the Upper and Lower Basins (Figure 2). The slightly higher activity in Upper Basin sediments apparently reflects greater inputs and deposition of suspended sediments from the Colorado River. The bottom sediment layers where Cs-137 activity first appeared were evident in all cores from deep stations and were assigned the 1955 marker. The Cs-137 profiles in middle Las Vegas Bay, Boulder Basin, Virgin Basin, and the Overton Arm generally followed the classic pattern that has been found in other reservoirs. Cs-137 activity increased after 1955, reached a peak, and then decreased again in recent sediments. The peak activity layer in these cores was assigned the 1963 marker.

Data collected in Bonelli Bay and the inner Las Vegas Bay were, however, more difficult to interpret. In Bonelli Bay, peak Cs-137 activity occurred at 17-19 cm sediment depth, far below that found at the other Upper Basin stations. In Virgin Basin, the peak activity occurred at 8-9 cm, and in the Overton Arm, it occurred at 3-4 cm sediment depth. In order to resolve the obvious discrepancies with other Upper Basin cores, we assigned the 1963 marker to the secondary Cs-137 maximum that occurred 3-4 cm from the sediment surface in Bonelli Bay. This is consistent with changes in other chemical parameters of this layer [17] and reasonable in terms of known reductions in suspended sediment loading and siltation in the Upper Basin after 1963.
Figure 2. Cesium-137 Profiles of Lake Mead Sediments and Dates of Various Sediment Layers.

The Cs-137 profile in the inner Las Vegas Bay was also difficult to interpret because activity was found in gravel layers deep in the core. This station was shallow and in the past has been subject to water level fluctuations and peri-

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This area was dry until 1958, very shallow (1-2 m) during 1947 and from 1951-57, and then dry again from 1963-69. Because of possible reworking of sediment during dry or low water years, we were unable to use the disappearance of Cs-137 activity to indicate the 1955 marker. Moreover, the peak in Cs-137 activity must reflect 1969 rather than 1963, because this area was dry over the period from 1963-69.

Apart from some difficulties in interpreting Cs-137 profiles in Bonelli Bay and the inner Las Vegas Bay, the Cs-137 data provide reliable markers of the 1955 and 1963 sediment layers. It is also possible to establish a third marker, the old reservoir floor of 1935, by obvious discontinuities between pre-reservoir soils and reservoir sediments. Sediments were underlain by gravel in the middle Las Vegas Bay, gravel and soft rock in Boulder Basin, unconsolidated desert soils in Virgin Basin, and sand in Bonelli Bay. A similar discontinuity existed in Overton Arm, but the sediment depth here was also influenced by delta deposits from the Virgin River as the reservoir was filling. Gould [19] reported that in 1935 and 1936 the mouth of the Virgin River was located at Bitter Wash, a few kilometers upstream from our station. He was, therefore, unable to distinguish between sand deposited by the river and that in the pre-reservoir deposits. Clay sediments were deposited once lake levels increased and caused the point of river inflow to recede up the Overton Arm. This occurred in 1940. Layers below that represent siltation from the Virgin River inflows during 1935-40.

Sediment Chemical Structure

Organic carbon in Lake Mead sediments was very low. Values ranged from 0.3% of sediment dry weight in early sediments to 1.7% in recent sediments (Figure 3). Total phosphorus concentrations of Lake Mead sediments were appreciable and ranged from 300 ppm of dry weight in old reservoir sediments to 1000 ppm in recent sediments (Figure 4). In the inner and middle Las Vegas Bay, phosphorus increased steadily in sediments deposited after 1963, but elsewhere phosphorus concentrations decreased or remained stable. The organic carbon:phosphorus ratios were very low, ranging from 10 to 20. These ratios are tenfold lower than found in plankton and considerably lower than those reported in other lake sediments [17]. The low C/P ratios were caused by the presence of large amounts of biologically unavailable particulate phosphorus which entered Lake Mead from the Colorado River [20].
Figure 3. Organic Carbon Content of Lake Mead Sediments
(Range in Replicate Analyses Shown by Shading).

Figure 4. Total Ph
Spatial and Temporal
The Cs-137 dat estimate annual sed
Spatial and Temporal Patterns in Sedimentation

The Ca-137 data and chemical analyses enabled us to estimate annual sedimentation rates for organic carbon and...
phosphorus during three periods of reservoir history (1935-54, 1955-62 and 1963-79). In addition, it was possible to partition autochthonous (in-reservoir) and allochthonous (river-borne) components of organic carbon on the basis of previous analyses of bottomset delta deposits made during the 1948-49 sediment survey in Lake Mead [19]. A 15-30 m bottomset delta, comprised primarily of fine clay materials, was formed in the Colorado River thalweg of Virgin and Boulder Basin during the first 13 years of impoundment. The bottomset delta deposits were fairly uniform in organic carbon (0.55%) and calcium carbonate (16%) and were comprised of nearly pure allochthonous material due to the enormous rate of siltation. Siltation in non-thalweg areas of the reservoir is much lower, since we found at most 46 cm of sediments in either basin.

These non-thalweg deposits are comprised of both autochthonous and allochthonous materials. It was possible to partition these materials by measuring organic carbon and carbonate concentrations in various layers of the non-thalweg sediments, and subtracting out that reported in bottomset delta sediments. This separation is analogous to that for tripton from resuspended sediment by Gasith [21]. The details of calculations for autochthonous and allochthonous organic carbon in Lake Mead are presented by Prentki et al. [17].

There was considerable spatial and temporal variation in sedimentation patterns in Lake Mead (Figure 5). In the period from 1935-54, organic carbon sedimentation was highest in the Overton Arm and Bonelli Bay, lower in Virgin Basin, and the Lower Basin. Phosphorus sedimentation was extremely high in the Upper Basin (up to 17 g/m^2·yr) and closely related to dry weight and allochthonous carbon sedimentation. The low C/P (ca.12:1) ratios of sedimented material again indicated that most of the sediment phosphorus was not associated with limnetic plankton remains. Sedimentation rates were extremely low in the Lower Basin during this period. There was no measurable accumulation of sediment in Boulder Basin prior to 1955. Similarly, in Las Vegas Bay, sedimentation rates were extremely low in the early history of Lake Mead.

Sedimentation rates increased in the Upper Basin during the period from 1955-62. This was especially evident in Bonelli Bay and Virgin Basin where autochthonous carbon sedimentation increased twofold over the preceding period. Phosphorus sedimentation also increased in the Upper Basin but not as drastically as what was observed for carbon. It is somewhat surprising that these sedimentation rates increased during this period because average suspended sediment loading decreased by 34%. The suspended load in the Colorado River averaged 110 x 10^6 t/yr prior to 1955 but then decreased to 114 years [22]. Allochthonous rates, however, in Virgin Basin in significant change in inputs across the
then decreased to $73 \times 10^6 \text{ t/yr}$ during the 1955-62 water years [22]. Allochthonous organic carbon sedimentation rates, however, increased by 20% in the Overton Arm and 400% in Virgin Basin indicating that there must have been a significant change in the distribution of suspended sediment inputs across the Upper Basin.

![Sedimentation Rates](image)

**Figure 5.** Sedimentation Rates for Organic Carbon and Phosphorus During Three Periods (1935-54, 1955-62, 1963-79) of Lake Mead History.

The Colorado River has historically formed an overflow during spring and a shallow interflow during summer in the Upper Basin [5]. During spring runoff, this resulted in dispersal of fine suspended sediments across the Upper Arm of Lake Mead (Gregg Basin, Temple Basin). High spring runoff and flooding occurred in the Colorado River during 1956-58 and in 1962 (USGS data), and this apparently caused greater dispersal of suspended sediments into non-delta areas of the Virgin Basin, Bonelli Bay and the Overton Arm. The magnitude of spring runoff and seasonal frequency of flooding appear to be more important factors than is average, annual suspended sediment loading in determining sedimentation in non-delta areas of the reservoir. However, even during years of extreme spring runoff, it does not appear that much Colorado River suspended sediment is transported into the Lower
Basin. There was only a slight increase in sedimentation rates of allochthonous organic carbon in Boulder Basin during the period 1955-62 (Figure 5). There was a greater increase in sedimentation in the middle Las Vegas Bay, but this was probably due to increased discharge of sewage effluents into the Lower Basin.

Suspended sediment loading in the Colorado River decreased to an average of $16 \times 10^6$ t/yr in the period after Lake Powell was formed in 1963 [22]. This was accompanied by a drastic reduction in sedimentation of both phosphorus and organic carbon throughout the Upper Basin (Figure 5). In contrast, sedimentation increased slightly in Boulder Basin and decreased in middle Las Vegas Bay. Sedimentation patterns in Lake Mead were reversed after 1962 in that rates in the Lower Basin exceeded those in the Upper Basin.

Reservoir-wide Sedimentation as Related to Phosphorus Loading

The sedimentation rates given in Figure 5 provided a basis for estimating reservoir-wide sedimentation during three periods of Lake Mead history. However, it was necessary to extrapolate sedimentation rates at each station to larger areas of the reservoir using area estimates of Lake Mead from Lara and Sander's [4] sediment survey. The areas represented by our stations are shown in Table II. These only accounted for 77-78% of the total reservoir area because sampling was not conducted in the Upper Arm (Temple Basin, Gregg Basin, Iceberg Canyon and Grand Wash). In order to obtain an estimate of reservoir-wide sedimentation, we used data from station 5 to characterize the Upper Arm of Lake Mead.

The formation of Lake Powell markedly reduced phosphorus sedimentation in the Upper Basin of Lake Mead. Phosphorus sedimentation in the Upper Basin was extremely high during the early history of Lake Mead but decreased by 93.5% after formation of Lake Powell (Table III). Phosphorus sedimentation in the Lower Basin decreased by only 2% in the post-Lake Powell period. Reservoir-wide phosphorus sedimentation, however, decreased from an average of 5200 t/yr during 1955-62 to 623 t/yr after 1962.

There are no long-term loading data for phosphorus, but it must have been high, particularly during 1955-62, to account for the high rates of phosphorus sedimentation during the pre-Lake Powell years. Phosphorus loading was probably on the order of that recently measured for Lake Powell by Gloss et al. [7]. They estimated that the Colorado River currently provides 5224 t/yr of total phosphorus to Lake Powell. However, only 229 t/yr of phosphorus is currently discharged from Glen Canyon Dam [7], and about the same amount, 198 t/yr entered Powell [23]. These numbers suggest that phosphorus loading increased abruptly during the post-Lake Powell period.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Level (m)</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1954</td>
<td>350</td>
<td>447</td>
</tr>
<tr>
<td>1955-62</td>
<td>352</td>
<td>465</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>353</td>
<td>475</td>
</tr>
</tbody>
</table>

**Lake level from [22]**

**Combined with station 5 data**

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Whole Reserve Sedimentation (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1954</td>
<td>2470</td>
</tr>
<tr>
<td>1955-62</td>
<td>5200</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>623</td>
</tr>
</tbody>
</table>

Sewage effluent discharge into Las Vegas Wash, however, was lower during the Powell period. Las Vegas Wash is a phosphorus-rich Las Vegas Wash Basin. Phosphorus sedimentation in this basin maintained, therefore, a steady 2% decrease in the post-Lake Powell period (Table III). The historical phosphorus loading to Lake Mead has been shown to change in sedimentation in response to changes in loading. Hence, phosphorus loading (parent sedimentation) measured in this study.

Phosphorus loading from the Colorado River and 263 t/yr because the Virgin River was the main source of phosphorus to the reservoir. Hoover Dam was 123 t/yr.
amount, 198 t/yr enters Lake Mead from the Colorado River [23]. These numbers represent a 96% reduction in total phosphorus loading into Lake Mead which accounts for the abrupt decrease in phosphorus sedimentation in the Upper Basin.

Table II. Reservoir Mean Surface Areas (km²) Characterized by Sediment Coring Stations.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Mean Lake Level (m)</th>
<th>Total Lake Area (km²)</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 5</th>
<th>Station 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1954</td>
<td>350</td>
<td>447</td>
<td>21.7</td>
<td>101.7</td>
<td>35.8</td>
<td>108.7</td>
<td>80.0</td>
<td></td>
</tr>
<tr>
<td>1955-62</td>
<td>352</td>
<td>465</td>
<td>22.1</td>
<td>103.6</td>
<td>37.0</td>
<td>112.5</td>
<td>85.1</td>
<td></td>
</tr>
<tr>
<td>≥ 1963</td>
<td>353</td>
<td>475</td>
<td>21.4</td>
<td>104.2</td>
<td>37.7</td>
<td>114.3</td>
<td>87.3</td>
<td></td>
</tr>
</tbody>
</table>

*Lake level from [22] and USGS (unpublished).
**Combined with station 2

Table III. Average Reservoir-Wide and Individual Basin Sedimentation of Phosphorus in Lake Mead (t/yr).

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Whole Reservoir</th>
<th>Lower Basin</th>
<th>Upper Basin</th>
<th>Lower and Upper Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1954</td>
<td>2470</td>
<td>15</td>
<td>1780</td>
<td>1795</td>
</tr>
<tr>
<td>1955-62</td>
<td>5200</td>
<td>273</td>
<td>3390</td>
<td>3663</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>623</td>
<td>268</td>
<td>220</td>
<td>488</td>
</tr>
</tbody>
</table>

Sewage effluent discharges and nutrient loading from Las Vegas Wash, however, rose steadily in the post-Lake Powell period. Las Vegas Wash now contributes 60% of the phosphorus input to Lake Mead [23]. The morphometry and hydrodynamics of Lake Mead [15] are such that the phosphorus-rich Las Vegas Wash inflow is confined to the Lower Basin. Phosphorus sedimentation in the Lower Basin has been maintained, therefore, at levels equal to that in the 1955-62 period (Table III).

The historical patterns of phosphorus sedimentation in each basin of Lake Mead generally agree with historical changes in loading. However, there is a considerable difference in sedimentation estimated from nutrient budgets (apparent sedimentation) [23] and absolute sedimentation measured in this study.

Phosphorus loading to Lake Mead was 198 t/yr from the Colorado River and 263 t/yr from Las Vegas Wash in 1977-78 [23]. Total phosphorus loading to Lake Mead was about 460 t/yr because the Virgin and Muddy Rivers contribute minimal phosphorus to the reservoir [24]. Phosphorus loss from Hoover Dam was 123 t/yr in 1977-78 [23]. The fish harvest
also resulted in an annual loss of 25 t of phosphorus from
the reservoir [25]. The combined phosphorus losses from Lake
Mead would therefore be 148 t/yr. Apparent phosphorus sedi-
mentation would be 312 t/yr. Absolute phosphorus sedimenta-
tion, as measured in this study, was 268 t/yr in the Lower
Basin, 220 t/yr in the Upper Basin and 623 t/yr in the whole
reservoir during the post-Lake Powell period (Table III).
Absolute sedimentation thus exceeded 1977-78 apparent sedi-
mentation by 311 t/yr. It is unknown whether loading for
1977-78 reflects average annual loading in recent years.
However, the discrepancy between the two retention numbers
is most likely caused by a higher nutrient output from Lake
Powell during the first years of impoundment than is now
occurring [2,20].

Organic Carbon Sedimentation and Phytoplankton Productivity

The historical changes in nutrient loading to Lake Mead
have also been accompanied by marked changes in organic car-
bon sedimentation and, as will be shown, phytoplankton pro-
ductivity. Reservoir-wide autochthonous carbon sedimentation
was low prior to 1955 but increased sharply during the peri-
od from 1955-62, followed by an abrupt decrease in the post-
Lake Powell period (Table IV). The same trends were also
evident for allochthonous organic carbon sedimentation.
Organic carbon sedimentation was consistently higher in the
Upper Basin during the pre-Lake Powell period and accounted
for over 90% of reservoir-wide organic carbon sedimentation.
This pattern was reversed after 1962, and the Lower Basin
now contributes over 50% of organic carbon sedimentation in
Lake Mead. However, reservoir-wide sedimentation has still
been reduced by 76.8% of that which occurred in the 1955-62
period.

Table IV. Reservoir-Wide and Individual Basin Sedimenta-
tion of Autochthonous and Allochthonous
Organic Carbon in Lake Mead (t C/yr).

<table>
<thead>
<tr>
<th>Interval</th>
<th>Whole Reservoir</th>
<th>Lower Basin</th>
<th>Upper Basin</th>
<th>Lower and Upper Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Autochthonous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤ 1954</td>
<td>7710</td>
<td>48</td>
<td>6150</td>
<td>6198</td>
</tr>
<tr>
<td>1955-62</td>
<td>33400</td>
<td>2290</td>
<td>20300</td>
<td>22590</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>7720</td>
<td>3830</td>
<td>2450</td>
<td>6280</td>
</tr>
<tr>
<td></td>
<td>Allochthonous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤ 1954</td>
<td>18900</td>
<td>85</td>
<td>13800</td>
<td>1385</td>
</tr>
<tr>
<td>1955-62</td>
<td>32500</td>
<td>1710</td>
<td>21700</td>
<td>23410</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>3300</td>
<td>1200</td>
<td>1320</td>
<td>2520</td>
</tr>
</tbody>
</table>
For the post-Lake Powell period, autochthonous organic carbon sedimentation in various locations of Lake Mead (Figure 6) was closely related to recent phytoplankton productivity measurements made at these locations by Paulson et al. [15]. There was a good correlation ($r=0.979$, $N=6$) between annual autochthonous organic carbon sedimentation and annual phytoplankton productivity (1977-78) at the six sediment sampling stations (Figure 6). Linear regression of organic carbon sedimentation against phytoplankton productivity (Equation 1) provided a means of predicting historical productivity in the reservoir.

$$PPR = -7 + 19.7 \times \text{AOC}$$  \hspace{1cm} (1)

where $PPR =$ rate of phytoplankton productivity \\
$(g \text{ C/m}^2 \text{.yr})$

$\text{AOC} =$ autochthonous organic carbon sedimentation \\
$(g \text{ C/m}^2 \text{.yr})$

![Figure 6. Relationship of Recent Estimates of Phytoplankton Productivity in Lake Mead to Autochthonous Organic Carbon Sedimentation in the Post-Lake Powell Period.](image)
Rates of phytoplankton productivity estimated for each station with Equation 1 were extrapolated over larger areas of the reservoir to estimate reservoir-wide and individual basin total annual production (Table V). The spatial and historical trends in total production (Table V) necessarily follow those for autochthonous organic carbon sedimentation (Table IV) and thus do not provide different information. However, historical rates in units of productivity enable us to better reconstruct the trophic history of Lake Mead.

Table V. Reservoir-Wide and Individual Basin Estimates of Historical Rates of Phytoplankton Production (t C/yr x 10$^3$).

<table>
<thead>
<tr>
<th>Interval</th>
<th>Whole Lake</th>
<th>Lower Basin</th>
<th>Upper Basin</th>
<th>Lower and Upper Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1954</td>
<td>146</td>
<td>0.6</td>
<td>117</td>
<td>118</td>
</tr>
<tr>
<td>1955-62</td>
<td>651</td>
<td>43</td>
<td>395</td>
<td>438</td>
</tr>
<tr>
<td>≥ 1963</td>
<td>144</td>
<td>73</td>
<td>44</td>
<td>117</td>
</tr>
</tbody>
</table>

In the early decades of Lake Mead, only 600 of 146,000 t/yr production occurred in the Lower Basin (Table V). In the subsequent 1955-62 period, productivity of the reservoir increased to 651,000 t/yr apparently because of both high nitrate loading [17] and strong spring overflows of phosphorus-rich, Colorado River water. Lower Basin productivity then accounted for 7% of whole reservoir production.

Since the impoundment of Lake Powell in 1963, there has been a drastic reversal of the productivity of Lake Mead. Productivity has dropped to 144,000 t/yr, 4.5 times lower than in 1955-62 and 49% of the entire, 1955-62, pre-Lake Powell average. The Upper Basin is now severely phosphorus limited and productivity of this basin is now only 22% of the pre-Lake Powell average, 11% of the 1955-62 rate. The Lower Basin now accounts for 51% of total reservoir primary production.

We attribute almost all of this Lower Basin production to fertilization by sewage effluents from Las Vegas Wash. Without this latter input, the decline in the productivity of Lake Mead would have been even more dramatic than documented here.

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