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Limnology of Lake Powell and the Chemistry of the Colorado River

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INTRODUCTION

Lake Powell is a large, dendritic reservoir that fills the Glen Canyon segment of the lower Colorado River. Operation of Lake Powell in turn controls the hydrodynamics of the Colorado River through the Grand Canyon National Park to Lake Mead. The limnology of the reservoir is greatly influenced by (1) the morphometry and geology of the canyon it fills, (2) the design and operation (including the economics of hydropower production) of the dam, (3) the hydrodynamics and chemistry of the inflowing rivers, and (4) climatic variability. The limnology of the reservoir, coupled with dam operations, therefore determines the limnology of the Colorado River downstream from Lake Powell. The purpose of this paper is to review the limnology of Lake Powell in relation to the volume and quality of influent and effluent waters and to discuss the ramifications of reservoir operations on the biophysiology of the Colorado River.

Since our review of the ecology of the Colorado River (Stanford and Ward 1986a-c; Ward et al., 1986), other detailed syntheses have been forthcoming: Graf (1985), Bureau of Reclamation (1987), NRC (1987), Carlson and Muth (1989), and Potter and Drake (1989). Data and interpretations in these lengthy documents are pertinent to this paper. Potter and Drake (1989) is required reading for anyone interested in the developmental history and limnology of Lake Powell, as it summarizes results of a 10-year, multidisciplinary study funded by the National Science Foundation. However, Potter and

Drake (1989) is rather popularly written, and where possible we cite herein the various technical reports and published papers that were forthcoming from the study. Few papers containing original data pertaining to the limnology of Lake Powell and its effects on the riverine environment downstream have been published since the study summarized by Potter and Drake (1989) was concluded in 1980.

MORPHOMETRY AND HYDRODYNAMICS OF LAKE POWELL

Glen Canyon Dam

Glen Canyon Dam is an arch structure with a 107-m (350-ft) base and 476-m (1,560 ft) crest and is composed of 3.6×10^9 m^3 of concrete. It plugs sheer walls of Navajo sandstone bedrock incised over the millennia by the Colorado River. The dam has a crest elevation at 1,132 m (3,715 ft) above sea level, which is 216 m (710 ft) above bedrock and 164 m (583 ft) above the river channel. Eight penstocks discharge a maximum of 943 m^3/s (33,000 ft^3/s) to generators rated for 1.3 MW of hydropower production at full capacity. The penstocks draw water from an elevation of 1,058 m (3,471 ft). The authorized full pool elevation is 1,127.76 m (3,700 ft) above mean sea level. Four bypass tubes and two concrete-lined spillways that release water above 1,122 m (3,680 ft) elevation can pass an additional 7,867 m^3/s (278,000 ft^3/s). This spill volume was needed because flood flows of >5,660 m^3/s (200,000 ft^3/s) have been recorded within Glen Canyon. The dam was closed in September 1963, after a total project construction expenditure of $272 million. Through 1987, gross electrical production exceeded $700 million (Potter and Drake, 1989).

Physical Features of the Reservoir

Lake Powell, named in memory of Colorado River explorer and surveyor J. W. Powell, is impounded by Glen Canyon Dam. Glen Canyon was named by Powell in 1869 for the cottonwood (*Populus fremontii*) glens that dominated the pristine riparian forests on the terraces along the river within the steep-walled canyon. It is the second-largest reservoir in the United States, next to Lake Mead located ca. 250 km downstream on the Colorado River.

Full pool in Lake Powell was first reached on June 22, 1980. At full pool the reservoir yields morphometrics as listed in Table 5-1. Full pool was exceeded by 3 m on July 4, 1983 (only 2.5 m below the crest of the dam) as a result of a period of high flows in the Colorado and Green rivers. Since 1983, the reservoir has filled to capacity every year and has fluctuated only about 8 m annually.

TABLE 5-1 Morphometric features of Lake Powell.

Feature	Value
Surface area (km^2)	653
Volume (km^3)	33.3
Maximum depth (m)	171
Mean depth (m)	51
Maximum length (km)	300
Maximum width (km)	25
Shoreline development	26
Shoreline length (km)	3,057
Discharge depth (m)	70
Maximum operating pool	1,128
Drainage area (km^2)	279,000
Approximate storage ratio (yr)	2

SOURCE: Modified from Potter and Drake, 1989.

Air temperatures range in the Lake Powell area from ca. 5°C (January) to 36°C (August), while the surface water temperatures vary from 6°C (January) to 27°C (August). Average annual precipitation is 14.5 cm, occurring in about equal increments per month. These data summarize a 25-year record at Page, Arizona (Potter and Drake, 1989).

The geology of the reservoir basin is composed of a variety of Jurassic and Triassic sediments. Outcrops of Navajo and Wingate sandstones and the varied shales of the Chinle formation are more notable features of the Glen Canyon. The geology of the Colorado plateau dominates the catchment of Lake Powell and consists of uplifted Tertiary and cretaceous shale and sandstone formations with some areas of Tertiary volcanic extrusion. The Mancos shale formation outcrops over wide areas. The principal feature of the geology relative to the limnology of Lake Powell and its tributary rivers is the omnipresence of calcium, sulfate, and bicarbonate as the predominant dissolution ions within easily eroded substrata (Stanford and Ward, 1986a). Potter and Drake (1989) provide a more detailed review of area geology.

River Discharge and the Water Budget of Lake Powell

Ninety-six percent of the inflow to the reservoir is derived from the catchments of the Colorado and San Juan rivers (Figure 5-1), and 60% of the annual water budget is received in May-July as a result of snowmelt in the headwaters (Irons et al., 1965; Evans and Paulson, 1983).

In 1922 the Colorado River Compact apportioned water allocation based on a virgin (preregulation) flow of 22.2 km^3 at Lee's Ferry. However, the virgin flow is now estimated at 20.72 for the precompact period and 17.52

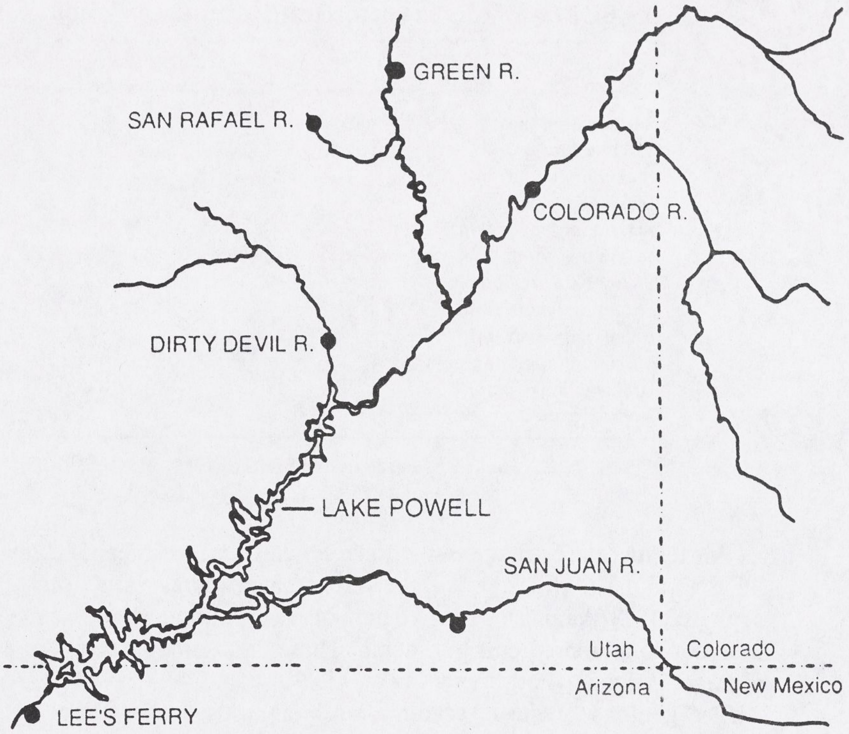

FIGURE 5-1 Lake Powell and tributaries showing sites where flows and water quality have been monitored.
SOURCE: Messer et al., 1983.

since 1922 (Holbert, 1982; Upper Colorado River Commission, 1984). Long-term flows estimated from tree ring data (Stockton and Jacoby, 1976) suggest that the long-term yield of the basin is 16.7 km^3, corroborating the lower virgin flow estimate. Moreover, the tree ring analysis strongly suggests that the Colorado River flows in the 1900s were well above the long-term (ca. 370-year) average. This is important because the Colorado River is regulated to the extent that the legal allocation between the upper and lower basins largely determines the water budget of Lake Powell most years. The Colorado River Compact divided the Colorado River into upper and lower basins at the confluence of the Paria and Colorado rivers, which is located ca. 30 km downstream from Glen Canyon Dam. Note that during the period 1967-1983 only slightly more than the legal allocation to the lower basin (8.9 km^3 = 7.2 million acre-feet) was discharged from Glen Canyon Dam (Figure 5-2). However, only 28.8% of the flow at Lee's Ferry

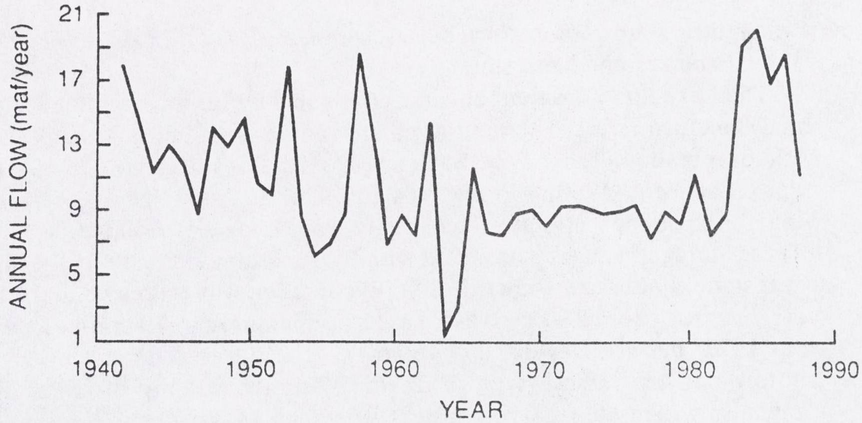

FIGURE 5-2 Annual flows in the Colorado River at Lee's Ferry, located 24 km downstream from Glen Canyon Dam.
SOURCE: Modified from Bureau of Reclamation, 1989.

is water previously impounded in the largest upstream reservoirs (Flaming Gorge, Morrow Point, Blue Mesa, and Navajo), owing to consumptive use and downstream water recruitment (Irons et al., 1965). During future low water years, inflow to the reservoir probably will be insufficient to meet the legal allocation downstream and Lake Powell will have to be drafted to make up the difference. In essence, Lake Powell buffers delivery of water from the upper basin to the lower basin.

In the decade of the 1980s, flows in the Colorado River system were generally well above the long-term average (Figure 5-2) and allocation of water to fulfill legal rights was not a problem. Indeed, flows during the spring freshet in 1983 were the highest on record, owing to late season snow accumulation, accelerated snowpack ablation, and high initial reservoir levels (Vandivere and Vorster, 1984). Streamflow forecasts also were not suitable for the climatic extremes in the basin in 1983 (Rhodes et al., 1984; Dracup et al., 1985). Reservoir elevation in Lake Powell exceeded full pool by 3 m during July 1983, and the dam operators were forced to bypass flood flows. The next year, 1984, also generated extreme runoff in the upper basin, and flood flows were again bypassed. Considerable damage to riverine environments downstream occurred, including severe erosion of beach and terrace environments within the Grand Canyon National Park.

Ground water inflows to Lake Powell apparently are related to aquifers in the Navajo sandstone, which is associated with the major surficial features of the reservoir and its dam (Blanchard, 1986). Quantities of groundwater inflow are not known but are probably insignificant in relation to fluvial sources and bank storage.

The Lake Powell water budget is dominated by inflow from the Colorado and San Juan rivers, although a major volume is included in bank storage and evaporation (Table 5-2). Bank storage increases over the life of a reservoir (Langbein, 1960). From 1964 to 1976, an estimated 10.5 km^3 went into bank storage at Lake Powell, for an average of 740,000 m^3 year^{-1}. These storage rates are consistent with the measured porosity of the Navajo sandstone (Potter and Drake, 1989). Evaporation was estimated at 6.2×10^8 m^3 year^{-1} or about 180 cm/year, based on measures in 1973-74 (Jacoby et al., 1977; but see Dawdy, this volume). The difference between riverine inflow and the losses given in Table 5-2 is the volume of water stored annually within the reservoir as it is filled and is fairly consistent with the reservoir's elevation volume trend for the period.

The volume stored annually is determined from runoff delivered by the rivers to Lake Powell in excess of the release mandate of the Colorado River Compact for the lower basin. The initial filling of the reservoir was accomplished a decade sooner than predicted from average flows, as a result of high flows during the 1980s. This again brings out the point that in future dry years lower basin allocation could cause Lake Powell to be drafted well below the volume that may be supplied by runoff in excess of reservoir storage from the upper basin. Hence, a major problem for the legal pundits involves determination of which reservoirs, if any, in the system have filling priority over Lake Powell. For the limnologist it means that prediction of pool levels in the reservoir and flows downstream require greater model-

TABLE 5-2 Water budget for Lake Powell based on average data for the period 1964-1975, the period when the reservoir was filling. Data are km^3.

River Inflow	
Colorado River	10.6408
San Juan River	1.6881
Losses	
Bank Storage	.7404
Evaporation[1]	.6170
Outflow measured at Lee's Ferry	10.0818
Difference	
Reservoir storage	2.2471

[1] corrected for precipitation and based on reservoir two-thirds full

SOURCE: Modified from Jacoby et al., 1977.

ing sophistication than currently exists. Without a verified hydrological model, predicting ecological responses to regulation is problematic.

The presence of Lake Powell has vastly altered the hydrograph of the river downstream of the dam. Indeed, Lake Powell hydropower operations effectively control downstream hydrodynamics (Table 5-3). Except in years of high-volume inflow to the reservoir (e.g., 1983 and 1984; Figure 5-3), flow seasonality is absent (e.g., 1982; Figure 5-3), as a result of reservoir storage. Flows from the dam fluctuate between 85 and 570 m^3 (3,000-20,000 ft^3) in a "yo-yo" fashion over short time periods (days) in response to the economics of hydropower (Figure 5-3).

TABLE 5-3 Hydrological, thermal, and sediment transport characteristics of the Colorado River below Glen Canyon Dam based on the 1941-1977 period of record.

Measurement	Lee's Ferry[a]		Grand Canyon[b]	
	Pre-dam	Post-dam	Pre-dam	Post-dam
Daily average flow equaled or exceeded 95% of the time (m^3/s)	102	156	113	167
Median discharge (m^3/s)	209	345	232	362
Mean annual flood (m^3/s)	2434	764	2434	792
Annual maximum stage (m)				
Mean	5.04	3.56	6.89	4.79
Standard deviation	0.96	0.17	0.35	0.15
Annual minimum stage (m)				
Mean	1.76	1.46	0.46	0.70
Standard deviation	1.40	0.23	0.85	0.45
Annual average temperature (°C)	10	10	11	12
Range (°C)	2-26	7-10	2-28	5-15
Mean sediment concentration (mg/liter)	1500	7	1250	350
Sediment concentration equaled or exceeded 1% of the time (mg/liter)	21000	700	28000	15000

[a] 24 km downstream from Glen Canyon Dam

[b] 165 km downstream from Glen Canyon Dam

SOURCE: Dolan et al., 1974; Paulson and Baker, 1981; Petts, 1984; U.S. Geological Survey, unpublished data.

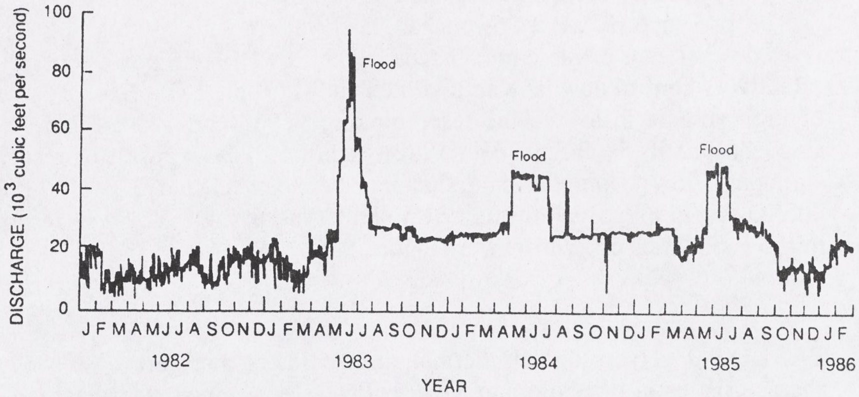

FIGURE 5-3 Inter- and intrayear variation in discharge of the Colorado River at Lee's Ferry as a consequence of hydropower and flood control operations at Glen Canyon Dam for the period 1982-1986.
SOURCE: Modified from Potter and Drake, 1989.

Seasonal Stratification

Lake Powell is warm (i.e., the annual heat budget is 40 kcal/cm^2), monomictic, and intensely stratified during most of the year. The intensity of seasonal stratification is determined by temperature, salinity, suspended solids, depth of the water column, and extent of riverine advection. Indeed, the reservoir mixes convectively only during the winter cooling period, when pelagic temperatures are 10°C (Paulson and Baker, 1983a) and mixing does not extend to the bottom (Johnson and Merritt, 1979). Lack of convective circulation is also partly due to the fact that 53% of the entire shoreline is vertical cliff (Potter and Pattison, 1976), which reduces wind-driven circulation within the water column of the reservoir. Overflow or interflowing density currents from the Colorado River occur annually in relation to the intensity and duration of the freshet. The relatively warmer and less saline waters from the freshet form a pycnocline between colder and more saline waters on the bottom of the reservoir. This over- or interflowing wedge of water from the rivers moves down the reservoir, gradually thinning as it reaches toward the dam by late summer (Gloss et al., 1980). Advection, therefore, mechanically sets the depth and extent of seasonal thermal stratification (Johnson and Merritt, 1979).

Because of the relatively shallow morphometry and substantial effects of river inflow, the upper reaches of the reservoir are dominated by advective mixing. Average retention time for reservoir volume north of Bullfrog Bay in the San Juan arm is less than 8 months (Potter and Drake, 1989).

A widespread halocline occurs in Lake Powell. Because of lack of wind circulation, there is a monimolimnion from the dam to the upper reaches of the reservoir. Convective circulation penetrates only to about 60 m (Johnson and Merritt, 1979). However, bottom water remains aerobic (i.e., >3 mg/liter dissolved oxygen), owing primarily to advective circulation generated by saline underflows from the Colorado and San Juan rivers during low winter discharge (Johnson and Page, 1981).

Metalimnetic oxygen depletion (negative heterograde profile) occurs virtually lakewide in the late summer (Stewart and Blinn, 1976; Johnson and Page, 1981; Sollberger et al., 1989); anoxia presumably is caused by decomposition of senescent phytoplankton that accumulates on the chemocline after settling from the mixolimnion (Hansmann et al., 1974; Johnson and Page, 1981). Metalimnetic oxygen stagnation begins in the bay mouths and temporally develops toward the dam. Convective circulation reduces oxygen depletion in early winter (Johnson and Page, 1981; Sollberger et al., 1989).

Because of reoxygenation by winter river underflows noted above and trapping of organic matter in the metalimnion, the monimolimnion remains aerobic. This limits nutrient mobilization from the sediments, and nutrients released by mineralization are not returned to the epilimnion due to the lack of convective circulation (Gloss et al., 1980, 1981). Calcite precipitation also may scavenge dissolved substances, particularly phosphate, via adsorption (Reynolds, 1978). Moreover, the depth of convective circulation and halocline formation in Lake Powell is marked by a strong withdrawal current at ca. 30-50 m (Johnson and Merritt, 1979) which removes epilimnetic nutrient loads (Gloss et al., 1980). Thus, there is a persistent nutrient deficiency in the euphotic zone. Bioproduction in Lake Powell is phosphorus limited and dependent on seasonal advective nutrient renewal via the spring overflow of the river turbidity plume (Gloss, 1977; Gloss et al., 1980).

Edinger et al. (1984) describe a longitudinal and vertical hydrodynamic and transport model called LARM. This model allows study of seasonal circulation, heat, and salinity transport and predicts equilibrium relationship over an entire reservoir volume. Thus, changes in solute concentrations, due to precipitation and dissolution, may be evaluated by using LARM.

PARTICULATE AND DISSOLVED SOLIDS DYNAMICS

Long-term data bases that describe the temporal chemistry of the rivers above and below Lake Powell (i.e., the sites in Figure 5-1) are maintained by the U.S. Geological Survey in their WATSTORE file. Flow, total dissolved solids (TDS) and specific conductance data are evaluated annually to document trends as related to salinity control projects within the Colorado

River basin (Bureau of Reclamation, 1989). These long-term data bases are readily available in electronic media and have been used extensively in studies of the biogeochemistry of Lake Powell (e.g., Messer et al., 1983; and Edinger et al., 1984).

Suspended Sediment

Stanford and Ward (1986a) characterized the Colorado River as one of the most erosive in the world. The virgin river was very turbid except at low flows, and sediment dynamics greatly influenced the riverine ecology, both within the river channel and in its floodplains and terraces. Most of the historical and current sediment load is derived from erosion of the soft sedimentary formations of the Colorado plateau (Irons et al., 1965).

Construction of mainstem dams has vastly altered the sediment transport processes of the river. Lake Powell receives 40-140 million tons of suspended sediment annually from its tributaries. Upstream dams on the Gunnison, San Juan, and Green rivers have not reduced the load (Mayer and Gloss, 1980), again substantiating the influence of the middle reaches of the Colorado, Green, and San Juan rivers on the water and sediment supply to Lake Powell (Irons et al., 1965). Retention of fluvial sediments within Lake Powell reduces the suspended sediment load in the Grand Canyon segment of the Colorado River by 70-80% (Evans and Paulson, 1983; Table 5-3). About 25% of the historic sediment load at Lee's Ferry was derived from side flows to Lake Powell such as the Dirty Devil and Escalante rivers (Potter and Drake, 1989). The Little Colorado River, which joins the Colorado River within the Grand Canyon, and the Paria River can contribute heavy sediment loads to the river during short-term spates, but the sediment load of the Colorado River is now virtually controlled by retention in Lake Powell.

The fluvial sediments entering Lake Powell are dominated by the montmorillinite clay lattice and have an average in situ bulk density of 1.5 with a mean grain density of 2.65 g/cm^3 dry mass, based on analysis of cores (Potter and Drake, 1989; but see Kennedy [1965] and Mayer [1973] for clay mineralogy of Colorado River suspended sediments). Mass balance calculations show that 60×10^9 m^3 of sediment is stored on the bottom of the reservoir annually. Most of the fluvial sediments are presently deposited near the mouths of the Colorado and San Juan rivers. Maximum sedimentation rates were better than 3 m/year through 1974 within the Colorado River arm and about 2 m/year within the San Juan arm of the reservoir. Over 50 m of sediment has accumulated near the mouth of the Colorado River and over 15 m has accumulated on the San Juan River delta as determined from 1987 sonar profiles presented by Potter and Drake, (1989). Bank slumping has contributed additional sediment at various sites on the reservoir shoreline, particularly in areas of sidehill dunes and steep gradient soils. Rockfalls from partially inundated cliff walls have also occurred. Sedimentation rates determined from echo soundings suggest that the reservoir basin will fill completely in about 700 years (Potter and Drake, 1989).

Riverine suspended sediments in the smallest size fraction (e.g., 10-30 µm may be transported far into the pelagic zone of the reservoir). These fine sediments are nutrient rich, relative to dissolved constituents within the water column, and fertilize the reservoir. However, the sediment-laden river waters usually interflow through the reservoir because advectively circulated flood waters are typically colder and more dense than the upper portions of the water column (Gloss et al., 1980, 1981).

Nitrogen, Phosphorus, and Silica

Because of the patterns of seasonal stratification described above, nutrients such as nitrogen, phosphorus, and silica are most uniformly distributed within the water column of Lake Powell during the winter and early spring. Advective circulation, driven by the annual spring freshet, establishes firm stratification and loads the epilimnion with nutrients. Phytoplankton production increases, thereby depleting nitrate, silicate, and soluble reactive phosphorus within the water column during the summer growing season. Since the epilimnion is essentially isolated by thermal and haline stratification, much of the microbial biomass produced within the epilimnion sinks toward the bottom. This is corroborated by oxygen depletion in the metalimnion, where biomass deposited on the pycnocline begins to decompose, creating the oxygen demand described above. As primary production increases, calcite precipitation also may increase, which in turn may allow additional phosphorus loss as a function of adsorption to calcite particles. Moreover, soluble and particulate nutrients are lost via the withdrawal current from the dam. Nutrients entrained in the hypolimnion or bottom sediments are not regenerated within the water column, owing to the lack of convective circulation and an inverse redox gradient (Gloss et al., 1980).

Thus, the reservoir is a nutrient sink, especially for phosphorus. Flow-weighted mass balance calculations provide retention coefficients of .74 for dissolved phosphorus and .96 for total phosphorus (Gloss et al., 1981; Miller et al., 1983). Total nitrogen is more conservative; Gloss et al. (1981) estimated 9% retention. The nitrogen load is ca. 47% organic N and 45% nitrate, and inflow and outflow values of the various forms of nitrogen are similar. The retention coefficient for silica is estimated at .14, with losses attributed to uptake by diatoms and subsequent sedimentation (Gloss et al., 1981).

Over 95% of the fluvial phosphorus reaching Lake Powell is particulate, associated with clays in the suspended sediments (Gloss et al., 1981; Evans and Paulson, 1983). Thus, most of the load is sedimented within the reservoir basin. However, Mayer and Gloss (1980) estimated that about 20-30 µg/liter of inorganic phosphorus may be maintained within Colorado River water by progressive desorption from the clay particles. Since microbial production within the water column appears to be phosphorus limited and inversely related to the concentration of dissolved nutrients (i.e., production increases until nutrients are depleted; Gloss, 1977), apparently bioproduction in Lake Powell is directly related to the intensity and duration (spatial and temporal) of the enriched spring freshet event.

Some bays apparently are locally eutrophied, relative to the pelagic areas of the reservoir, by concentrated human activities (Hansmann et al., 1974).

Bioavailability of Particulate Phosphorus

Because of the importance of the phosphorus budget to lakewide bioproduction, the question of how much of the incoming phosphorus load is actually biologically labile or bioavailable is especially relevant. As noted above, Colorado River suspended sediments may desorb 20-30 µg/liter soluble reactive phosphorus (SRP), as determined from sequential measures of SRP after progressively placing suspended sediments in fresh aliquots of filtered lake water (Mayer and Gloss, 1980; Gloss et al., 1981). SRP is generally thought to be 100% bioavailable (Wetzel and Likens, 1979). Thus, suspended sediments are clearly an important source of bioavailable phosphorus. Using NaOH extractions of sediments obtained from Colorado River water, Evans and Paulson (1983) determined that only 7-19% (mean, 11.2%) of the particulate phosphorus is bioavailable. However, NaOH extractions may not provide an accurate estimate of bioavailable phosphorus since results are not often comparable to estimates derived from algal assays and kinetic experiments (Ellis and Stanford, 1988). Using algal bioassays and stoichiometric analyses of whole water, Watts and Lamarra (1983) determined that 21 and 49% of total phosphorus in Colorado River water at Moab Bridge in September 1978 and October 1978 was bioavailable; most of the extractable phosphorus was in the form of calcium-bound phosphorus, involving phosphorus adsorption on a lattice of the calcite crystal or coprecipitation of phosphorus during calcite formation. Although SRP concentrations are typically low in Colorado River water (usually <10 µg/liter), primary productivity of the river water does not appear to be nutrient limited; rather, Watts and Lamarra (1983) found an inverse relationship between turbidity and primary production, suggesting that the in situ light regime and concentration of calcite-bound phosphorus may interact to control algal production. Swale (1964) and Lund (1969) had similar conclusions for the calcareous River Wye in England.

On the basis of these data and interpretations, the issue of bioavailability of particulate phosphorus derived from the spring freshet is not explicitly worked out. It is apparent that bioproduction is stimulated by the freshet event, but only a small percentage of the sediment-bound phosphorus is actually mobilized by the food web. It is not surprising that Lake Powell does not fit the empirical models used to predict eutrophication from nutrient loading (Labough and Winter, 1981; Mueller, 1982). Indeed, on the basis of the net flow-weighted phosphorus budgets, which apparently vary from less than 2,060 to greater than 7,295 million tons/year as a function of the freshet volume, one would expect Lake Powell to be hypereutrophic (Gloss et al., 1981). Clearly that is not the case, because >95% of the annual phosphorus load is associated with riverine sediments (Evans and Paulson, 1983) that settle to the bottom of the reservoir before large amounts of the particulate phosphorus are either chemically desorbed or actively mobilized by microbiota (see Ellis and Stanford, 1988).

Salinity

Total dissolved solids (TDS) in Lake Powell are dominated by SO_4^{2-}, HCO_3^-, Ca^{2+}, and Na^+ ions (Table 5-4). Calcium and sodium sulfates dominate the riverine TDS load, owing to the predominance of gypsum substrata within the catchment (Stanford and Ward, 1986a). TDS concentrations are extremely dynamic over time (i.e., similar to the pre-1960s period in Figure

TABLE 5-4 Composition of the major ions contributing TDS in the Colorado River at Lee's Ferry compared to Lake Powell water discharged from Glen Canyon Dam.

	Lee's Ferry 1948-1962		Lee's Ferry 1948-1962 (Corrected for Evaporation)		Glen Canyon Dam Discharge, 1972-1975	
Ion	µE/liter	mg/liter	µE/liter	mg/liter	µE/liter	mg/liter
Ca	4,012	81.8	4,249	86.6	3,607	73.6
Mg	1,990	24.2	2,107	25.6	2,051	24.9
Na	2,975	68.4	3,151	72.4	3,293	75.7
K	107	4.2	113	4.5	105	4.1
HCO_3	3,098	189.0	3,280	200.0	2,506	159.0
SO_4	4,538	218.0	4,806	231.0	5,016	241.0
Cl	1,323	46.9	1,401	49.7	1,441	51.1
Total		633		670		629

SOURCE: Gloss et al., 1981.

5-3) in the main tributaries of Lake Powell, as a consequence of flow variability. Freshet flows tend to dilute the dissolved solids concentrations. Average concentrations are three times higher in the San Rafael River (Figure 5-4), but average annual flow-weighted loads are highest in the Colorado River. Because of the stabilization of flow by the dam, the salinity of the Colorado River at Lee's Ferry has been fairly uniform; the gradual decline in the decade of the 1980s (Figure 5-5) is apparently due mainly to dilution caused by above-average flows, calcite precipitation in Lake Powell, and a decrease in gypsum dissolution from the bed of Lake Powell (Paulson and Baker, 1983b).

The Lake Powell TDS budget has been a primary study topic because of the general conception that evaporation and dissolution of bed substrata in reservoirs is purported as a primary cause of increasing salinity in the Colorado River. (Salinity in the Colorado River at Imperial Dam increased from 380 mg/liter during pristine times to 825 mg/liter by 1975 [Gardner and Steward, 1975]. Salinity trend models indicate that additional water diver-

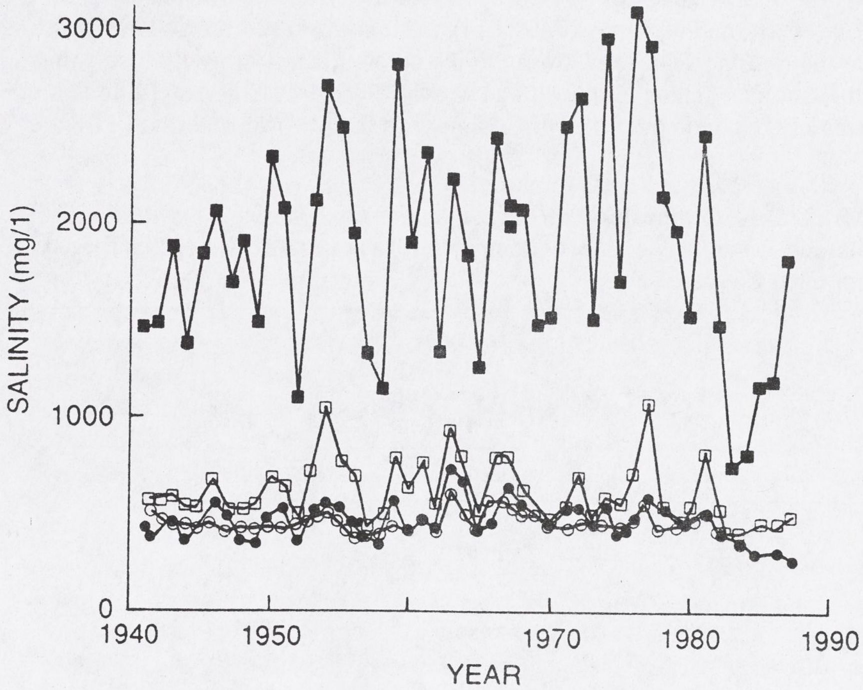

FIGURE 5-4 Average annual concentrations of TDS derived from daily measurements at the tributary sites shown in Figure 5-1 for the period 1941-1987.
SOURCE: Bureau of Reclamation, 1989.

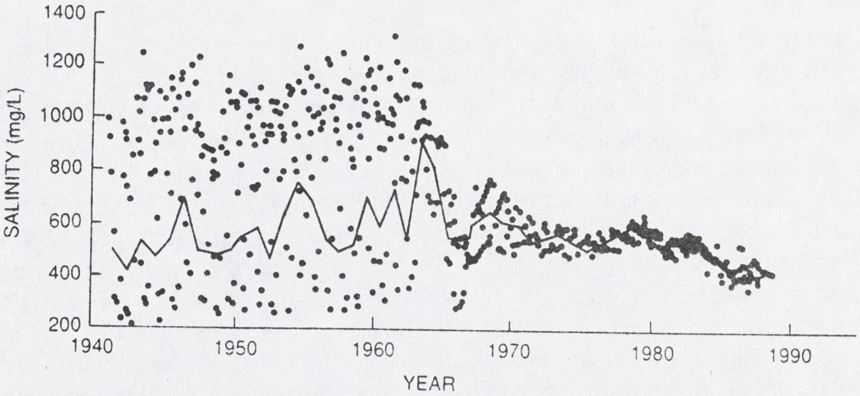

FIGURE 5-5 Time series trend for salinity in the Colorado River at Lee's Ferry. **SOURCE:** Bureau of Reclamation, 1989.

sions may increase salinity to >1,150 mg/liter by the end of the century [Kleinman and Brown, 1980; Law and Hornsby, 1982]) Indeed, Gloss et al. (1980) noticed a slight increase in SO_4 at Lee's Ferry after impoundment of Lake Powell and attributed it to gypsum dissolution that should decrease in time. On a mass balance basis and under steady-state conditions, evaporation and leaching of sulfate from the reservoir bed apparently could account for an annual increase in salinity of ca. 40 mg/liter below the dam. However, this increase is apparently offset by appreciable calcite precipitation. Thus, pre- and post-dam salinities in the Colorado River at Lee's Ferry are about the same (Table 5-4) (Reynolds and Johnson, 1974; Gloss et al., 1980). However, Paulson and Baker (1983b) gave flow-weighted averages for common ions and TDS for the period 1970-1979; they estimate annual calcite ($CaCO_3$), gypsum ($CaSO_4$) and halite (NaCl) precipitation rates in Lake Powell to be 23 (9), 16 (5), and 5 mg/liter (Ca^{2+} concentration in parentheses) on the basis of ion budgets. These loss rates are high enough to partially account for the decline in river salinity in recent years (Figure 5-5). On the other hand, Messer et al. (1983) calculated a salinity mass balance based on data for the period 1941-1975 which left 8.1×10^6 million tons of salt or 8% of the calculated input either in bank storage or lost to the sediments by some biogeochemical removal process (i.e., precipitation or coprecipitation with inorganic particles, such as clays), coagulation (involving polysaccharide fibrils of microbes), and bioassimilation (by microbiota)). Assuming bank storage of 11×10^9 million tons and flow-weighted TDS of 569 mg/liter, 6.2×10^6 million tons of salt was bank stored, leaving only 1.9% that couldhave been removed by biogeochemical processes. Messer et al. (1983) considered their budget to be conservative, since bed dissolution processes were not included. They concluded that massive biogeochemical salt removal (i.e. calcite precipitation) could not have occurred. This conclusion was corroborated by the LARM hydrodynamics model (Edinger et al., 1984), which showed that 1% of the salt load could precipitate in the epilimnion annually, but redox conditions in the lower water column were sufficient to resolubilize the precipitant. We note that all of the mass balance calculations are based on measurements of river discharge and TDS well upstream from Lake Powell (Figure 5-1) and that many of the side flows into the reservoir are not monitored at all. Given the size of the reservoir and the inaccuracies of loading estimates, it is doubtful that the actual impact of calcite precipitation on salinity trends in the Colorado River will be verified from mass balance calculations. That the rate of calcite precipitation in Lake Powell is influenced by fluvial salt loading, bed dissolution of $CaSO_4$, phytoplankton productivity, and polyphenol inhibition (Reynolds, 1978) seems conclusive.

Heavy Metals and Other Pollutants

Potter and Baker (1989) noted that filling of the reservoir provided a unique opportunity to examine bioamplification of heavy metals resulting from erosion of natural geologic deposits. Indeed, natural weathering of the complex geologic deposits within the Colorado plateau contributes a variety of metals to Lake Powell, mostly in association with fluvial sediments (Graf, 1985).

The mercury story is best documented. Forty-percent of the mercury load (2,200 kg/year) is derived from the Green River catchment, where the source rocks appear to be the Chinle and Morrison formations (Graf, 1985). Mercury concentrations in Lake Powell sediments average 30 parts per billion (range, 5-53) (Standiford et al., 1973); in the turbid upper reaches of the reservoir water column concentrations approach 6 parts per billion, which Blinn et al. (1977a) showed to be inhibitory to phytoplankton primary productivity. Tompkins and Blinn (1976) assayed mercury effects on growth of two of the common planktonic diatoms and found that *Fragilaria crotonensis* was considerably more sensitive than *Asterionella formosa.* Concentrations in fish tissues ranged from 5 to 700 µg/mg dry mass, suggesting a ca. 43-fold increase relative to average concentrations in the catchment substrata (Potter et al., 1975).

Relatively high selenium concentrations have been observed in Colorado River tributaries draining Mancos shale formations (Stanford and Ward, 1986a). Relatively high concentrations were observed in the larger fishes of Lake Powell (Potter and Drake, 1989) and warrant further work, as selenium may inhibit egg production in squawfish and other native fishes of the Colorado River.

Heavy metal contamination within the headwater reaches of the Colorado River has been a concern for years because of hard rock mine effluents in many locations (e.g., Gunnison, Dolores, and San Miguel rivers). How much of this contamination reaches Lake Powell is unknown. Heavy metals associated with emissions from coal-fired generating plants in the Lake Powell area have been shown to reduce photosynthesis and respiration in microcosms containing water from Lake Powell (Medine et al., 1980; Medine and Porcella, 1980). However, Potter and Drake (1989) concluded that mercury and selenium were the only heavy metals reaching Lake Powell in sufficient concentrations to affect the food web.

Radioactive pollutants enter the reservoir from several sources: (1) naturally associated with basin geology; (2) from waste ponds and heaps located at various sites (e.g., San Miguel River); and (3) in association with coal-fired generating plants in the basin (Graf, 1985). The impact within the food web is apparently unknown.

LAKE POWELL FOOD WEB

Phytoplankton

Gloss et al. (1980) reported primary productivity in the reservoir of 2-60 mg of ^{14}C m^{-3} day^{-1} during the summers of 1975 and 1976. Values varied an order of magnitude spatially during a given sampling period. Maximum productivity occurred between 1 and 3m in depth. Hansmann et al. (1974) reported that in 1971 the highest productivity (1,066 mg of C m^{-2} day^{-1}) occurred in July and the lowest (33 mg of C m^{-2} day^{-1}) was measured in February. Yearly productivity was estimated at 184 g of C m^{-2}. Blinn et al. (1977a) reported similar values. Because of the variable amounts of sediments suspended in the water column, productivity varies greatly within the reservoir in relation to light attenuation (Blinn et al., 1977b). Chlorophyll concentrations in the water column averaged 5 μg/liter near the Colorado River and 1.5 μg/liter lakewide during 1982-1983 (Paulson and Baker, 1983a) and 1987-1988 (Sollberger et al., 1989).

Seasonal phytoplankton succession in Lake Powell involves a spring diatom pulse (*Fragilaria crotonensis* and *Asterionella formosa*), a diverse summer community (*Dinobryon sertularia* and Chloroccocales), a late autumn pulse of diatoms (*Synedra delicatessima* var. *augustissima*) and dinoflagellates, and no abundant winter forms (Stewart and Blinn, 1976; Blinn et al., 1977b). The spring pulse yielded chlorophyll values of 1.8 μg/liter in the downstream end of the reservoir (Sollberger et al., 1989). This vernal diatom bloom is common in large oligotrophic lakes (e.g., Flathead Lake, Montana) and does not suggest extreme or abnormal nutrient loading. Indeed, blue-green blooms do not occur in Lake Powell as commonly occur in large upstream impoundments (e.g., Flaming Gorge Reservoir on the Green River) (Miller et al., 1983). This is undoubtedly due to lower concentrations of bioavailable nutrients in Lake Powell and the fact that thermal and haline stratification promotes nutrient loss via withdrawal and hypolimnetic entrainment. Relatively high salinity does not seem to play much of a role, although indigenous Lake Powell diatoms are apparently more tolerant of salinity additions than are standard bioassay test algae (Cleave et al., 1981). On the basis of the general nutrient regime and importance of allochthonous sediments, we suspect that picoplankton (i.e., cells <10 µm in size) are probably very important in Lake Powell, but the size distribution of the plankton has apparently not been investigated.

Zooplankton

Stone and Rathbun (1969) reported that *Daphnia*, *Cyclops*, and *Diaptomus* were dominant zooplankters with densities that varied between 15 and 100 individuals per liter in the upper 30 m of the water column. Densities were higher in the summer and at the upper end of the reservoir. At the downstream end, samples rarely exceeded 20 per liter and did not vary much seasonally.

In a more detailed study conducted in 1987-1988, Sollberger et al. (1989) found 36 species (8 *Copepoda*, 13 *Cladocera*, and 15 *Rotifera*); *Cyclops bicuspidatus*, *Mesocyclops edax*, and *Diaptomus ashlandi* were the most common copepods, whereas *Bosmina longi-rostris*, *Daphnia galeata* and *D. pulex*, *Collotheca* sp., *Polyarthra* sp., and *Syncheata* sp. were the most common cladocerans and rotifers. Copepods were the most abundant group. Densities of total zooplankton in the water column were normally 20 per liter and never exceeded 50 per liter, with the higher concentrations occurring in the upper 20 m of the water column during April (average densities ranged from 3 to 26 per liter within the upper 40 m). These data are surprisingly similar to the counts made two decades earlier by Stone and Rathbun (1969), suggesting little if any decline in productivity. Density of zooplankton was inversely related to chlorophyll content. Densities declined through the summer, perhaps as a result of predation. No significant vertical migration was observed, and zooplankters primarily inhabited the epilimnion. The lipid-ovary index was generally <0.5 for the *Daphnia*, and egg ratios were <0.2, indicating that populations were food limited most of the year.

Benthos

Artificial substrata (plastic trees) placed in the littoral zone of Lake Powell were colonized by 69 diatom taxa, 6 of which made up 65-94% of the periphyton community numerically. Maximum periphyton occurred in spring and fall. Macroinvertebrate communities colonizing the substrata were dominated by chironomids, with *Physa*, jellyfish (*Craspedacusta sowerbyi*), water mites, and damselflies occasionally present (Potter and Louderbough, 1977).

Potter and Pattison (1976) used a bilge pump and scuba equipment to collect natural benthic biofilms and found an average of 2.14 g/m^2 with an average chlorophyll content of 352 mg/m^2, or about ten times greater than average concentrations in the water column. In doing this work they noticed that wood rat (*Neotoma*) middens, submerged upon closure of the dam, could be identified by plumes of benthic periphyton. The benthic algae was apparently stimulated by nutrients leached from the middens.

Since so much of the shoreline is near vertical cliffs (54%), the high water line is marked by epilithic biofilms. This biofilm is oxidized during the drawdown period, leaving a white bathtub ring that grades into characteristic black streaks on red sandstones. The latter is caused by cementing of clays with oxides and hydroxides resulting from the oxidation of minerals and organics by mixotropic bacteria (Dorn and Oberlander, 1982).

Fishes

Fisheries in Lake Powell are derived from a hodgepodge of native and introduced species. The introduced species predominate. Indeed, the status of the endemic big river fishes (e.g., squawfish, humpback chub, and razorback sucker; Stanford and Ward, 1986c; Carlson and Muth, 1989) that inhabited Glen Canyon prior to impoundment is unknown. Persons and Bulkley (1982) reported that *Dorosoma petenense* (threadfin shad) were primary food items in guts of *Merone saxatalis* (striped bass) that spawned in the mixing zone of the Colorado River. They observed that none of these reservoir fish moved very far upstream, and no evidence of predation on endemic fishes was found. Dynamics of the pelagic shad and striped bass populations appear to be the most economically significant aspect of the Lake Powell fisheries. Other bass (*Micropterus salmoides*, *M. dolomieui*), channel cat (*Icralurus punctatus*), northern pike (*Esox lucius*), walleye (*Stizostedion verreum*), crappie (*Pomoxis nigromaculatus*, *P. annularis*), and sunfishes (*Lepomis cyanellus*, *L. gulosus*, *L. macrochirus*, *L. microlophus*) are common, especially near shore. Rainbow trout (*Onocorhynchus mykiss*) and brown trout (*Salmo trutta*) occupy cooler waters in the lower end of the reservoir.

Quantitative food web relationship for the fishes relative to reservoirwide plankton production have not been established. The trophic status of Lake Powell appears to be oligotrophic, on the basis of primary production, average chlorophyll content, and the depressed nutritional status of the zooplankton. Thus, Lake Powell fisheries should not be expected to be very productive, and populations may fluctuate as bioproduction of the plankton waxes and wanes in response to riverine nutrient loading and drafting for hydropower and downstream water demands. Fluctuations may also manifest as a consequence of angler harvest, disease, poor recruitment (e.g., related to reservoir operations), and/or introduction of new species (e.g., rainbow smelt [*Osmerus mordax*], a pelagic planktivore, may be introduced in an attempt to supplement forage for striped bass and other piscivores; Courtenay and Robins, 1989; Gustaveson et al., 1990).

Indeed, the food web currently appears to be destabilized. Densities of threadfin shad have decreased from >600 adult fish per standardized trawl in 1977-1978 to 0 in 1989. Concomitantly, the mean size of striped bass declined from 620 mm (24 inches) to 348 (14 inches); the mass/length rates declined from 1.6 to 1.0. Formerly abundant walleye and largemouth bass populations have also declined (Gustaveson et al., 1990). Destabilization of the food web appears to have occurred from the top down, since the fertility of the reservoir seems to have changed very little and zooplankton crops are about the same today as in 1969 (see above). The striped bass cohorts that were dominated by large-bodied individuals in the late 1970s probably were very productive, and subsequent high recruitment of juveniles may have gradually reduced the shad forage. Moreover, juvenile striped bass are able to forage in the warm upper layers of the reservoir (>10 m) where shad densities are greatest; adult bass are more stenothermic and habitually reside in deeper waters (Larry Paulson, personal communication). Rainbow smelt prefer colder waters and could be good forage for the larger bass cohorts. However, the net growth potential of the Lake Powell food web is limited because of its oligotrophic status, and productivity can be packaged only in so many ways. The bass-shad relation could be long-term cyclic and/or strongly influenced by angler harvest. Introduction of another planktivore may only further destabilize the food web and produce unanticipated negative effects (see Moyle et al., 1986). Moreover, smelt may rapidly disperse above and below the reservoir, perhaps compromising recovery of the endangered native fishes and creating a plethora of other problems (Courtenay and Robins, 1989).

Riparian Systems

The flora of the xeric uplands of the Lake Powell area is characterized by patches of piñon-juniper (*Pinus edulia-Juniperus spp.*) and a wide variety of desert shrubs, such as blackbrush (*Coleogyne ramosissima*), Mormon tea (*Ephedra spp.*), sagebrush (*Artimesia spp.*), shrub oak (*Quercus* spp.), and *Yucca galeata*. These trees and bushes occur commonly on the rim and flanks of Glen Canyon and, prior to impoundment, graded into terrace flora that included deep-rooted shrubs (such as four-winged saltbrush [*Atriplex* *canescens*], greasewood [*Sarcobatus* spp.], rabbitbrush [*Chrysothammus* spp.] and squawbush [*Rhus trilolata*]) which formed irregular patches. The riparian flora was mainly large galleries of Fremont cottonwood (*Populus fremontii*) interspersed with patches of willows (*Salix* spp.), hackberry (*Celris reticulata*), gambel oak (*Quercus gambeli*), saltgrass (*Distichilis* spp.), slender dropseed (Sporobolus spp.), and clumps of tall reed (*Phragmites* sp.). Many species of birds and mammals seasonally inhabited these plant communities (Stanford and Ward, 1986a).

Potter and Drake (1989) provided an excellent summary of the shoreline vegetation and associated changes as impoundment ensued, based on original work by Potter and Pattison (1977). The main conclusion is that most of the preimpoundment riparian forests and other streamside plants are gone and availability of riparian habitat is limited within the reservoir landscape. Only 3% (ca. 1,000 hectares) of the shoreline is sandy and aggraded. These areas have been uniformly invaded by exotic saltcedar (*Tamarisk chinensis*). The few cottonwood seedlings that managed to root in a few places were largely eliminated by dense and fast-growing saltcedar stands. Saltcedar remain very viable throughout the upper drawdown zone of the reservoir and are very tolerant of flooding. The lower drawdown zone is colonized by Russian thistle (*Salsola kali*).

INFLUENCE OF LAKE POWELL ON ENVIRONMENTS DOWNSTREAM

Lake Powell as a Heat and Materials Sink

River temperatures at Lee's Ferry in summer are on the average 11°C colder than prior to regulation because the dam discharges water from the metalimnion of the reservoir. Winter temperatures in the post-dam river average 8°C warmer than pre-dam conditions (Table 5-3). Consequently, there is little or no seasonality to the river temperatures until insolation and side flows begin to reestablish the riverine heat budget within the Grand Canyon.

Materials balance calculations show that most of the sediments and most of the phosphorus and other metals entering the reservoir are retained in the basin either in the profundal waters and sediments or in bank storage. Thus, the reservoir sequesters the solids load of the Colorado River. On the other hand, soluble phosphorus, nitrate, and silicate are depleted within the epilimnion by the withdrawal current (see above). Therefore, dam tailwaters are continually transparent and loaded with labile nutrients. These conditions persist downstream into the Grand Canyon and greatly promote bioproduction within the riverine food web, as evidenced by presence of dense mats of green algae (*Cladophora*) and large biomasses of invertebrates (*Gammarus*) and fish (Stanford and Ward, 1986c; Blinn and Cole, this volume).

Controversy persists concerning the effects that Lake Powell and other Colorado River storage projects have on salinity. Paulson and Baker (1983a,b) suggest that reservoir operations can control salinity; Messer et al. (1983) and Edinger et al. (1984) report that the reservoirs have little or no effect (see above). We note that the error terms on the mass balance estimates are often higher than the estimated TDS retention (in excess of bank storage). The issue may be academic except for the fact that salinity at Lee's Ferry is indeed declining (Figure 5-5). Is the decline due to salinity control measures in the headwaters, salinity losses in the reservoirs, or more mesic conditions in the last decade? The question is relevant because considerable money continues to be spent on salinity control projects in the Colorado River basin (Bureau of Reclamation, 1987) when the predominant ions contributing salinity are sulfate and bicarbonate salts that have little effect on agricultural or potable uses. Indeed, sulfate constitutes one-half of the TDS in the Colorado River (Paulson and Baker, 1983b). Mancos and other shale formations, which are widespread on the Colorado plateau (Schumm and Gregory, 1986), are the sources of most of the water, sediments, and salts entering Lake Powell. Harmful NaCl is localized in the Paradox Valley and Glenwood and Dotsero springs areas in the headwater reaches (Paulson and Baker, 1983b). Resolution of the salinity question probably requires continued monitoring of conditions in the rivers above and below Lake Powell.

Retention of >80% of the riverine nutrient load in Lake Powell has greatly decreased the fertility and bioproduction of Lake Mead; shad-striped bass fisheries have also declined, and reduced fertility has been inferred as the cause (Paulson and Baker, 1981; Stanford and Ward, 1986c). However, we note that a similar destabilization of the food web occurred in Lake Powell with little or no change in overall trophic status. Moreover, Lake Powell is oligotrophic despite the fact that the reservoir sequesters the riverine solids load. Attempts to artificially fertilize Lake Mead to increase bioproduction and recover the fishery did not provide sustained results; rather, the artificial fertility pulses quickly attenuated and also desynchronized cohorts of predator and prey species (as described above). These observations support the idea that the producer components of lacustrine food webs are not affected much by cyclic or transient changes in the higher consumer populations (i.e., trophic status and food webs generally are controlled bottom up by nutrient supply). We suggest that greater attention be given to cohort-specific growth patterns and the effects of angler harvest in an attempt to better explain shad-bass dynamics in Lake Powell and Lake Mead. However, it is clear that the presence of Lake Powell has vastly altered the chemistry and bioproduction of both the Colorado River and Lake Mead.

Paulson (1983) also showed that cold water from Lake Powell has reduced the net heat budget of Lake Mead, causing less evaporation and an average salinity decrease of at least 9 mg/liter, and suggested that salinity control would be enhanced if water were discharged from the surface rather than the hypolimnion of Lake Mead. This would also retain nutrients and perhaps stimulate productivity, in turn which would encourage calcite precipitation, providing a secondary control mechanism.

Clearly, management of water quality or fisheries must take into account the effects of upstream regulation and management actions in addition to reservoir-specific considerations.

Stream Regulation and the Manifestation of Serial Discontinuity

Production of algae, mainly *Cladophora glomerata*, is maintained by conditions of constancy (i.e., transparent summer-cool, winter-warm waters, stable substratum, and nutrient regime) in the tailwaters. Large populations of invertebrates, especially amphipods (*Gammarus lacustris*) support a very productive trout fishery. Similar biogeochemistry exists in headwater segments upstream. Thus, Lake Powell resets river conditions to reflect habitats that exist 400+ km upstream (two to three stream orders). This discontinuity (sensu Ward and Stanford, 1983) is gradually ameliorated in the Grand Canyon segment and then reset again by Lake Mead (Stanford and Ward, 1986b).

AN ECOSYSTEM APPROACH TO MANAGEMENT

The limnology of Lake Powell is influenced by hydrodynamics of the rivers that fill the reservoir. Moreover, the hydrodynamics of the reservoir, as related to use of the dam to store flood waters and generate hydropower, control the biophysiology of the Colorado River downstream from Lake Powell through the Grand Canyon. The limnology of Lake Mead is also coupled to Lake Powell. Thus, it seems reasonable to expand the idea of the Glen Canyon area as an ecosystem (Marzolf et al., 1987) to include the tributaries of Lake Powell, the reservoir itself, the Colorado River from Glen Canyon Dam to Lake Mead, and Lake Mead. However, even bounding the ecosystem in this manner is probably flawed, since the limnology of the upper basin has a major influence on the quality and quantity of water reaching Lake Powell and effluents from Lake Mead clearly influence downstream environments. We conclude that (1) an ecosystem perspective is requisite because of the biophysical connectivity of the reservoir and rivers and (2) the ecosystem boundaries must be determined by the nature of the management or scientific question.

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