Chapter 4

Water Quality in Lake Powell and the Colorado River

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Introduction

Water temperature, nutrient concentrations, turbidity, and other water-quality parameters are of interest to managers and scientists because these parameters influence a range of ecosystem components, from support of aquatic microorganisms and invertebrates to the behavior of native and nonnative fishes. For example, declines of Colorado River Basin native fishes and changes in their condition have been attributed, in part, to low water temperatures downstream from dams, such as Glen Canyon Dam, that release water from deeper portions of the reservoir (Clarkson and Childs, 2000). Similarly, water quality is an important determinant of food-web structure in aquatic habitats and abundance of consumers like fish in those food webs (Carpenter and Kitchell, 1996; Wetzel, 2001).

Any investigation of the dynamics of the Colorado River ecosystem in Grand Canyon must not only document and understand the water quality in Grand Canyon itself but also the water quality in Lake Powell, the reservoir created by Glen Canyon Dam. The impoundment of a river system in a reservoir alters downstream water quality in many ways (Nilsson and others, 2005). The formation of Lake Powell in 1963 was accompanied by reductions in suspended-sediment and nutrient transport and by changes in seasonal temperatures, discharge levels, and benthic community structure of the Colorado River (Paulson and Baker, 1981; Stevens and others, 1997; Topping and others, 2000 a, b). More recently, reservoir and downstream water quality has been affected by reservoir drawdown from a 5-yr basinwide drought in the Western United States. Water released from Glen Canyon Dam in 2003 and 2004 was the warmest recorded since August 1971, when Lake Powell was in its initial filling period (initial filling of the reservoir began in 1963 with the closure of Glen Canyon Dam, and it reached full pool of 3,700 ft for the first time in 1980). Changes in stratification and the fate of inflow currents in Lake Powell under various storage conditions, as well as various operational scenarios such as experimental releases and a proposed temperature control device, could have significant effects on the quality of water released from Glen Canyon Dam.

This chapter provides an overview of water-quality trends and conditions in Lake Powell and the Grand Canyon ecosystem. Because Lake Powell and Glen Canyon Dam operations have a strong influence on downstream water quality, the water quality of the reservoir is discussed in some detail. The chapter also addresses recent drought-induced changes and the effects of the modified low fluctuating flow (MLFF) alternative. The monitoring of water quality in Lake Powell is conducted by the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center under separate funding from the Bureau of Reclamation and is not funded by the Glen Canyon Dam Adaptive Management Program.

Background

Glen Canyon Dam has a structural height of 710 ft (216 m). This high, concrete-arch dam backs up water for 186 mi (299 km) to form Lake Powell, the second largest reservoir in the United States. Lake Powell had an original capacity of 27.1 million acre-feet (maf) (33,414 million m^3) and a surface area of 161,390 acres (65,315 ha) at full pool elevation of 3,700 ft (1,128 m). By 1986, this capacity had been reduced to 26.2 maf (32,305 million m^3) because of an estimated loss of capacity of 30,000 acre-feet (af) (36,990,000 m^3) per year resulting from sedimentation (Ferrari, 1988). Water can be released from Glen Canyon Dam through three separate structures (spillways, penstocks, and river outlet works). The majority of water is routed through eight penstocks, which feed the powerplant turbines. The penstock inlets are at an elevation of 3,470 ft (1,058 m) and have a maximum combined discharge capacity of approximately 33,200 cubic feet per second (cfs) when the reservoir is full. Water can also be released from (1) the river outlet works at an elevation of 3,374 ft (1,028 m) and (2) two spillways at an elevation of 3,648 ft (1,112 m), both of which bypass the powerplant turbines and have discharge capacities of 15,000 cfs and 208,000 cfs, respectively (Bureau of Reclamation, 1981) (fig. 1).

Lake Powell

Glen Canyon Dam began storing water on March 13, 1963, and full pool elevation was reached on June 22, 1980. Ninety-six percent of the reservoir's inflow is received from the Colorado and San Juan Rivers; the majority of this inflow is received from May to July as the result of snowmelt in the Rocky Mountains (Stanford and Ward, 1991). The impoundment of the Colorado River by Glen Canyon Dam altered the quality, seasonal release volumes, and the amount of daily fluctuations for the Colorado River ecosystem downstream of the dam. Colorado River water is now transformed by an approximate 2-yr residence time in Lake Powell and by the structure and operation of Glen Canyon Dam. These factors influence the temperature, suspended and dissolved solids, nutrients, and organisms that pass downstream as well as the volume of water released and the magnitude of fluctuations.

Lake Powell has a maximum depth immediately upstream of Glen Canyon Dam of approximately 515 ft (157 m) at full pool elevation; the lake is vertically stratified into density layers and differs longitudinally as the currents move through the reservoir. Vertical stratification varies seasonally and is determined by the relative density of the different layers of the reservoir. Density is determined by water temperature and the amount of dissolved minerals and suspended solids. The surface layer of the reservoir, or epilimnion, warms through summer and is eventually mixed with deeper water by the wind and convective currents during the winter cooling period, which extends from October to early March. The epilimnion exhibits the highest level of biological activity because of warm temperatures and light availability. Water temperature decreases with depth in the metalimnion, the layer that separates the epilimnion from the bottom layer of the reservoir, or hypolimnion. The hypolimnion consistently exhibits lower temperatures, lower dissolved oxygen levels, and higher salinity concentrations than the other layers of the reservoir. Because of the subsurface position of the penstocks, water may be withdrawn from the epilimnion, metalimnion, or hypolimnion depending on reservoir level, reservoir hydrodynamics, timing and strength of stratification, and magnitude of withdrawals.

Longitudinal variation in water quality is the result of currents moving through the reservoir. The portions of the reservoir farthest from the dam exhibit characteristics similar to those of the river entering the reservoir, with more variable temperature and salinity patterns and higher sediment and nutrient concentrations. Primary productivity from photosynthesis is limited by light availability in this more turbid riverine zone. The deeper portions of the reservoir closest to the dam, or the lacustrine zone, exhibit characteristics similar to those of a lake system, with more stable temperature and salinity patterns, low suspended-sediment concentration, and lower nutrient concentrations. Primary productivity in this zone is limited by nutrient availability. A transition zone of intermediate characteristics separates the riverine and lacustrine zones (Kimmel and Groeger, 1984; Department of the Army, Corps of Engineers, 1987; Ford, 1990). The relative location of these zones depends on reservoir levels and the magnitude of inflows. In the

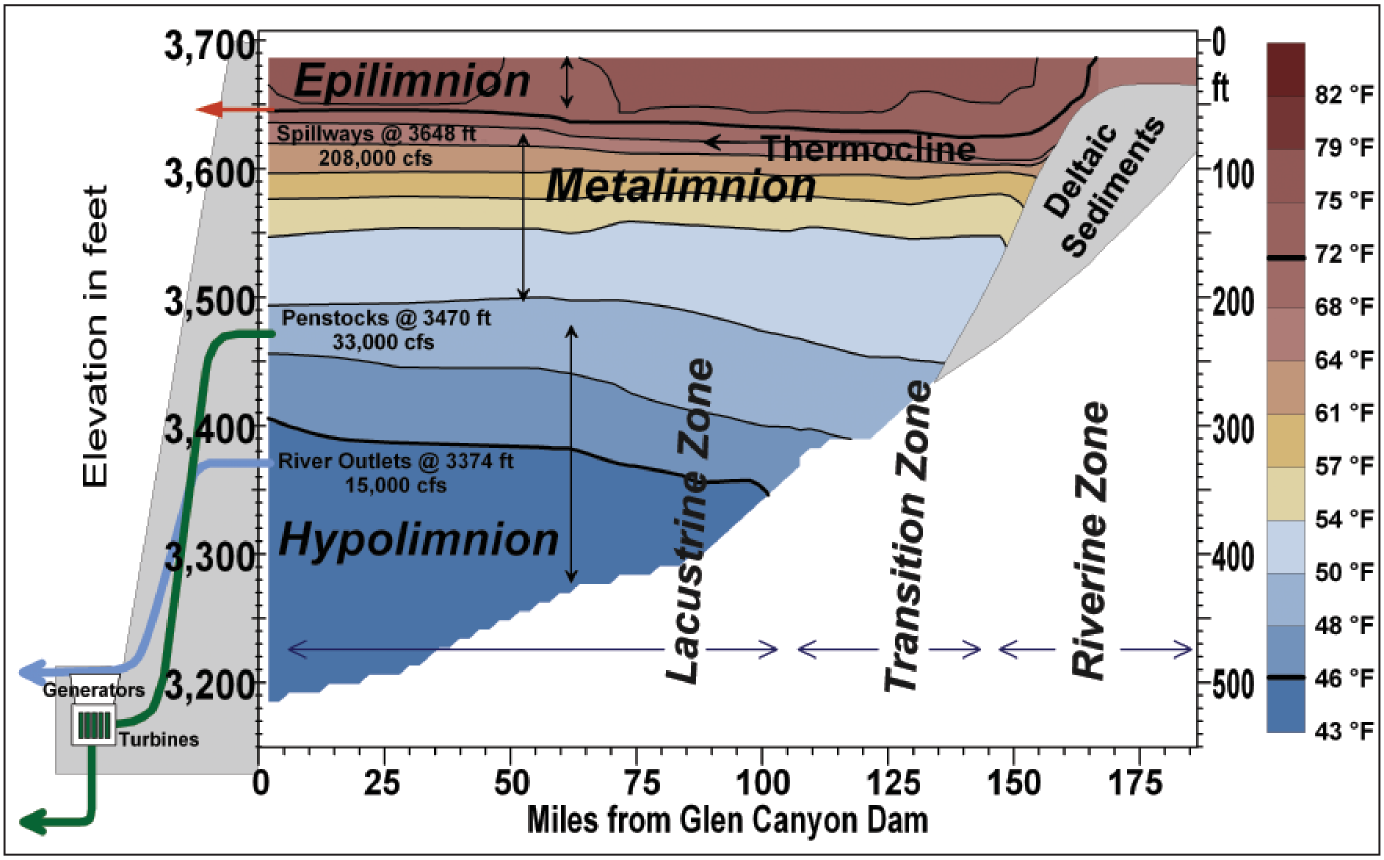


Figure 1. Profile of Lake Powell from Glen Canyon Dam to the inflow of the Colorado River, illustrating the vertical stratification and horizontal zonation of the reservoir at or near full pool elevation, September 1999. Also shows the elevations of each of the three release structures and their capacities as well as an approximation of the wedge of deltaic sediments. Y axis on left is measurement of elevation above mean sea level and on right is actual depth.

main channel of Lake Powell, the riverine zone extends from the Colorado River inflow to Hite Bay, the transition zone extends from Hite Bay to the Bullfrog Bay area, and the lacustrine zone extends from Bullfrog Bay to Glen Canyon Dam (figs. 1 and 2).

The depth at which river water enters the reservoir is dictated by its density relative to the density of the water already in the reservoir. Spring and early summer snowmelt runoff entering the reservoir tends to be dilute, has warmed during its passage through the canyonlands, and represents the lowest density water entering the reservoir during the year. Consequently, this water travels through the reservoir as an overflow density current. During the winter months, inflows are colder and more saline and represent the highest density water entering the reservoir. Depending on the relative density of the hypolimnion, winter inflows will either flow along the bottom of the reservoir, routing fresh water to the hypolimnion and displacing older water upward, or flow into intermediate layers, leaving deeper waters stagnant.

Convective mixing takes place in the epilimnion as the reservoir cools during the fall and winter months. By the end of the calendar year, convective mixing in the upper layers progresses to the point that penstock withdrawals begin to exhibit characteristics of the epilimnion, which contains the warmest water in the reservoir at that time of year, despite the cooler weather conditions. This convective mixing results in the warmest release temperatures of the year occurring in late fall or early winter.

Downstream of Glen Canyon Dam

Changes to the chemical and physical quality of the water of the Colorado River after its release from Glen Canyon Dam are affected by ambient meteorological conditions, primary production and respiration from the aquatic environment, aeration from rapids, inputs from other tributary sources and overland flow, and various aspects of the operation of Glen Canyon Dam.

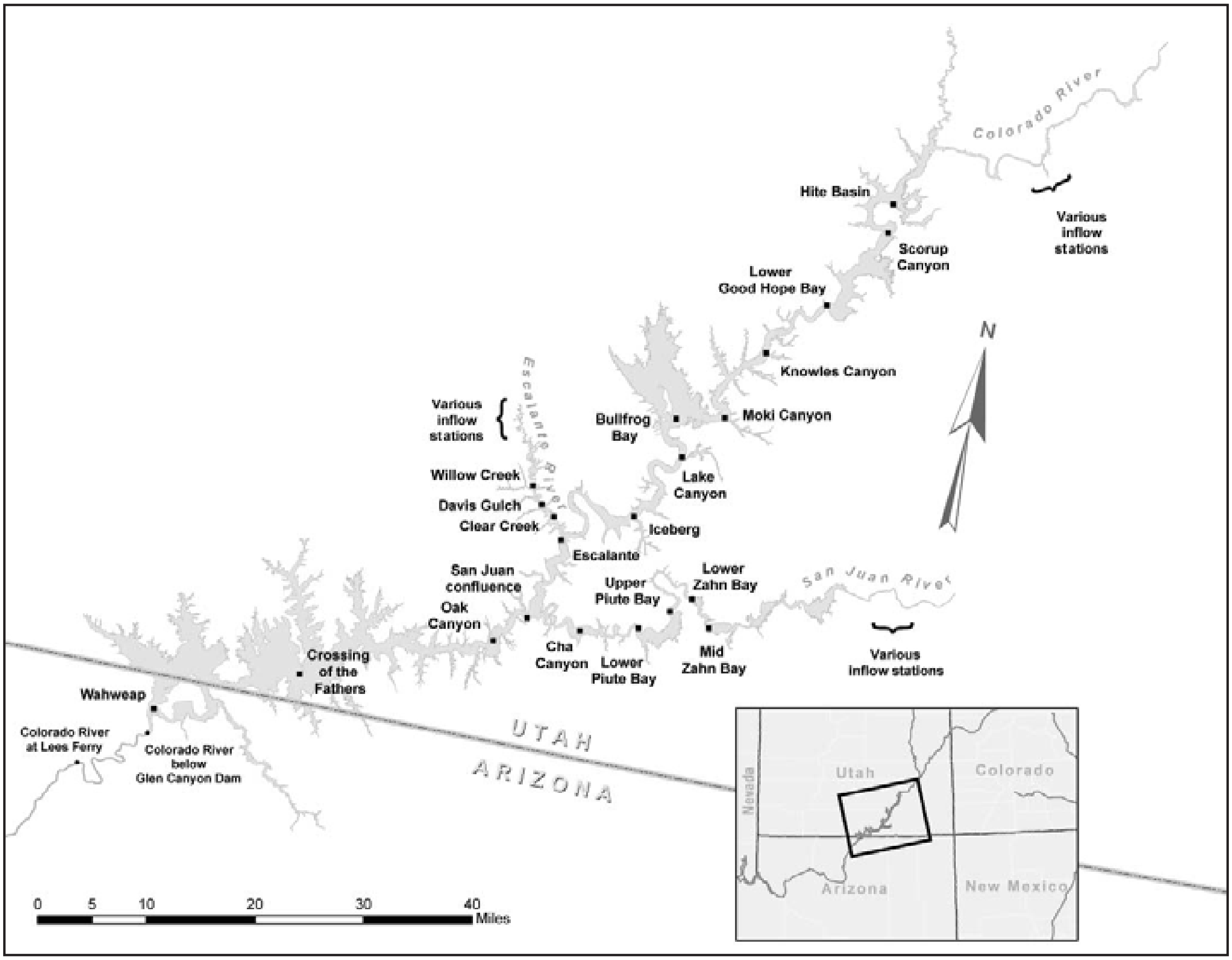


Figure 2. Lake Powell water-quality sampling sites.

Water released from Glen Canyon Dam is usually colder than the surrounding environment and warms as it flows downstream with exposure to solar radiation and warmer ambient air temperatures. The exception to this pattern is during portions of the winter months when dam releases are slightly warmer than the surrounding environment and cool as they flow downstream before warming again in lower elevation reaches.

The aquatic environment affects dissolved oxygen concentrations and pH in the tailwater (referred to as the Lees Ferry reach elsewhere in this report), which is the 15 mi (24 km) of the river that extends downstream from Glen Canyon Dam to Lees Ferry. This area is free of significant tributary sediment inputs that limit light availability for primary production (Yard and others, 2005). As a result of photosynthetic activity, therefore, dissolved oxygen concentrations and pH in the tailwater display daily oscillations at Lees Ferry. During daylight hours dissolved oxygen concentrations and pH increase because of the addition of oxygen and removal of carbon dioxide during photosynthesis. The opposite occurs at night when respiratory processes become dominant (Marzolf and others, 1999; U.S. Geological Survey, 2001).

Under normal powerplant discharges, limited aeration of the river occurs in the tailwater reach of the river compared to downstream reaches. Generally, released water that may be lower in dissolved oxygen does not reach full saturation until the first rapids in Marble Canyon, where the water is aerated by turbulence; however, during periods when the river outlet works are operated, such as during the 1996 beach/habitat-building flow or the 2004 experimental high flow, turbulence immediately below the dam is sufficient to bring release water up to full oxygen saturation (Hueftle and Stevens, 2001).

Various tributaries that enter Grand Canyon can significantly affect water quality of the Colorado River below Glen Canyon Dam. The Paria and Little Colorado Rivers can carry large amounts of fine sediment that limit light availability for primary production and may enhance conditions for native fish that use turbid water for cover from predation (Shannon and others, 1994; Topping and others, 2000 a, b). Some tributaries, such as the Little Colorado River, are significant sources of salinity to the mainstem Colorado River (Cole and Kubly, 1976).

Water-quality Monitoring

Lake Powell

The purpose of water-quality monitoring in Lake Powell is to document and understand the water-quality changes that occur during the residence time of the water in the reservoir and how those changes may affect the quality of water being released from Glen Canyon Dam under various conditions.

Water-quality monitoring of Lake Powell currently has two main components. Monthly surveys of the forebay, the pool of water in front of the dam, take place at the mouth of Wahweap Bay, approximately 1.5 mi (2.4 km) upstream of Glen Canyon Dam, to document the quality of water in dam releases. Reservoir-wide surveys are conducted quarterly to describe seasonal changes in the stratification and hydrodynamics of the reservoir and to better understand the reason for observed changes in downstream releases.

Water-quality sampling in Lake Powell was initiated by the Bureau of Reclamation in 1964 and continued through 1990, including several phases of differing sampling frequencies for the reservoir and forebay. Glen Canyon Environmental Studies conducted the monitoring from 1990 to 1996. The USGS Water Resources Discipline conducted monitoring in Lake Powell on several dates in 1992, 1994, and 1995 (U.S. Geological Survey, 1998). Since 1997, monitoring has been conducted by the USGS Grand Canyon Monitoring and Research Center.

Monthly monitoring of the forebay allows for the observation of conditions immediately upstream of Glen Canyon Dam and for the description of the dynamics of the water column that is the immediate source for downstream releases. Quarterly reservoir-wide sampling describes seasonal conditions at 20–25 stations throughout the reservoir during the maximum extent of winter convective mixing, spring runoff, post runoff/late summer stratification, and early winter conditions during the early phases of convective mixing (fig. 2, table 1).

At each station, data on basic water-quality parameters—temperature, specific conductance, dissolved oxygen, pH, oxidation-reduction potential, and turbidity—are collected through the water column. At selected depths, chemical (major ions and nutrients) and biological (chlorophyll and plankton) sampling is performed to characterize the major strata in the water column. Major ions are the common negative (e.g., chloride) and positive (e.g., calcium) ions that constitute the majority of minerals dissolved in water. Nutrients represent the total and dissolved fractions of compounds of phosphorus and nitrogen, which are essential for the production of plant life (algae or phytoplankton).

Glen Canyon Dam Tailwater

Water-quality monitoring activities in the dam's tailwater assess the initial quality of water leaving the reservoir and entering Grand Canyon. These baseline measurements are important for detecting changes occurring in Grand Canyon and for understanding the relationship between the quality of water leaving the reservoir and its relationship to the downstream aquatic ecosystem (fig. 3).

The USGS recorded daily instantaneous water temperatures at Lees Ferry from 1949 to 1977 (U.S. Geological Survey, 2004). Since then, temperatures recorded at Lees Ferry reflect mean daily values of multiple observations (U.S. Geological Survey, 1985–2004). Glen Canyon Environmental Studies began monitoring the temperature and conductivity of dam releases in 1988 by using remotely deployed, continuously logging monitors. In 1991, this program was expanded to include continuous monitoring at Lees Ferry. Dissolved oxygen and pH measurements were added to the monitoring protocol shortly afterwards.

Tailwater monitoring activities currently include the continuous measurement of temperature, salinity, dissolved oxygen, and pH and monthly sampling for phosphorus, nitrogen, major-ion chemistry composition, and biological indicators such as chlorophyll and plankton.

Table 1. Lake Powell and tailwater sampling sites.

Site name	Distance in miles (kilometers) from Glen Canyon Dam	Chemical and biological sampling
Tailwater		
Colorado River below Glen Canyon Dam	0	X
Colorado River at Lees Ferry	-15.5 (-24.9)	X
Colorado River main channel		
Wahweap	1.5 (2.4)	X
Crossing of the Fathers	28.1 (45.2)	X
Oak Canyon	56.2 (90.5)	X
San Juan River confluence	62.2 (100.1)	
Escalante	72.6 (116.9)	X
Iceberg	86.7 (139.5)	
Lake Canyon	98.6 (158.7)	
Bullfrog Bay	104.3 (167.9)	X
Moki Canyon	111.8 (179.9)	
Knowles Canyon	120.1 (193.3)	
Lower Good Hope Bay	129.6 (208.5)	X
Scorup Canyon	140.1 (225.5)	
Hite Basin	148.3 (238.7)	X
Colorado River inflow	149.1–185.8 (240.0–299.0)	X
San Juan River arm		
Cha Canyon	12.0 (19.3)	X
Lower Piute Bay	20.4 (32.9)	
Upper Piute Bay	26.8 (43.1)	X
Lower Zahn Bay	38.8 (62.5)	
Mid Zahn Bay	42.6 (68.6)	
San Juan inflow	32.3–54.1 (52.0–87.0)	X
Escalante River arm		
Escalante at Clear Creek	4.5 (7.2)	
Escalante at Davis Gulch	7.4 (11.9)	X
Escalante at Willow Creek	12.4 (20.0)	
Escalante inflow	13.7–24.8 (22.0–40.0)	X

Downstream Thermal Monitoring in Grand Canyon

Downstream thermal monitoring provides an indication of status and trends in water temperature and how warming is affected by river reach, seasonality, and dam operations. Concerns about the effects of the thermal regime on both native and nonnative fish resulted in the development of a continuous thermal monitoring program in Grand Canyon beginning in 1990. Thermal monitoring was conducted at 10 mainstem stations at intervals of roughly 30 mi (48 km) and at 8 additional sites on major tributaries. Tributary sites have been monitored since 1994, providing thermal baseline data for streams that may act as warmwater refugia for many aquatic species, particularly native fish. In 2005, thermal monitoring in tributaries was reduced to four sites, the Paria River, the Little Colorado River, Kanab Creek, and Havasu Creek.

In 2002, the thermal monitoring program in the mainstem Colorado River was expanded to include multiparameter monitoring stations throughout Grand Canyon to collect time-series measurements of water temperature, specific conductance, dissolved oxygen, and pH at five sites where suspended-sediment transport is also monitored. In 2005, mainstem monitoring was reduced to temperature and specific conductance measurements (fig. 3).

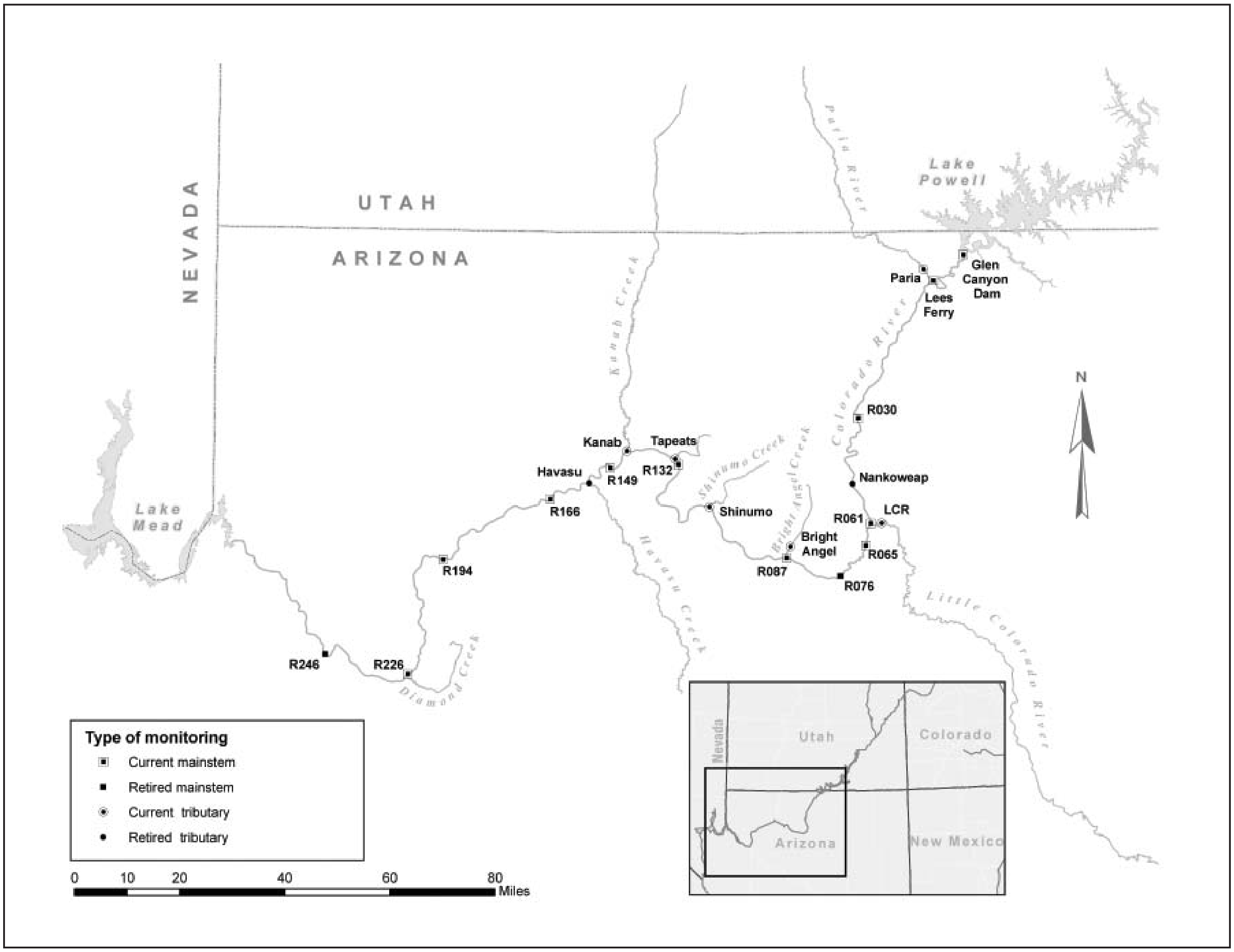


Figure 3. Grand Canyon water-quality sampling sites.

Trends and Current Conditions

Hydrology

Because of a prolonged drought between 2000 and 2005, Lake Powell water storage was reduced by approximately 60%. Water year (WY) 2004, which ended on September 30, 2004, was the fifth consecutive year of below-normal inflows to Lake Powell; inflows were at 51% of average in WY 2004 (table 2). Inflow in WY 2002 was the lowest observed since the completion of Glen Canyon Dam in 1963. This drought period resulted in a 130 ft (40 m) drop in reservoir elevation and a 13 maf (16,029 million m^3) decline in storage in Lake Powell by the end of WY 2004 (fig. 4). While precipitation in the upper Colorado River Basin increased substantially during the first part of WY 2005, storage in Lake Powell continued to decline until the reservoir reached an elevation of 3,555 ft (1,084 m) on April 8, 2005, after which snowmelt runoff and reduced dam releases increased the reservoir elevation. Average unregulated inflow to Lake Powell is 12.056 maf (14,865 million m^3), as determined from the 30-yr record that spans WY 1971 through WY 2000 (Tom Ryan, Bureau of Reclamation, oral commun., 2005); however, the average inflow for the water years from 2000 to 2004 was 5.962 maf (7,351 million m^3) (table 2).

Table 2. Recent inflows and releases at Glen Canyon Dam (maf = million acre-feet).

Water year (WY)	April–July unregulated inflow (maf)	Percent of average	WY unregulated inflow (maf)	Percent of average	Glen Canyon Dam release (maf)	End of year storage (maf)	End of year elevation (ft)
1998	8.625	112	13.661	116	13.511	22.403	3687.7
1999	7.621	99	12.71	108	11.202	22.997	3691.6
2000	4.352	56	7.310	62	9.380	20.939	3677.8
2001	4.301	56	6.955	59	8.238	19.135	3664.8
2002	1.115	14	3.058	25	8.230	14.468	3626.5
2003	3.918	51	6.358	53	8.228	12.110	3603.8
2004	3.640	46	6.128	51	8.231	9.169	3570.8

Salinity

Salinity levels are of concern throughout the entire Colorado River Basin because high salinity can be damaging to soils and crops. Furthermore, treaty obligations with Mexico limit the salinity of water that can be delivered to that country. As the Colorado River flows to the Gulf of California, it leaches salts from soils and other geologic substrates through and over which it flows. Salinity levels are also increased by irrigation returns, by evaporation in storage facilities, and by rate of flow (slow-flowing water picks up higher levels of dissolved solids than do high flows during runoff).

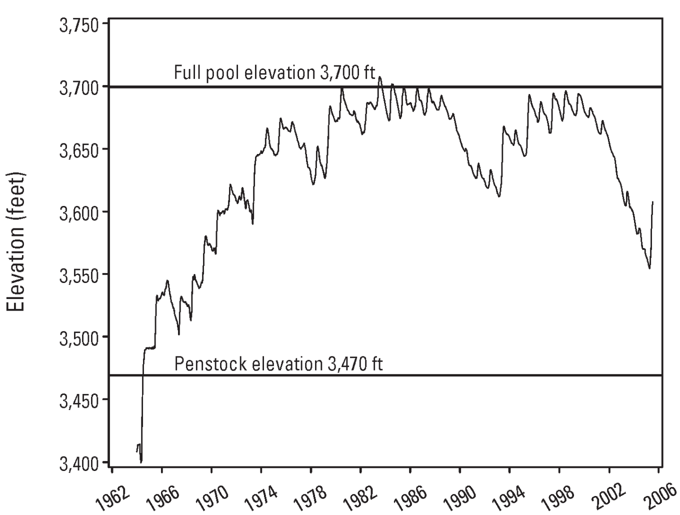


Figure 4. Lake Powell surface elevation, 1963–2005.

Periodically the salinity of water released from the dam increases as a result of drought. This increase is due to a combination of factors, including increases in the salinity of base flows into the reservoir, lack of large volumes of dilute snowmelt runoff, and reduced reservoir volume to dilute the effects of reservoir inflows. At the end of WY 2004, releases from Glen Canyon Dam had a specific conductance of approximately 850 microsiemens per centimeter (µS/cm) at 25°C, corresponding to a total dissolved solids concentration of 575 mg/L (fig. 5).

Water Temperature

Impounding water in Lake Powell significantly affected the water temperature of dam releases to the Colorado River ecosystem because of reservoir stratification and the location of the penstock release structures (fig. 1). During the summer months, the epilimnion of Lake Powell warms considerably from inflows, ambient air temperature, and solar radiation, reaching temperatures as high as 86°F (30°C); however, the hypolimnion is isolated from these processes, maintaining temperatures between 43°F and 48°F (6°C and 9°C).

Before closure of the dam, mean water temperature for what is now the tailwater was approximately 57°F (14°C), ranging from 32°F to 80°F (0°C to 27°C) over the course of a year (U.S. Geological Survey, 2004). Before 1973, during the reservoir's initial filling stage, release temperatures were affected by surface or epilimnetic withdrawals because of the proximity of the reservoir's surface to the penstock withdrawal zone. Max-

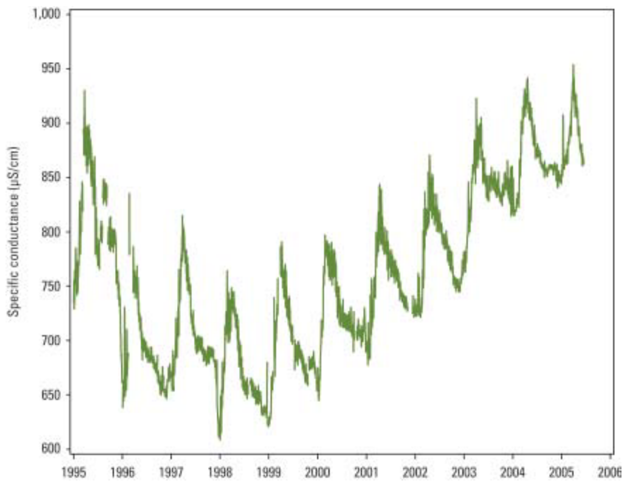


Figure 5. Mean daily specific conductance (in microsiemens per centimeter (µS/cm) at 25°C), an indicator of salinity, below Glen Canyon Dam, 1995–2005.

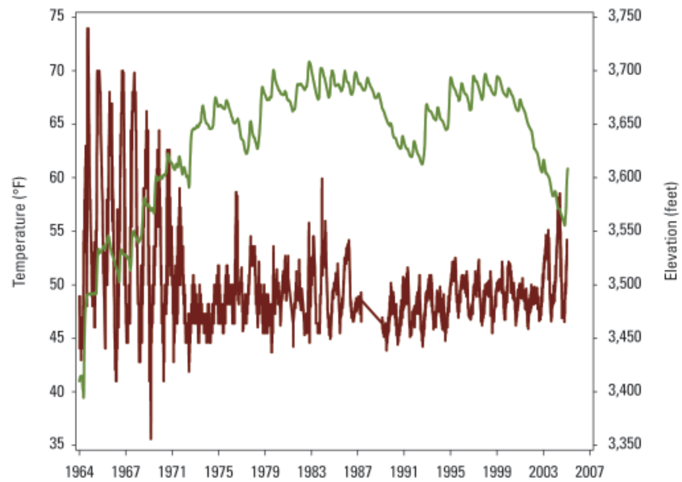


Figure 6. Daily water temperature (red line) at Lees Ferry as affected by changes in Lake Powell's elevation (green line).

imum release temperature during that period occurred during the months of August and September, reflecting the surface warming of the reservoir.

Trends in water temperature of the tailwater stabilized from 1973 to 2003, when the reservoir surface elevations were above 3,600 ft (1,097 m) and the epilimnion was situated above the penstock withdrawal zone. During this period, release temperatures as measured at Lees Ferry averaged 48.7°F (9.3°C). Temperatures fluctuated between 44°F and 54°F (7°C and 12°C), with minor excursions beyond this range during periods of spillway releases (fig. 6). Under these conditions, there was some seasonality to Glen Canyon Dam release temperatures, with slight warming beginning in May and June and increasing through the year. The highest temperatures occurred at the end of December as a result of the influence of the relatively warm, convectively mixed epilimnion on penstock releases. Peak temperatures under these conditions appeared to be affected by the volume of the previous year's snowmelt runoff, which affects the thickness of the warm epilimnion near the dam during the latter months of the year. Although seasonality in temperature patterns exists in the postdam era, the annual variation has been reduced to approximately 9°F (5°C) from approximately 48°F (27°C) in the predam era. Also, the highest river temperatures immediately below the dam now occur in late fall or winter instead of in summer, which is when they occurred in the predam, unregulated river.

The water level of the reservoir dropped more than 140 ft (42 m) between 1999 and 2005 as a result of a basinwide drought that began in 2000 (fig. 4). This drop placed the warmer epilimnetic water much closer to the penstock withdrawal zone and resulted in reservoir releases being drawn from this epilimnetic layer. Substantially warmer release temperatures have occurred in the fall and early winter months since 2003. An annual maximum mean daily release temperature of 55°F (12.9°C) was observed on November 14, 2003; on November 6, 2004, the annual maximum mean daily temperature reached 59°F (15°C) (fig. 6). These values represent the highest release temperatures from Glen Canyon Dam since August 1971, when the reservoir was filling. As of July 11, 2005, the mean daily release temperatures had reached 56.4°F (13.6°C), showing earlier warming and higher temperatures than had occurred in the past 2 yr.

Seasonal and longitudinal water temperature patterns in Grand Canyon have been measured from 1994 to 2005 from Glen Canyon Dam to Diamond Creek, 241 mi (388 km) below Glen Canyon Dam (fig. 7). During summer months, gradual downstream warming occurs because of the transfer of heat from the warmer surrounding air mass, heat stored in the canyon walls adjacent to the river, and solar radiation.

A comparison of weekly average increase in water temperature between Glen Canyon Dam and Diamond Creek to average weekly discharge during mid-June from 1994 to 2004 demonstrates the effect of Glen Canyon Dam releases on warming patterns in the Colorado River in Grand Canyon (fig. 8). High steady flows of approximately 26,000 cfs in 1997 resulted in 9°F (5°C) warming at Diamond Creek, while low steady flows of

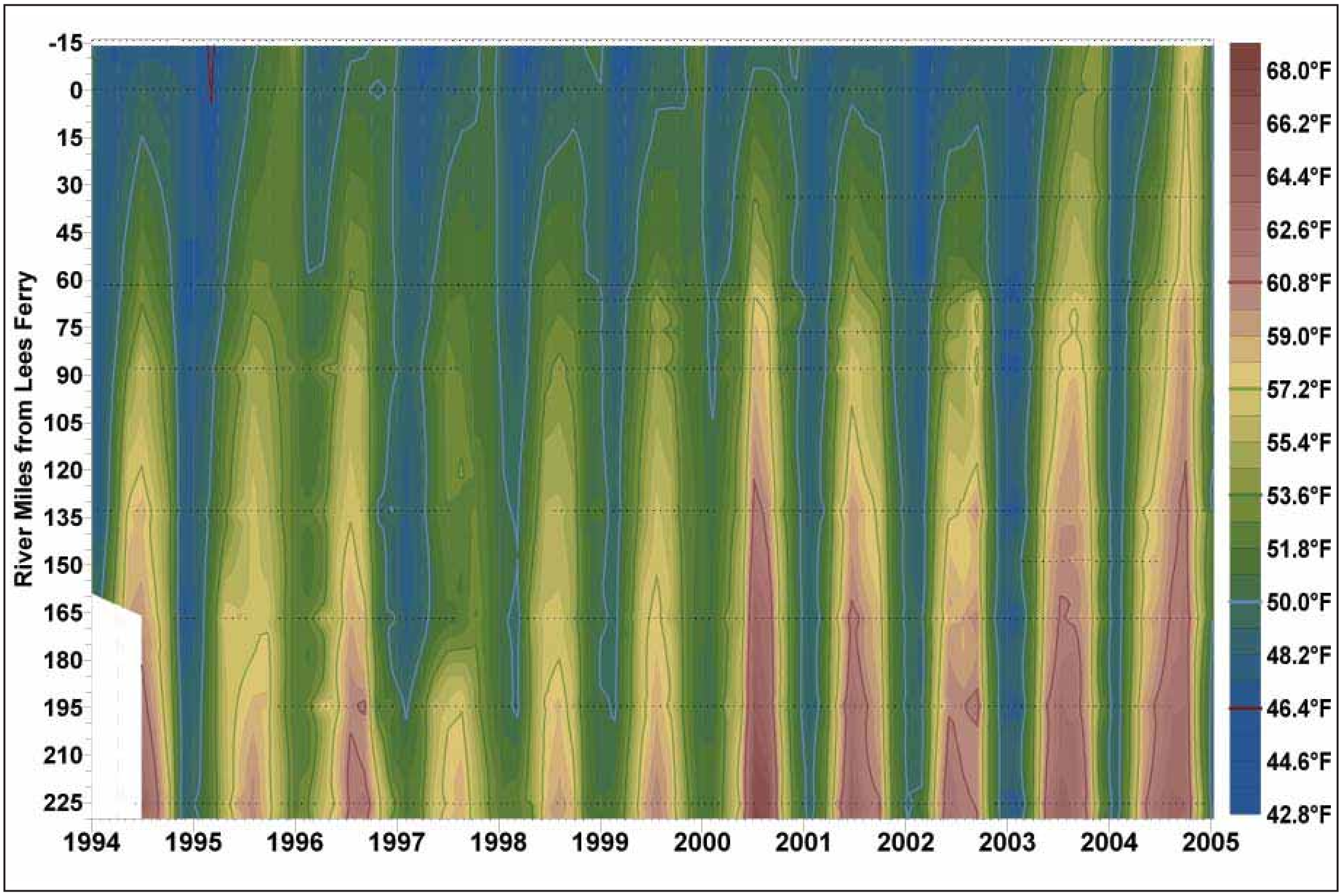


Figure 7. Water temperatures along the Colorado River from Glen Canyon Dam to Diamond Creek, 1994–2005. Black dots represent monitoring locations.

8,000 cfs in 2000 exhibited 18°F (10°C) warming. This difference is because large volumes of water have greater mass and a lower surface area to volume ratio as well as less exposure time for atmospheric heat exchange that is due to higher velocity, reducing the amount of warming from ambient temperatures and solar radiation. The warming occurring at low discharges affects water temperatures in lower Grand Canyon to a greater degree than the elevated release temperatures observed in the past 2 yr.

Lateral variation in river temperature also occurs throughout Grand Canyon. Substantial warming occurs in various nearshore environments, ranging from shallow, open-water areas to enclosed backwaters. Water in certain nearshore environments becomes isolated from mixing with the main channel current and warms with solar radiation and equilibration with ambient temperatures. These environments may be important to the survival, growth, and eventual recruitment of the larval life stages of native fish (see chapter 2, this report).

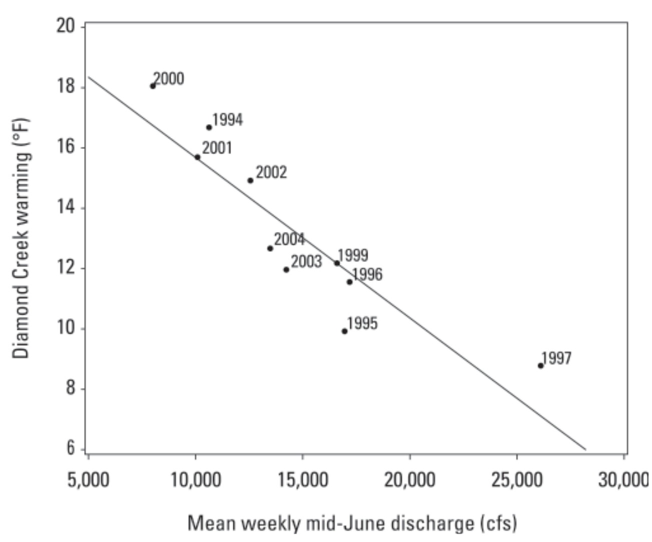


Figure 8. Mid-June warming above release temperatures at Diamond Creek, 1994–2004, as a function of mean weekly discharge (in cubic feet per second). Warming at Diamond Creek = 0.000532 * Q + 21.01.

Turbidity and Suspended Sediment

Construction of Glen Canyon Dam dramatically altered the sediment-transport processes of the Colorado River. Before the completion of Glen Canyon Dam, the total sand supply to Grand Canyon, from the Colorado River upstream from Lees Ferry, with the Paria and Little Colorado Rivers combined, was approximately 29 million tons (26 million Mg). Today, because Lake Powell traps all of the sediment upstream from Glen Canyon Dam, the Paria River is the primary source of sand to Marble Canyon, supplying approximately 6% of predam sand levels (see chapter 1, this report). Only a small portion of the suspended sediment entering Lake Powell is transported for any distance because most of it is deposited near the inflows of major tributaries.

Turbidity and suspended-sediment concentrations are of interest in the downstream environment because water clarity affects the amount of light available for photosynthesis for downstream algal communities, which are an important part of the overall food base for native and nonnative fishes. Turbidity also affects the behavior and distribution of various native and nonnative fishes in providing cover from various predators or by affecting sight-feeding abilities. Turbidity is measured in both Lake Powell and downstream. Turbidity measurements in Lake Powell indicate the location of advective tributary inflows and also can be used as an indicator of primary productivity in the reservoir because increased turbidity indicates the presence of phytoplankton. The rather abrupt decrease in filamentous green alga below Lees Ferry most probably results from inputs of sediment from major tributaries, including the Paria and Little Colorado Rivers, which reduce light penetration (Cole and Kubly, 1976; Stevens and others, 1997).

Nutrients

Nutrients such as phosphorus, nitrogen, and silica are essential for microbial production and algal growth. Most phosphorus entering Lake Powell is associated with suspended clays in the inflows of river water. The reservoir acts as a nutrient sink, especially for phosphorus. More than 95% of phosphorus reaching Lake Powell is in particulate form or is associated with suspended sediment particles. A large fraction of this phosphorus load is deposited within the reservoir by sedimentation (Gloss, 1977). Most of the remaining dissolved phosphorus is removed from the water by uptake from biological activity.

Bioproduction in Lake Powell apparently is directly related to the intensity and duration of enriched spring inflow events that are responsible for delivering the bulk of nutrient capital to the reservoir (Gloss and others, 1980). Surface concentrations of dissolved phosphorus generally decline from the upper end of the reservoir to the dam because of the uptake from primary production, to the point that dissolved phosphorus is usually below detection limits within 30–60 mi (48–97 km) upstream from the dam in the upper water column. Phosphorus is the limiting factor for primary production near the dam, while low light availability is the limiting factor to productivity in the upper portion of Lake Powell because of turbidity from inflow currents, especially during early summer months (Gloss and others, 1980) (fig. 9a).

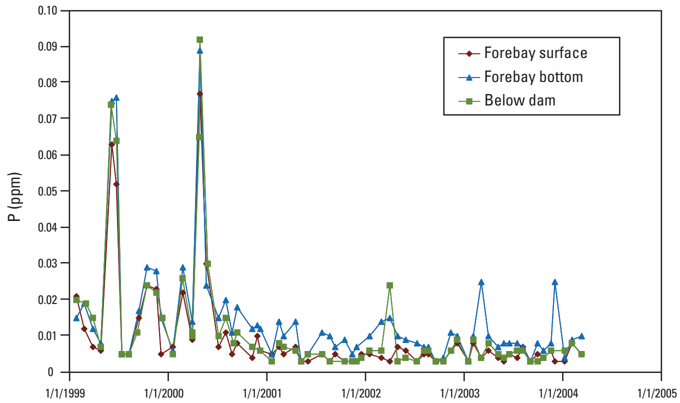
Nitrate-nitrogen concentrations from the surface of the reservoir forebay fluctuate in a manner that reflects the utilization of the nitrogen by algae and begin to increase in fall as primary production slows. Nitrate-nitrogen concentrations show a peak in winter when temperatures are coolest and productivity is relatively low. During the summer months, when primary productivity is at a maximum, nitrate-nitrogen concentrations reach a minimum because of uptake by primary producers. From 1999 to 2004, surface nitrate-nitrogen concentrations in the forebay above Glen Canyon Dam averaged 0.09 parts per million (ppm). Nitrate-nitrogen concentrations in the deepest part of the hypolimnion averaged 0.39 ppm, about four times higher than surface concentrations. For the same period, nitrate-nitrogen concentrations in Glen Canyon Dam releases averaged 0.29 ppm (fig. 9b).

The highest productivity in Lake Powell is seen in surface waters of the reservoir and results from a combination of temperature, light availability, and nutrient concentrations. Because primary productivity processes consume nutrients, nutrient concentrations are eventually depleted in the surface waters of Lake Powell and remain at elevated concentrations in the hypolimnion, where there is little primary production taking place. Consequently, hypolimnetic releases from Glen Canyon Dam are relatively nutrient rich. Periods of epilimnetic releases from Glen Canyon Dam may cause a reduction in the amount of nutrients available to the downstream ecosystem.

Dissolved Oxygen

Dissolved oxygen concentrations in Lake Powell are affected by inflow, seasonal water-circulation patterns, and biological processes (Johnson and Merritt, 1979).

A.



B.

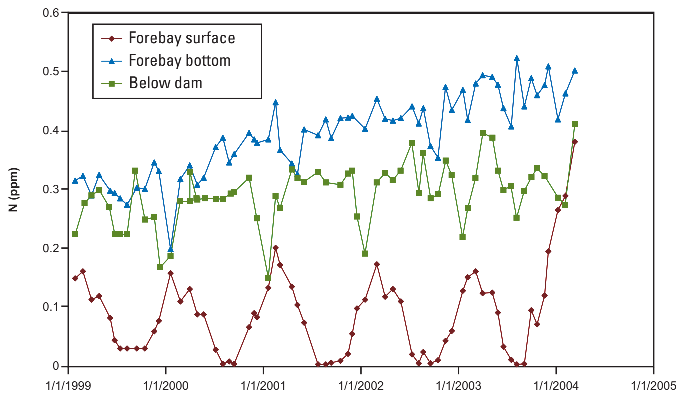


Figure 9. A. Total phosphorus concentrations measured (in parts per million) in the forebay of Lake Powell and Glen Canyon Dam releases, 1999–2004. B. Dissolved nitrate-nitrogen concentrations measured (in parts per million) in the forebay of Lake Powell and Glen Canyon Dam releases, 1999–2004.

The spring snowmelt runoff enters Lake Powell as an overflow density current, representing the lowest density water entering the reservoir during the year. This inflow current then travels through the reservoir slightly below the surface, eventually reaching Glen Canyon Dam by late summer or early fall. A large amount of suspended sediment, nutrients, and organic material may be associated with this inflow current. As the inflow current travels through the reservoir, the organic material undergoes bacterial decomposition, removing large amounts of oxygen from this water. This situation, combined with decomposition of plankton from the epilimnion, results in a marked reduction of dissolved oxygen in the metalimnion of the reservoir by late summer.

During periods of reservoir drawdown, as in the past several years, tributary inflows cause the resuspension of exposed deltaic sediments in the upstream portions of the reservoir. This resuspension entrains large amounts of suspended sediment and decomposing organic material in the advective inflow currents that move through the reservoir. In September 2003, the inflow plume extended downstream to Padre Bay, about 28 mi (45 km) above Glen Canyon Dam, at depths of 50–80 ft (15–25 m) (fig. 10). Dissolved oxygen concentrations at or near zero were observed throughout its extent. This plume reached Glen Canyon Dam by October and was eventually dissipated by convective mixing in the following months. The pattern was observed to a lesser extent in 2004 because runoff volumes were smaller.

The hypolimnion of Lake Powell is isolated from photosynthetic oxygenation and reaeration caused by surface mixing and acts as a sink for organic matter falling through the water column. As a result, the water at the bottom of Lake Powell is often oxygen poor throughout the year. Depending on the density of cold winter inflows relative to that of the receiving reservoir, winter inflows will either form an interflow between layers of higher and lower density or may underflow the entire reservoir, displacing hypolimnetic water upwards for withdrawal by dam releases. In the former case, the density of the hypolimnetic water is too great to allow an underflow current, and as a result, the hypolimnion remains stagnant and oxygen concentrations continue to decline. In the latter case, the hypolimnion is refreshed with oxygenated water.

There have been three distinct periods of hypolimnetic stagnation during Lake Powell's history, usually lasting several years and characterized by a buildup of relatively saline water, followed by decreasing dissolved oxygen concentrations. These periods of hypolimnetic stagnation appear to have been dissipated by a series of above-average inflows that flushed the reservoir. Above-normal inflows to Lake Powell during the mid-1990s left the reservoir fairly dilute, and distinct winter underflows have occurred since 1999 (fig. 11).

Dissolved oxygen concentrations in the tailwater are usually slightly below saturation but have not dropped to concentrations low enough to affect the aquatic ecosystem in Grand Canyon. As the reservoir ages or there are periods of extended drought, however, it is likely that the chances of water low in dissolved oxygen being released from Glen Canyon Dam will increase.

Plankton

The epilimnion of Lake Powell is fairly warm and receives abundant sunlight for photosynthesis through much of the year. As a result, the majority of phyto-

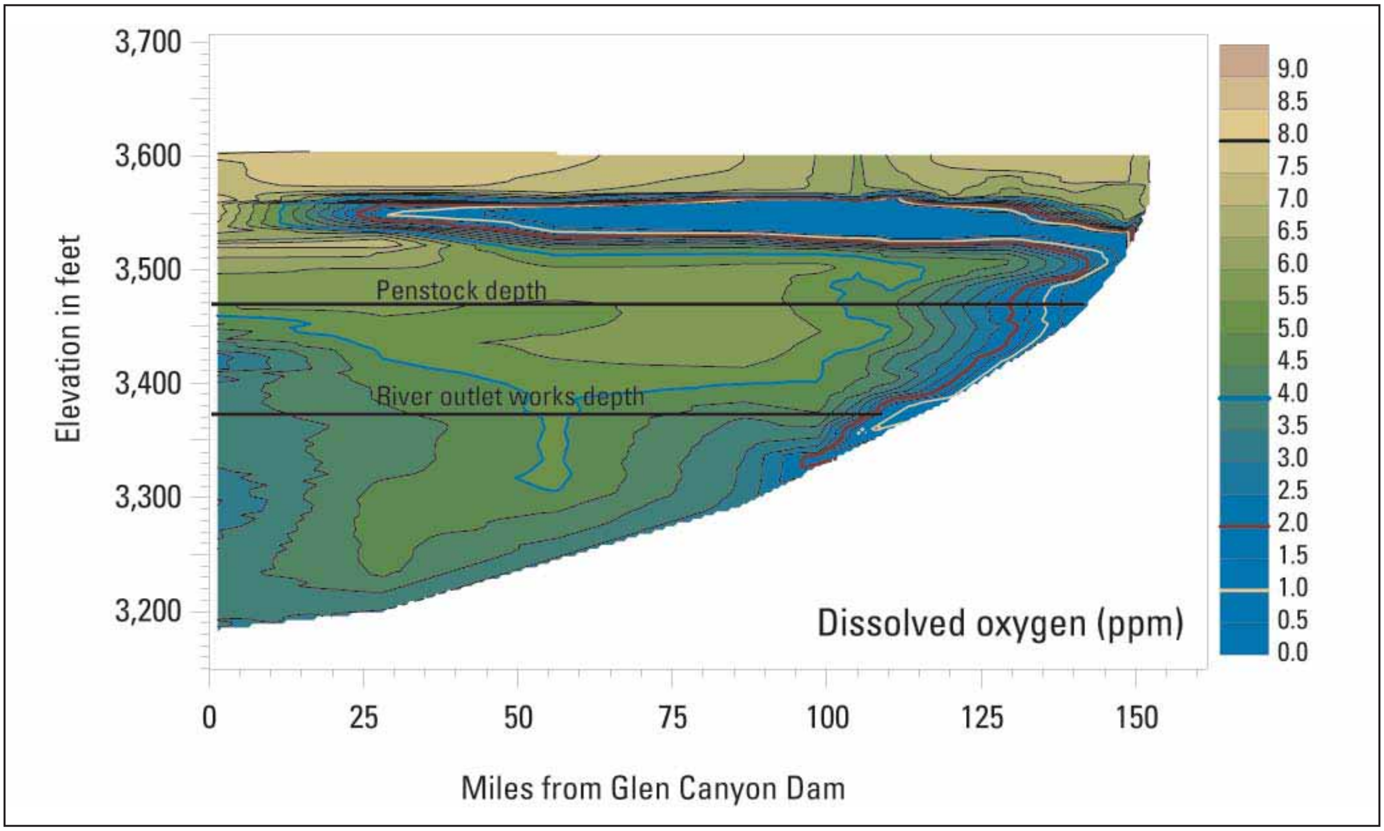


Figure 10. Dissolved oxygen concentrations (in parts per million) in the main channel of Lake Powell, from Glen Canyon Dam to the Colorado River inflow, September 2003.

plankton and zooplankton reside in this layer, supporting a recreational fishery in Lake Powell. Under periods of epilimnetic withdrawals—for example during winter mixing or during the recent late-summer events of 2003, 2004, and 2005, when warmer epilimnetic waters are released—plankton from the epilimnion can be released downstream, potentially providing an alternate food source for the downstream ecosystem (fig. 12). Little is known about the downstream importance of plankton and other organic matter released from Glen Canyon Dam.

Effects of Dam Operations

Operation of Glen Canyon Dam affects the water quality of Lake Powell and downstream releases. High sustained penstock releases during 1973, through the mid-1980s, and under modified low fluctuating flow (MLFF) operations in 1997 acted to route increased volumes of water through the reservoir. The operation of different release structures can affect the downstream environment by withdrawing water of different quality than that at the penstock elevation. Since the implementation of the 1996 Record of Decision and the MLFF alternative, the river outlet works have been used during the 1996 beach/habitat-building flow (Hueftle and Stevens, 2001) and the 2004 experimental high flow. During these events, water of cooler temperature and higher salinity and nutrient content was released, and the turbulence created downstream of the dam increased oxygen concentrations.

During periods of normal operations under the MLFF, daily fluctuations in temperature, specific conductance, and dissolved oxygen can be observed in Glen Canyon Dam releases because of the effects of various discharge volumes and fluctuation patterns on the dimension of the withdrawal zone in the reservoir. Large or fluctuating releases draw water from a thicker withdrawal zone than do small or steady releases (Monismith and others, 1988; Ford, 1990; Casamitjana and others, 2003).

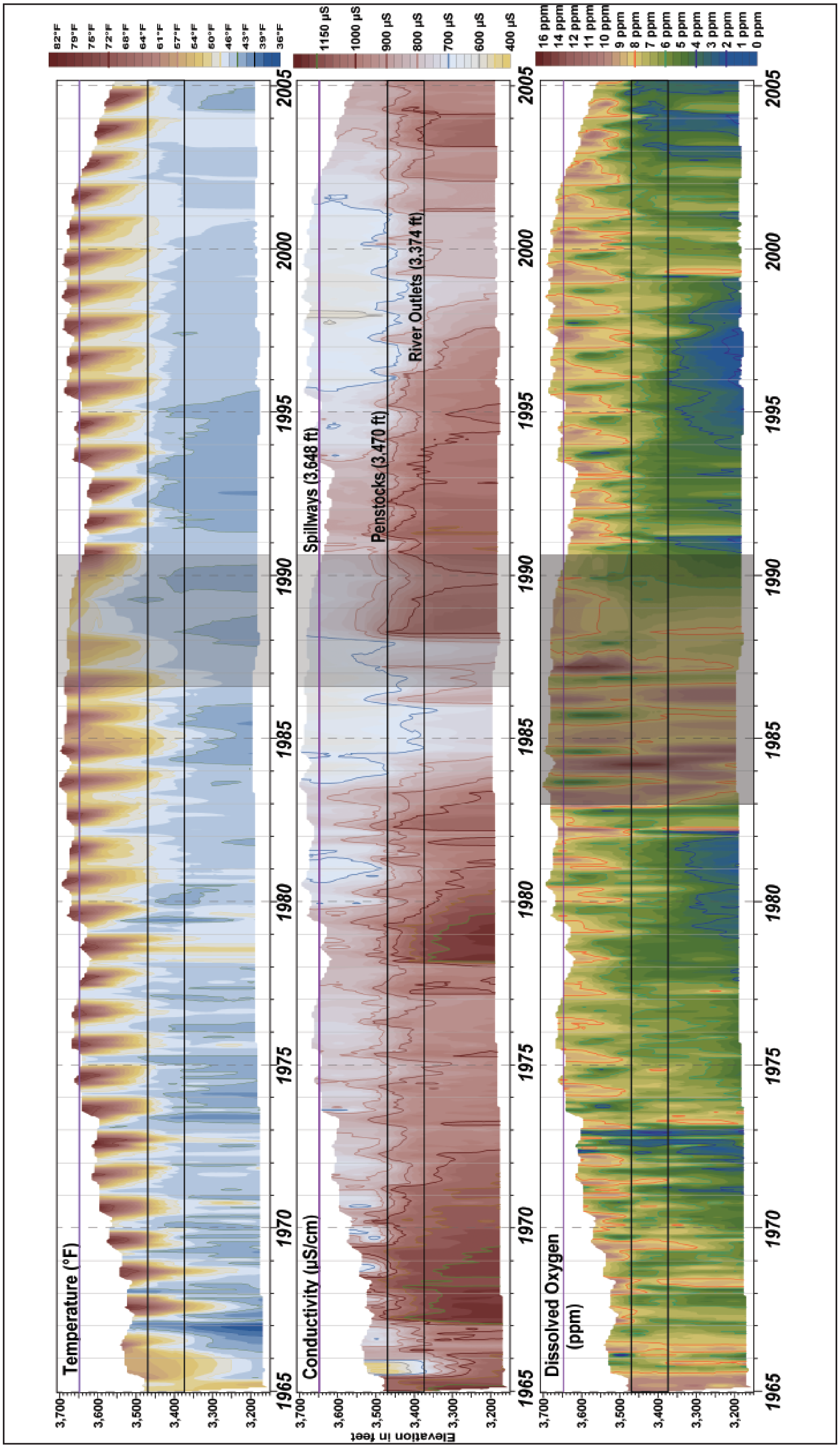


Figure 11. Forty-year temperature (degrees Fahrenheit), specific conductance (microsiemens per centimeter (µS/cm) at 25°C), and dissolved oxygen (parts per million) patterns in the forebay of Lake Powell, December 1964 to March 2005. Elevations of spillways, penstocks, and river outlet works are indicated by horizontal lines in each plot. Warmer colors represent higher values for each parameter. Shaded areas represent areas of low temporal resolution or poor data quality. Note three periods of hypolimnetic stagnation (red areas in conductance section), followed by periods of hypolimnetic hypoxia (blue areas in dissolved oxygen section). Dissolved oxygen section shows recent pattern of winter underflows since 1999.

In terms of downstream water quality, the magnitude of discharge and the volume of water in the river determine how much water is exposed to ambient air temperatures and solar radiation, which, in turn, determines the amount of in-stream warming in Grand Canyon. The magnitude of dam discharges also influences the amount of sediment in suspension, which can limit light availability to the downstream aquatic environment.

There are many interactions at work, and the use of a hydrodynamic water-quality model will help understand the changes in Lake Powell and their effects on downstream water quality.

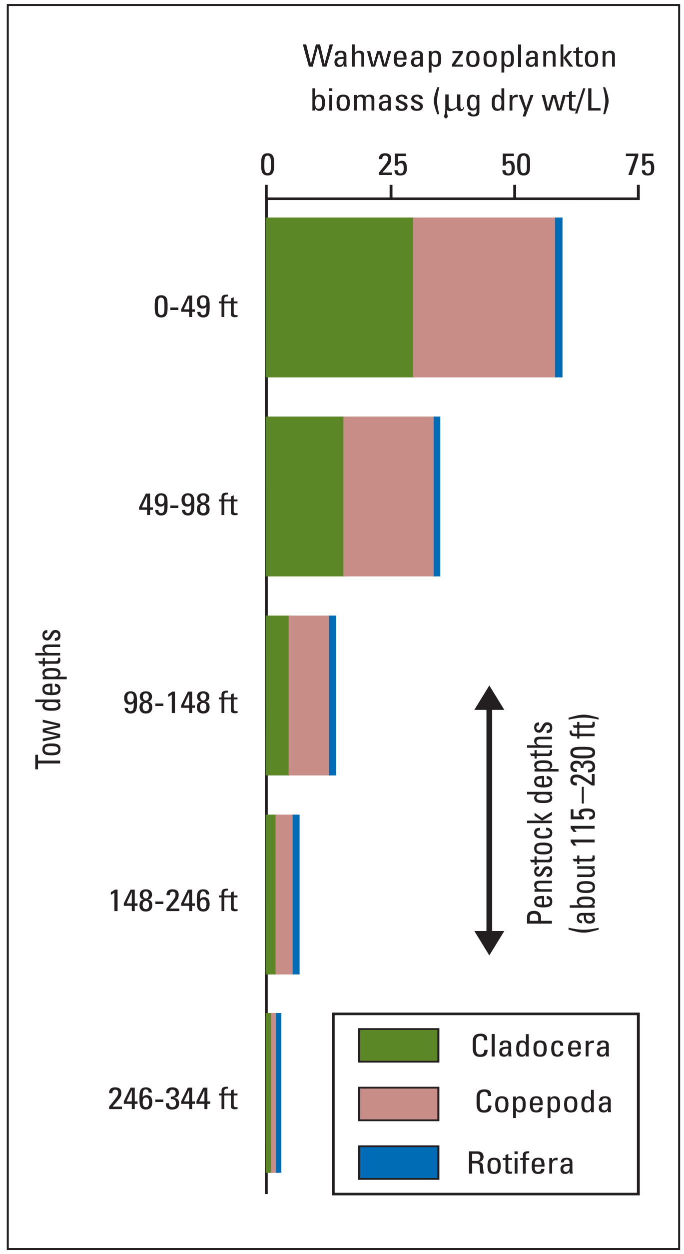


Figure 12. Plankton concentrations and biomass in Lake Powell forebay.

Conclusion and Recommendations

The current drought demonstrates how long-term climatic trends influence inflows to Lake Powell and affect the quality of dam releases. As the elevation of Lake Powell drops, the warmer surface water is drawn downstream through the penstocks, seasonally increasing downstream temperatures. Furthermore, salinity concentrations increase, more epilimnetic biota are exported downstream, and dissolved oxygen levels may decrease seasonally. Current dissolved-oxygen minimums are within the tolerance limits of tailwater organisms, including rainbow trout (*Oncorhynchus mykiss*). Entrainment of an oxygen-depleted inflow plume or hypolimnion, along with the aging of the reservoir, however, could affect the downstream ecosystem.

If the drought continues, these trends will be exacerbated as summer and fall releases draw increasingly from the warmer surface waters of the reservoir. Release patterns during an extended drought may replicate those of the 1960s when the reservoir began filling, including wider fluctuations in water quality that may begin to mimic predam conditions. These conditions create an opportunity to observe some of the possible effects in the Colorado River ecosystem of a temperature control device, which would route warmer surface waters through the Glen Canyon Dam powerplant.

Future Monitoring and Modeling

Current understanding of water quality downstream of Glen Canyon Dam in Grand Canyon is limited because more extensive sampling has only recently been initiated and because there has been a lack of modeling for river-water quality. Exceptions are water temperature and sediment concentrations (see chapter 1, this report), which have been more extensively monitored and analyzed. Future water-quality programs should emphasize a model-based approach and close linkages with other sampling programs like aquatic ecology and fine-sediment monitoring.

The extensive 40-yr database available for Lake Powell presents a very clear opportunity to model the hydrodynamic properties of the reservoir under a variety of inflow and operational conditions. Such modeling not only would increase the understanding and characterization of reservoir limnology but also would serve as an important predictive tool to anticipate what the quality of water released to the Colorado River ecosystem in Grand Canyon will be. A number of river-flow and water-quality models are available and could be used or modified to better understand and predict downstream changes in water quality and their effects on various components of the ecosystem.

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