# Downstream Effects of Glen Canyon Dam on the Colorado River in Grand Canyon: A Review

R.H. Webb[1], D.L. Wegner[2], E.D. Andrews[3], R.A. Valdez[4], and D.T. Patten[5]

Glen Canyon Dam, completed in 1963, has altered geomorphic and ecological processes and resources of the Colorado River in Grand Canyon. Before the dam was completed, the river transported large quantities of sediment during spring floods as large as 8500 $m^3/s$. After 1963, dam releases typically were less than 900 $m^3/s$ with large diurnal fluctuations and little sediment. The 2-yr peak discharge decreased by a factor of 2.5, resulting in aggraded rapids and a large increase in riparian vegetation. The clearwater releases from the dam eroded sand deposited on the bed and banks. Although pre-dam water temperatures varied seasonally, dam releases typically are about 8°C year round. Because of the clear, cold water and reduced flooding, post-dam aquatic productivity is considerably higher in the tailwater. Rainbow trout and other non-native fishes are now common, 3 native species have been extirpated, and the remaining species, including the endangered humpback chub, cannot successfully reproduce in the river.

## 1. INTRODUCTION

Construction of Glen Canyon Dam on the Colorado River has affected a number of aquatic and terrestrial resources downstream in lower Glen Canyon and in Grand Canyon (Figure 1). The Bureau of Reclamation manages the dam and its powerplant, which produces 3% of the summer power demand in the region [*Harpman*, this volume]. Flood control and diurnally fluctuating releases of clear, cold water are blamed for narrowing of rapids, widespread beach erosion, invasion of nonnative riparian vegetation, and losses of native fishes. The river passes through Grand Canyon National Park and Glen Canyon National Recreation Area and is on the boundary of the Navajo and Hualapai Reservations in Arizona. These management entities, as well as environmental and recreational groups, have a vested interest in managing the Colorado River to protect its resources.

Responding in part to pressure from conservationists, and to meet legal requirements for rewinding the generators in the dam's powerplant, the Bureau of Reclamation initiated the Glen Canyon Environmental Studies (GCES) Program in 1982 [*Wegner*, 1991; *Schmidt et al.*, this volume]. The studies conducted under the GCES Program are one of the most comprehensive and in-depth investigations of the effects of reservoir operations on the downstream physical and biological environment ever undertaken for a river. The purpose of this chapter is to review the salient results of numerous researchers who had worked in the riverine environment of the Colorado River in Grand Canyon prior to the 1996 controlled flood.

Initially, the GCES program was to be a 3-year effort. The scope and objective of the program quickly expanded to encompass the broad range of resources affected by the

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[1] U.S. Geological Survey, Tucson, Arizona
[2] Ecosystem Management International, Flagstaff, Arizona
[3] U. S. Geological Survey, Boulder, Colorado
[4] SWCA, Inc., Logan, Utah
[5] Department of Plant Biology, Arizona State University, Tempe, Arizona

The Controlled Flood in Grand Canyon
Geophysical Monograph 110

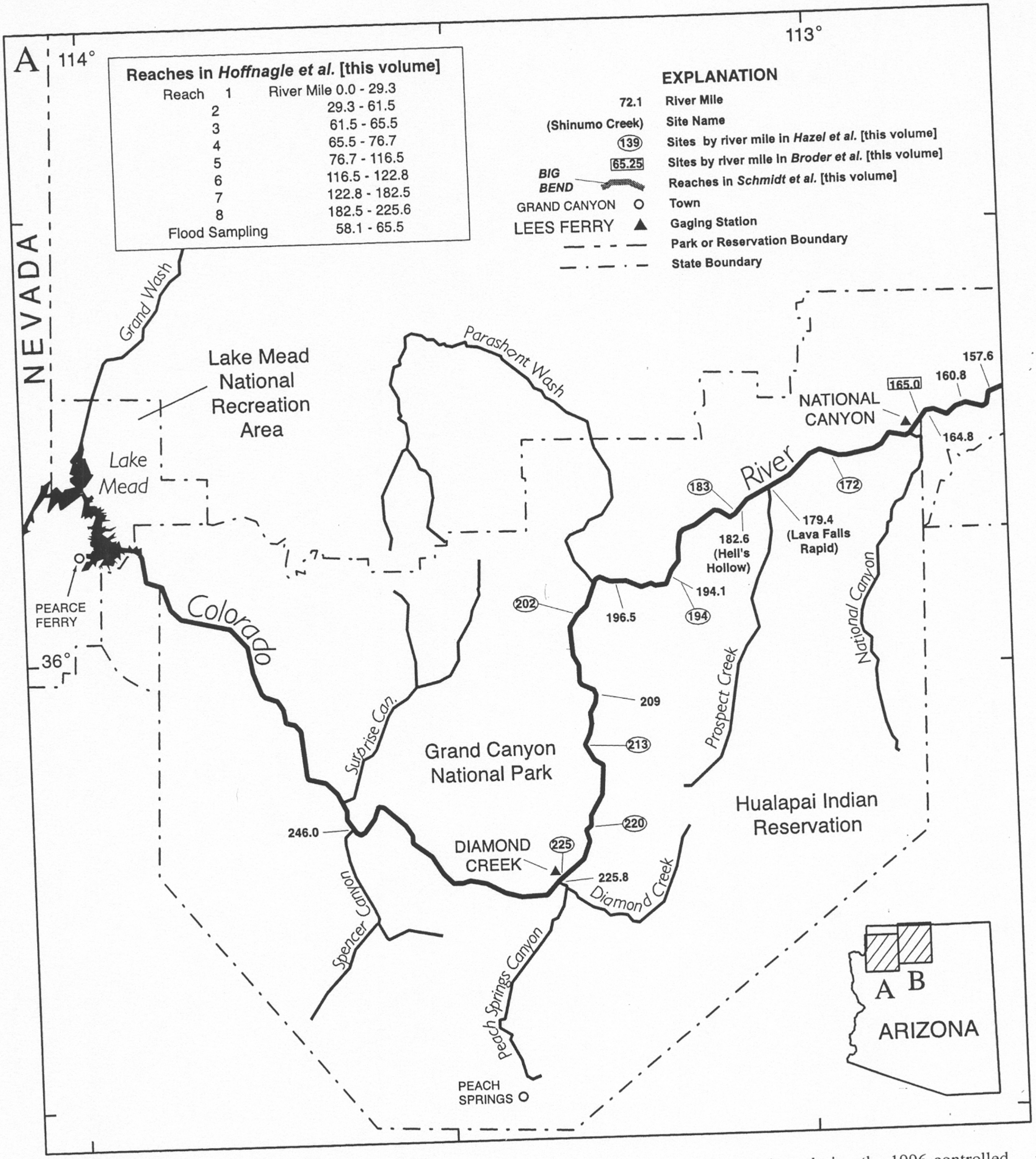

**Figure 1**. Map of the Colorado River in Grand Canyon showing primary study sites of researchers during the 1996 controlled flood on the Colorado River. A. Western Grand Canyon. B. Eastern Grand Canyon.

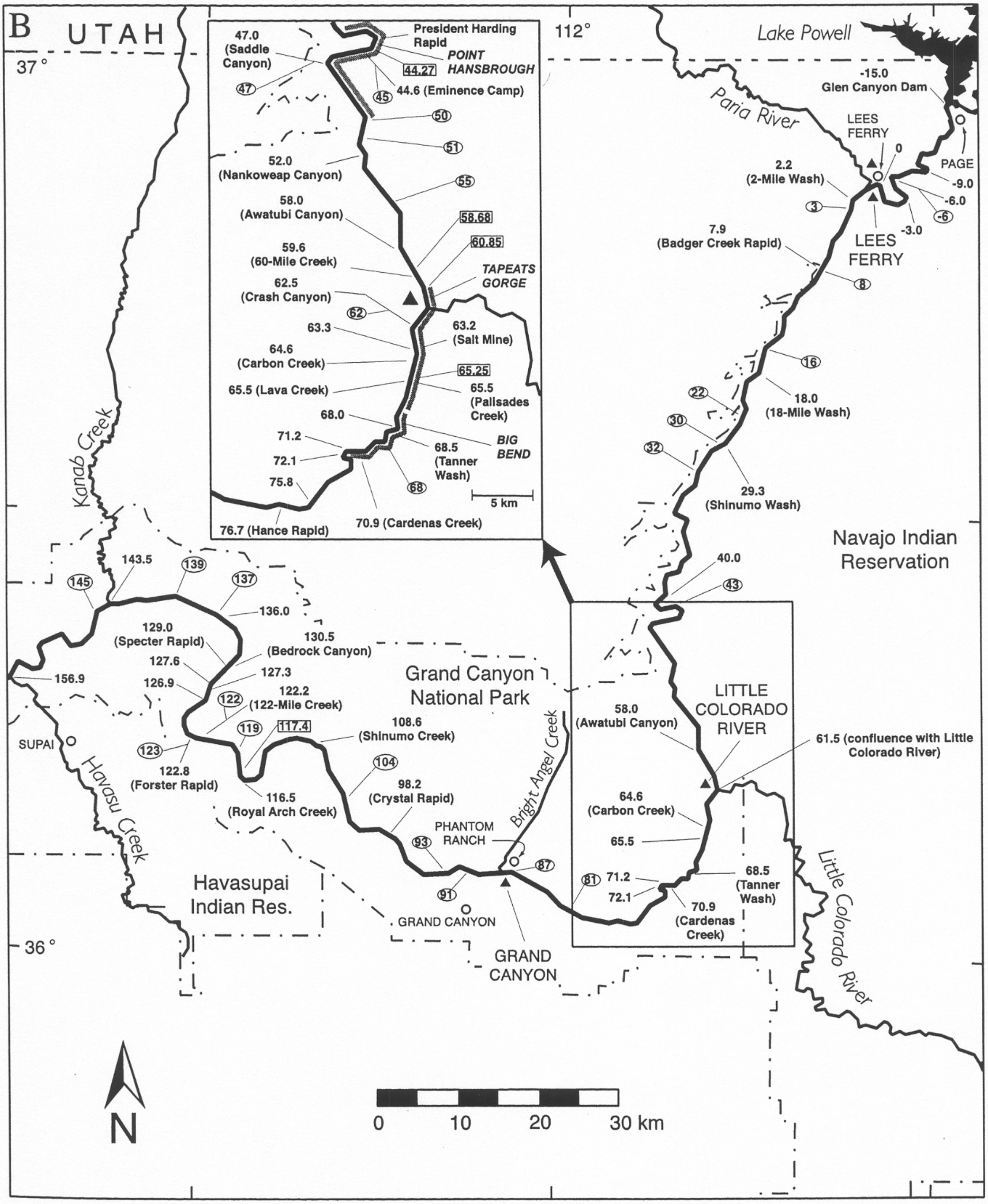

**Figure 1** (continued)

operation of Glen Canyon Dam. GCES Phase I, as it was known, resulted in numerous publications and summary volumes [*Bureau of Reclamation*, 1988a, 1988b] and was completed in 1987 [*Patten*, 1991]. The studies of GCES I were expanded to GCES Phase II in 1989 after the Department of Interior initiated the environmental impact statement process for operation of Glen Canyon Dam. Major features of GCES II were "research flows" (1990-1991) from Glen Canyon Dam to evaluate various alternatives being considered for the EIS [*Patten*, 1991], and in-depth studies to describe cause-effect relations of dam operations. Expansions of the program included studies of recreation and power-production economics, impacts to the power market, and the potential impacts to the Native American cultural resources along the river corridor. In 1992, the advent of restrictions on dam operations, known as the Interim Operating Criteria [*U.S. Department of the Interior*, 1995], changed some of the mission of GCES to monitoring. GCES II concluded with the 1996 controlled flood in Grand Canyon, and was reviewed in *National Research Council* [1996]. The 1996 controlled flood in Grand Canyon resulted from 14 yrs of research under the GCES Program.

## 2. THE RIVERINE RESOURCES OF GRAND CANYON

Many natural features of the river corridor are important because of their value to society in this, one of the most visited national parks in the United States. Riverine resources create public interest and generate public support for environmentally sensitive management of Glen Canyon Dam. The attention that scientific inquiry has focussed on how operations of Glen Canyon Dam affect these resources represents an essential connection between science and natural resource management [*Marzolf et al.*, this volume].

### *2.1. Recreation and Rapids*

When Congress authorized construction of Glen Canyon Dam on April 11, 1956, fewer than 500 people had navigated the Colorado River through Grand Canyon [*Lavender*, 1985]. The popularity of whitewater recreation increased dramatically during the two decades following development of the commercial river-running industry. In 1971, the National Park Service imposed a limit of 22,000 river runners per year through Grand Canyon. These recreationists are attracted by the world-class whitewater in the Colorado River. A plan-and-profile map of the Colorado River, surveyed in 1923 [*Birdseye*, 1924], documents the water-surface fall through major riffles and rapids and continues to be used to describe rapids [*Stevens*, 1990]. *Leopold* [1969] found that rapids account for only 10% of the distance, but most of the drop, through Grand Canyon.

Most rapids in Grand Canyon are created by debris fans, which control the hydraulics of rapids and locations of sand bars [*Dolan et al.*, 1978; *Howard and Dolan*, 1981]. Debris flows from tributary canyons create and maintain these debris fans [*Webb et al.*, 1988, 1989]. Debris fans are central to the fan-eddy complex that creates environments for sand-bar deposition upstream and downstream [*Schmidt and Rubin*, 1995]. Pre-dam floods reworked most of the smaller particles deposited by debris flows, leaving large boulders to form rapids [*Graf*, 1979; *Howard and Dolan*, 1981]. Debris flows after 1963 have aggraded many debris fans and have altered flow through major rapids [*Howard and Dolan*, 1981; *Melis et al.*, 1994; *Webb et al.*, 1997].

### *2.2. Sand Bars*

Sand bars, which river runners use as campsites, are an important resource in Grand Canyon [*U.S. Department of Interior*, 1995]. Historical photographs and aerial photography provide the only definitive evidence of sand-bar size and location in Grand Canyon before closure of Glen Canyon Dam. From analysis of historical photography, *Schmidt et al.* [1995] and *Webb* [1996] reported that sand bars were in the same locations in the 1890s and 1990s, indicating that the eddies in which sand is deposited are persistent. *Schmidt et al.* [1995] analyzed sand height around persistent rocks at Badger Creek Rapid and found considerable variation in the size of pre-dam sand bars. Pre-dam flood deposits, which contained mostly sand-sized particles [*McKee*, 1938], had higher silt and clay contents than those deposited after the dam was built [*Howard and Dolan*, 1981; *Schmidt and Graf*, 1990], which might confer internal strength to the deposit as well as a higher nutrient content for growth of riparian vegetation [*Stevens*, 1989]. Regular scouring and inundation limited riparian vegetation on most pre-dam sand bars [*Turner and Karpiscak*, 1980; *Webb*, 1996].

### *2.3. Riparian Vegetation*

The riparian vegetation of the pre-dam Colorado River is known from several floral surveys [*Clover and Jotter*, 1944; *Martin*, 1971] and repeat photography [*Turner and Karpiscak*, 1980; *Stephens and Shoemaker*, 1987; *Webb*, 1996]. Marshes were not present along the unregulated Colorado River [*Stevens et al.*, 1995; *Webb*, 1996] except where perennial springs discharged into or near the channel. *Clover and Jotter* [1944] described the "margin of moist sand" as a scoured zone devoid of perennial vegetation. Most riparian vegetation grew around the "pre-dam floodline" [*Turner and Karpiscak*, 1980] or the "old high-water line" [*Carothers and Brown*, 1991; *Johnson*, 1991]. The species comprising what is now called the old high-water zone change through the river corridor, but the most common species is *Prosopis glandulosa* (mesquite) [*Turner and Karpiscak*, 1980].

Certain nonnative plant species, particularly *Tamarix* sp. (saltcedar or tamarisk), were widely distributed in the Colorado River basin but were not common in Grand Canyon before construction of Glen Canyon Dam. *Tamarix* has become naturalized in all the major river systems in the Southwest, reproducing prolifically and establishing dense stands after its introduction in the late 1800s [*Horton*, 1964; *Robinson*, 1965; *Harris*, 1966]. It expanded rapidly throughout the western United States in the 1920s and 1930s [*Christensen*, 1962]. *Graf* [1978] proposed that *Tamarix* spread through Grand Canyon upstream from the Grand Wash Cliffs between 1900 and 1910. Repeat photography does not support this early arrival date but instead suggests invasion from tributaries such as the Paria River [*Webb*, 1996]. *Clover and Jotter* [1944] noted *Tamarix* at several sites in Grand Canyon in 1938; in 1936, it was present along the river between Nankoweap Creek and Tanner Rapid (miles 52 to 69) and near Phantom Ranch [*Patraw*, 1936; *Dodge*, 1936].

Little is known about wildlife usage of habitat in the old high-water line before Glen Canyon Dam. Southwestern willow flycatcher (*Empidonax trailli extimus*), an endangered species, nests in dense stands of riparian vegetation, which were not present along the unregulated river. Specimens of this species were collected near Lees Ferry and at the mouth of the Little Colorado River before Glen Canyon Dam [*Brown*, 1988].

### 2.4. Aquatic Resources

Because of the seasonally low light penetration caused by the high sediment load, low primary production, pool-rapid hydraulics, and long geological isolation from other drainage basins, the native fishes in the Colorado River basin have a 74% level of species endemism, which is the highest in North America [*Miller*, 1959]. Eight native fishes occurred in Grand Canyon; of these, the humpback chub (*Gila cypha*), speckled dace (*Rhinichthys osculus*), flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*C. discobolus*), and razorback sucker (*Xyrauchen texanus*) remain [*Minckley*, 1991]. Both the humpback chub and razorback sucker are federally listed endangered species. The native species likely spawned in both the Colorado River and in major tributaries, such as the Little Colorado and Paria rivers [*Valdez and Ryel*, 1995]. Warm waters in pre-dam backwaters are thought to be where some native fishes spent part of their first year of life. Important habitats formed in the mouths of perennial tributaries during spring floods, when river water impounded warmer tributary waters into sizeable pools that provided seasonal refugium.

Populations of native fishes declined before completion of Glen Canyon Dam [*Miller*, 1961]. Fragmentation of the river by dams, introduction of nonnative fishes, pollution, and water extraction decreased native fish densities. A total of 24 nonnative fish species have made their way into the Colorado River in Grand Canyon [*Valdez and Ryel*, 1995]; many of these were introduced in the Colorado River system in the 19th century [*Minckley*, 1991]. *Valdez and Ryel* [1995] provide a list of introduction dates for nonnative species including rainbow trout (*Oncorhynchus mykiss*), carp (*Cyprinus carpio*), channel catfish (*Ictalurus punctatus*), red shiners (*Cyprinella lutrensis*), and fathead minnows (*Pimephales promelas*). Anglers highly value the trout fishery between Lees Ferry and Glen Canyon Dam (Figure 1). Many of these species compete directly with native species for food or are piscivores of native fish eggs, larvae, and young of the year and displace native fish from their habitat [*Minckley*, 1991].

## 3. HYDROLOGY OF THE COLORADO RIVER IN GRAND CANYON

### 3.1. The Colorado River drainage

The Colorado River and its major tributaries, the Green and San Juan rivers, begin in the mountains of Colorado, Utah, and Wyoming in snowfields at elevations of over 4300 m. Over 70% of the total flow of the Colorado River originates in these states, mostly during spring runoff. Upstream from Grand Canyon, the river drains approximately 627,000 km$^2$ and flows for over 2200 km to its delta in Mexico. Extensive diversions prevent water from reaching the Sea of Cortez in most years. Development of water resources in the Colorado River basin began in the late 1800s and was essentially completed in the 1970s. Large scale land and river development began with passage of the Reclamation Act of 1902 and signing of the Colorado River Compact in 1922 [*Stevens*, 1988]. Distances along the Colorado River in Grand Canyon are traditionally measured in river miles [*Stevens*, 1990], with river mile 0, in both the upstream and downstream directions, at Lees Ferry (Figure 1).

### *3.2. Gaging Records of the Colorado River and its Tributaries*

Gaging stations have recorded discharges for the Colorado River at Lees Ferry since May 1921, and the Colorado River near Grand Canyon since October 1922 (Figure 2a). The Colorado River near Grand Canyon gaging station is located just upstream from the confluence with Bright Angel Creek (river mile 87.5; Figure 1). Discharges at Lees Ferry were affected to varying degrees by the early construction phases of Glen Canyon Dam between 1956 and 1962; flow at both gaging stations has been completely regulated by Glen Canyon Dam since March 13, 1963 [*Garrett and Gellenbeck, 1989*]. Streamflow gaging on the Paria River at Lees Ferry began in October 1923; the Paria River is unregulated. The legally defined point dividing the upper and lower basins is 0.4 km downstream from the mouth of the Paria River, and discharges of both the Colorado and Paria rivers are required for compliance with the Colorado River Compact. The primary gaging station on the Little Colorado River, near Cameron, Arizona, has operated continuously since June 1947; the Little Colorado River is partially regulated by several small, upstream reservoirs.

In addition to gaging stations at Lees Ferry and Grand Canyon, GCES funded 4 gaging stations between Glen Canyon Dam and Diamond Creek (Figure 1). The Colorado River below Glen Canyon Dam station (river mile -15) operated between October 1989 and March 1993. Gaging stations at the Colorado River just upstream from the mouth of the Little Colorado River (river mile 61.1); the Colorado River above National Canyon (river mile 166.5); and the Colorado River above Diamond Creek (river mile 225.0), operated at various times between 1983 and 1996 [*Garrett et al.*, 1993; *Rote et al.*, 1997].

Before completion of Glen Canyon Dam, seasonal peak discharges occurred between May and July, fed by snowmelt in the headwaters. For the Colorado River near Grand Canyon, the 2-yr and 10-yr floods in the pre-dam period were 2160 and 3950 $m^3$/s, respectively (Figure 2). The unregulated mean annual peak discharge was 2420 $m^3$/s; the maximum peak discharge in the gaging record is 6230 $m^3$/s in 1921 and a flood in 1884 was estimated to be about 8500 $m^3$/s [*Garrett and Gellenbeck*, 1989]. Four water years —1931, 1934, 1954, and 1955 — had peak discharges less than the 1996 controlled flood peak of 1345 $m^3$/s. The smallest annual peak discharge was only 720 $m^3$/s in 1934. After the snowmelt flood subsided, flow in the Colorado River typically fell to less than 200 $m^3$/s except during brief but occasionally substantial summer tributary flashfloods. The largest tributary floods increased the flow of the Colorado River to the magnitude of the annual snowmelt peaks, notably in September 1923.

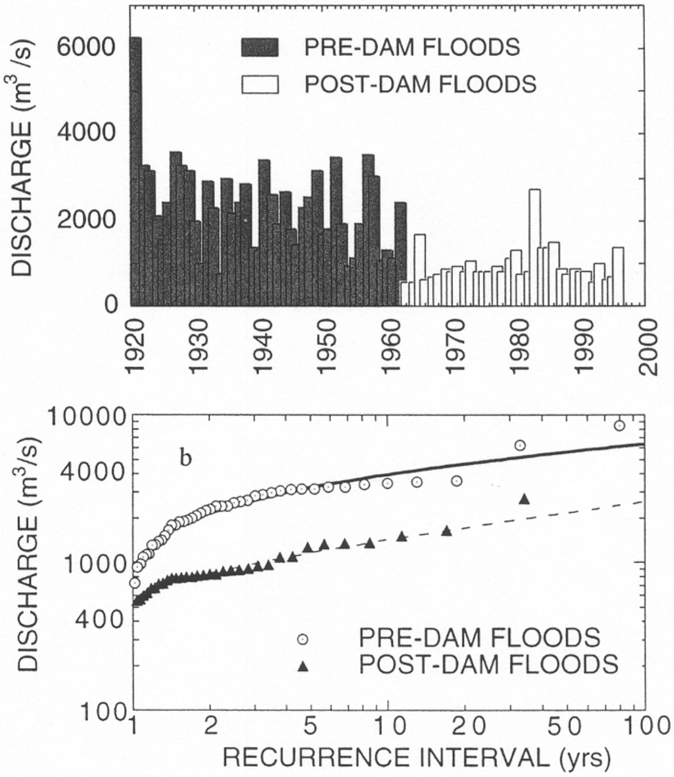

**Figure 2**. A. Annual peak flood series for the Colorado River near Grand Canyon, Arizona. B. Flood frequency for pre- and post-dam periods for the Colorado River near Grand Canyon, Arizona.

The unregulated flow of the Colorado River was highly variable. The highest and lowest mean annual flow volume passing Lee Ferry was 761 $m^3$/s in 1924 and 171 $m^3$/s in 1934, respectively [*Anderson and White*, 1979]. The average unregulated flow at Lees Ferry from 1922 to 1962 was 476 $m^3$/s; most of the high flow years were during the wet period between 1896 and 1930 where the average was approximately 666 $m^3$/s [*Dawdy*, 1991]. The difference in annual flow volume between Lees Ferry and Grand Canyon gages — 16 $m^3$/s — is primarily the contribution of the Paria and Little Colorado rivers [*Turner and Karpiscak*, 1980]. From tree-ring evidence in the headwaters, the long-term average natural flow is 539 $m^3$/s [*Stockton and Jacoby*, 1976].

### *3.3. Sediment Data Collection*

The sediment in the Colorado River mostly comes from tributaries that drain the semiarid sections of the basin.

These sections are composed primarily by Mesozoic and Cenozoic sandstones, mudstones, and shales from the Wingate and Navajo Sandstone; the Entrada, Morrison, Chinle, and Moenkopi Formations; and the Tropic and Mancos Shale [*Howard*, 1947; *Irons et al.*, 1965; *Howard and Dolan*, 1981; *Andrews*, 1986]. Snowmelt runoff had sediment concentrations of less than 10,000 parts per million (ppm). During summer flashfloods, sediment concentrations were higher than 20,000 ppm, and much of the sediment was silt and clay.

Daily sampling of the suspended-sediment concentration began at Lees Ferry in 1928 and at Grand Canyon in 1925. At Lees Ferry, daily sediment samples were collected between 1922 and 1933, 1942 and 1944, 1947 and 1965, and at various times after 1983 [*Garrett et al.*, 1993; *Rote et al.*, 1997]; the average sediment load between 1947 and 1957 was $60 \cdot 10^6$ metric tons/yr. At Grand Canyon, the average sediment load between 1941 and 1957 was $78 \cdot 10^6$ metric tons/yr.

From 1925 to 1941, the sediment load passing the Grand Canyon gaging station averaged $177 \cdot 10^6$ metric tons/yr [*Andrews*, 1990, 1991], or 2.3 times higher than the average from 1941 to 1957. As discussed by *Graf* [1987], *Andrews* [1991] and *Gellis et al.* [1991], sediment inflow may have decreased because regional arroyo cutting greatly slowed in the 1940s. *Hereford and Webb* [1992] and *Graf et al.* [1991] explained arroyo cutting and decreasing flood frequency, and their effects on sediment yield and floodplain formation, by changes in regional climatic variability, such as changes in storm frequency and rainfall intensity.

Suspended sediment was sampled daily from 1947 to 1976 at the Paria River at Lees Ferry and 1947 to 1972 at the Little Colorado River near Cameron; samples also have been collected at various times in the 1980s and 1990s [*Garrett et al.*, 1993; *Rote et al.*, 1997]. On average, $2.74 \cdot 10^6$ metric tons/yr of sediment enters the Colorado River from the Paria River, mostly in August [*Andrews*, 1991]. The Little Colorado River delivers $8.4 \cdot 10^6$ metric tons/yr of sediment, and Little Colorado River tributaries downstream from Cameron, primarily Moenkopi Wash, contribute an additional $2.7 \cdot 10^6$ metric tons/yr.

## 4. EFFECTS OF GLEN CANYON DAM

### *4.1. Dam Construction*

The Colorado River Compact led the way to authorization and construction of Hoover Dam, completed in 1935 [*Stevens*, 1988]. Hoover Dam was the first dam to significantly impact Grand Canyon. Lake Mead reservoir, which completely filled in 1939, impounds water into the lower 64 km of Grand Canyon. In addition, the reservoir serves as a refuge for nonnative fish species, which migrate from its relatively warm waters upstream into the Colorado River for spawning. One species, striped bass (*Morone saxatilis*), migrates upstream and may be a significant predator of young native fish [*Valdez and Leibfried*, 1999].

Congress authorized the Colorado River Storage Project and Glen Canyon Dam in 1956, and the diversion tunnels at the dam were sealed in March 1963 [*Martin*, 1989]. The dam is the major flow regulation structure controlling delivery of water from the upper-basin states of Wyoming, Colorado, Utah, and New Mexico to the lower-basin states of Arizona, Nevada, and California. Long-term average outflow of Glen Canyon Dam is limited to $10 \cdot 10^9$ $m^3$ of water [*U.S. Department of the Interior*, 1995]. Because of the annual outflow constraints, and the desire to maximize hydropower production, releases from Glen Canyon Dam rarely exceed the maximum powerplant capacity of 940 $m^3/s$ when the reservoir is full [*U.S. Department of the Interior*, 1995].

Lake Powell reservoir filled to its capacity of $30 \cdot 10^9$ $m^3$ for the first time on June 17, 1980, 17 yrs after storage began. The reservoir extends 300 km upstream at its maximum pool elevation, inundating the lower part of Cataract Canyon in east-central Utah and much of the San Juan Canyon in southeastern Utah [*Potter and Drake*, 1989]. The reservoir is in excess of 150 m deep at the base of the dam at full-pool elevation. The reservoir stratifies seasonally with a well-defined epilimnion and hypoliminion from late spring to fall. The hypolimnion consists of a large mass of cold, dense water, which can have high specific conductance (1100-1500 siemens) owing to large amounts of salts in the inflow water. The surface of the reservoir has never frozen. The combination of great depth, small fetch, and higher salinity at depth prevents complete mixing near the dam during the isothermal periods of most winters. Water is drawn from a depth of 70 m below the full-pool elevation of the reservoir for the 8 generators in the powerplant of Glen Canyon Dam.

### *4.2. River Discharge*

Glen Canyon Dam has profoundly changed the hydrology of the Colorado River in Grand Canyon. Flow regulation has greatly reduced interannual flow variability, although load-following hydroelectric power has increased the typical range of flow during a day [*Turner and Karpiscak*, 1980; *Howard and Dolan*, 1981; *Dawdy*, 1991]. Pre- and post-dam hydrographs for the Colorado River at Grand Canyon are significantly different (Figure 3a). Before Glen Canyon Dam, the annual flood peak typically

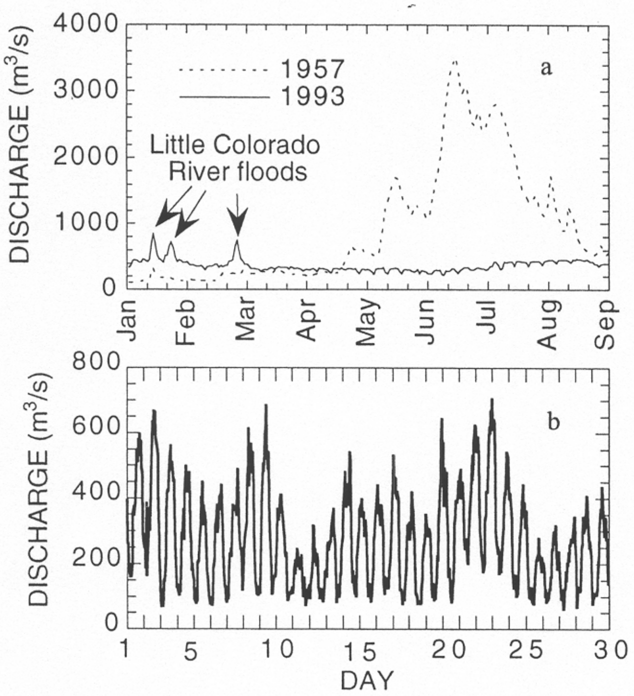

**Figure 3**. Hydrographs for the Colorado River near Grand Canyon, Arizona. A. Hydrograph of daily discharges for calendar years 1957 and 1993. B. Instantaneous discharge, measured every 15 minutes, in September 1982.

occurred between May and July with fluctuations and secondary peaks occurring in response to variability in snowmelt and summer flashfloods on major tributaries, particularly the Green and San Juan rivers. After construction of Glen Canyon Dam, discharges in Grand Canyon are more seasonally uniform, occasionally raised above powerplant releases by floods on either the Paria or Little Colorado rivers (Figure 3a). The peak discharge in the post-dam river typically occurs either in December-January or July-August when tributary floods coincide with high power production.

Flow regulation by Glen Canyon Dam has substantially reduced the annual range of river discharge at Lees Ferry. After 1963, the mean annual peak discharge of the Colorado River at Lees Ferry is 920 $m^3/s$. In 26 of 32 years of flow regulation, the annual peak discharge was less than the powerplant capacity of approximately 930 $m^3/s$. Legally mandated release of water from Lake Powell to Lake Mead caused a high release in 1965; similarly, a temporary legal limit on the surface elevation of Lake Powell caused the 1980 high release [*Martin*, 1989]. Flow substantially greater than powerplant capacity occurred throughout water years 1983 to 1986, as a result of unusually large runoff into a full reservoir [*U.S. Department of the Interior*, 1995]. The 2-yr and 10-yr floods for the Colorado River near Grand Canyon are 851 and 1440 $m^3/s$, respectively, which are reductions of about 38 and 40% from the historic frequency (Figure 2b). In the post-dam period, flow releases in excess of powerplant capacity, such as in the 1996 release, are considered “floods.”

Water stored in Lake Powell during the spring runoff is released throughout the remainder of the year. The volume of water released in a given month varies only by a factor of 2 throughout the year and reflects demands for electrical power and water in the Southwest and California. Typically, highest monthly releases occur in December and January when electricity is needed for heating and during July and August when it is needed for air conditioning and irrigation. Releases in September 1982 (Figure 3b), typical of the 1970s and early 1980s, reflect the daily and weekly variation in electrical power demand. Peak demand occurs in the morning and early evening. Flow through the powerplant is decreased to a minimum in the late evening as power usage diminishes [*U.S. Department of the Interior*, 1995]. Significantly less electrical power is needed on weekends, and flow releases from Glen Canyon Dam accordingly show a 7-day periodicity (Figure 3b). Only relatively large, infrequent tributary floods produced similar daily changes in discharge in the unregulated river.

Reservoir operations have significantly altered the duration of daily mean stream flows at Lees Ferry (Figure 4). The magnitude of relatively large, infrequent flows (those equalled or exceeded less than 10% of the time) have been reduced by 50%, and release of stored snowmelt runoff during the remainder of the year has increased the magnitude of relatively common flows (those equalled or exceeded between 30 and 99% of the time). The discharge equalled or exceeded 50% of the time since 1965, compared to the period between 1922 and 1957, increased 60%.

Interim flow operations [*U.S. Department of the Interior*, 1995] were implemented in 1992 after the GCES research flow studies were completed. These flows, with maximum peaks of 566 $m^3/s$ and minimums of 142 $m^3/s$, were designed to optimize sediment storage in the eddies and main channel from tributary inflows. After completion of the EIS and implementation of the Record of Decision, maximum powerplant releases were increased to 708 $m^3/s$.

### *4.3. Aggradation of Debris Fans*

Because Glen Canyon Dam is operated as a *de facto* flood control structure for water conservation, flow competence has been greatly reduced in Grand Canyon. *Graf* [1980] first called attention to the problem of aggradation of

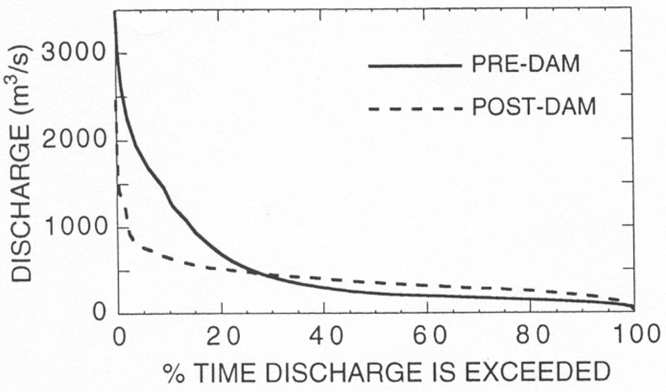

**Figure 4.** Duration of daily discharge for the Colorado River near Lees Ferry for the pre- and post-dam periods.

rapids downstream from dams on the Green River in Utah. For the post-dam period in Grand Canyon, the first significant debris flows occurred during an extraordinary storm in December 1966 [*Cooley et al.*, 1977]. Crystal Rapid changed from a minor rapid to one of the largest rapids in Grand Canyon [*Cooley et al.*, 1977; *Kieffer*, 1985; *Webb et al.*, 1989]. The same storm caused debris flows in Nankoweap Creek, Lava Canyon, Bright Angel Creek, and Prospect Canyon at Lava Falls Rapid [*Webb et al.*, 1989, 1997]. The Bright Angel Creek debris flow changed the stage-discharge relation by more than 1 m at the Grand Canyon gaging station several hundred meters upstream; the 1983 high releases washed out the constriction [*Burkham*, 1986]. By analyzing historical aerial photography, *Howard and Dolan* [1979, 1981] reported aggradation of 25% of the debris fans in Marble Canyon since the 1963 closure of Glen Canyon Dam.

Aggradation of debris fans was systematically documented after 1984 [*Melis et al.*, 1994]. An average of two debris flows occurred each year between 1984 and 1997 in Grand Canyon, creating 2 new rapids and enlarging debris fans at 9 existing riffles and rapids [*Webb et al.*, this volume]. *Griffiths et al.* [1996] developed a statistical model of debris flows in eastern and western Grand Canyon. They concluded that the frequency of debris flows is related to the location of shale in the drainage basin, as well as morphometric variables such as basin area. The frequency of debris flows is greatest in reaches where the Colorado River trends to the southwest; the highest frequency is in Marble Canyon.

Pre-dam floods removed all but the largest particles from debris fan and reshaped their configuration [*Graf*, 1979; *Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1997]. Using historical photographs, *Webb* [1996] documented only a few changes to major rapids before closure of Glen Canyon Dam in 1963. Certain rapids, particularly Lava Falls, changed considerably owing to repeated debris flows. Subsequent reworking by the pre-dam Colorado River was insufficient to widen the river to its former condition [*Webb et al.,* 1997]. *Graf* [1980], *Howard and Dolan* [1981], *Kieffer* [1985], and *Webb et al.* [1997] presented conceptual models of Colorado River reworking. *Kieffer* [1985, 1990] defined the constriction ratio of rapid width to upstream width, and *Melis* [1997] found that 444 debris fans constrict the river between 1 and 75%, with a median of 44.5%.

The amount of debris-fan reworking that could be achieved by low dam releases has been an area of scientific controversy. *Dolan et al.* [1974] stated that significant reworking occurred above 1410 m$^3$/s. *Kieffer* [1985], studying reworking of the Crystal Creek debris fan during the 1983 flood, concluded that a discharge of more than 11,300 m$^3$/s would be required to reduce the constriction to 50%. *Webb et al.* [1997] documented the nearly complete removal of debris fans at Lava Falls Rapid by pre- and post-dam floods as low as 1000 m$^3$/s. *Melis et al.* [1994] documented reworking of other aggraded debris fans by powerplant releases less than 850 m$^3$/s. The latter two studies indicate that floods of similar magnitude to the 1996 controlled flood would significantly rework aggraded debris fans in Grand Canyon.

### 4.4. Sediment Mass Balance and Bed Scour

Glen Canyon Dam releases are essentially clear because nearly all of the formerly prodigious sediment load entering Grand Canyon is deposited in Lake Powell. Sediment coarser than 0.5 mm comprised less than 1% of the pre-dam sediment load [*Smith et al.*, 1960]; the regulated river transports a higher percentage of coarser sand, depending on tributary influxes. Post-dam suspended-sediment transport is approximately 5% of the pre-dam value downstream from Lees Ferry and the Paria River and approximately 25% of the pre-dam value at Grand Canyon. Tributaries downstream from the dam supply limited but significant quantities of fine sediment to the Colorado River and the annual sediment load increases downstream. Suspended-sediment transport from the Paria and Little Colorado rivers is approximately 75% of the post-dam suspended sediment entering the river between Lees Ferry and Phantom Ranch; these tributaries represent 94% of the contributing drainage area in this reach [*Andrews*, 1991]. About 219 small ungaged tributaries [*Melis et al.,* 1994] supply the remaining 25% of the post-dam sediment input.

Bed scour begins downstream from major dams after closure [*Williams and Wolman*, 1984], eventually armoring the bed with coarser sediment. Following closure of the bypass tunnels at Glen Canyon Dam, fine sediment was scoured at progressively further distances away from the dam. By 1963, the scour zone extended 11 km downstream [*Pemberton*, 1976]. The first significant post-dam change in bed elevation at Lees Ferry, located 25 km downstream, occurred during the 1965 flood (Figure 5). Comparing the lowest point in cross section data collected during discharge measurements, *Burkham* [1986] documented 8.3 m of scour, followed by a rise of 3.7 m, resulting in a persistent, permanent scour of 4.6 m (Figure 5). By 1970, the bed of the Colorado River from the dam to the Paria River was armored in shallower reaches by coarse gravel and cobbles, and fine sediment was scoured from pools. Erosion slowed after 1975, but nearly $8.5 \cdot 10^6$ $m^3$ of sediment — mostly sand — had been eroded in the reach between the dam and Lees Ferry [*Pemberton*, 1976].

In 1984, *Wilson* [1988] collected data on the type of bed material, its location on the bed, and the depth of the river, and concluded that the percentage of the Colorado River bed composed of bedrock or boulders varied between 30 and 81%. The percentage of bedrock or boulders was highest in narrow reaches and lowest in wider reaches [see *Bureau of Reclamation*, 1988a, Table A-26]. At a discharge of 700 $m^3/s$, *Wilson* [1988] reported an "average thalweg depth" that ranged from 1.5 to 32.7 m. In 1965, *Leopold* [1969] measured a maximum river depth of 33.9 m near river mile 114.3 at a discharge of 1374 $m^3/s$.

Most researchers have concluded that sand accumulates on the bed between Lees Ferry and Grand Canyon at most dam releases because of sediment added by the Paria and Little Colorado rivers. *Howard and Dolan* [1981] calculated a net increase in sediment storage from 1965 to 1977 for the Lees Ferry to Grand Canyon reach (Figure 1). Using a modeling approach that did not account for the possibility of large dam releases, *Laursen et al.* [1976] concluded that emergent sand bars would only persist for 200 yrs after completion of Glen Canyon Dam.

*Orvis and Randle* [1988] and *Randle and Pemberton* [1988] developed a one-dimensional sediment transport model to calculate sediment transport through Grand Canyon based on *Wilson*'s [1988] 209 cross sections and estimates of bed particle size. *Randle and Pemberton* [1988] concluded that high-flow years, such as 1983-1985, resulted in significant loss of sand, but most scenarios of dam operations caused aggradation of sand between the Paria and Little Colorado rivers. *Bennett* [1993] modelled release scenarios proposed for the EIS [*U.S. Department of the Interior,* 1995] and noted trade-offs between sand stored on the bed versus on the margins as emergent sand bars; higher fluctuating flows deposited sand in usable locations at the expense of channel storage. Using a sediment mass-balance approach, *Smillie et al.* [1993] presented dam-release scenarios where sand could accumulate in the reach between the Paria and Little Colorado rivers; accumulation occurred if peak discharges were less than 566 $m^3/s$. These calculations suggested that sufficient sand was stored in the bed of the Colorado River to allow a regulated flood that would redistribute sand from the channel to its banks.

Additional sediment-transport modeling began to shed light on the underlying processes associated with sediment transport. Increasingly more complex operations of the dam required more sophisticated models, and data requirements increased. For example, attempts to predict unsteady flow hydrographs [*Lazenby*, 1988] and travel times [*Dawdy*, 1991] of water through Grand Canyon had considerable uncertainty. The travel time of water at various discharges is an important means of verifying the channel-geometry data used in most sediment-transport models. *Graf* [1995] used the dye-injection technique to determine travel times through Grand Canyon at several steady and unsteady dam releases. High-accuracy monitoring of cross sections [*Graf et al.*, 1995a, 1997] and extensive bathymetric mapping [*Graf et al.*, 1995b] supported development and verification of sediment-transport models.

Eventually, two types of models were developed to predict sediment transport. *Wiele and Smith* [1996] presented an improved one-dimensional sediment-transport model of Grand Canyon and found that less than 50% coverage of the bed with sand was required to maintain equilibrium sand transport through Grand Canyon. Video imagery and side-scan surveys since 1990 indicate that large areas of the bed are composed of gravel and cobbles [*Rubin et al.*, 1994]. To understand reach-specific changes, *Wiele at al.* [1996] developed a two-dimensional, vertically averaged flow model to predict deposition and cross-section changes just downstream from the mouth of the Little Colorado River after its 1993 floods (Figure 3a). They concluded that eddies immediately downstream from the Little Colorado River filled within 3 days during a flood whose suspended load had a concentration similar to floods before the dam; their work is the first quantification of the rates of sand accumulation in eddies during high flows.

### *4.5. Sand-Bar Erosion*

By the early 1970s, campsites along the river had been lost because of sand-bar erosion and the encroachment of thick stands of riparian vegetation [*Dolan et al.*, 1974, 1977; *Carothers and Brown*, 1991]. Without replenishment of sand by floods, erosion was inevitable. Many factors contribute to sand-bar erosion, including 1) low suspended-

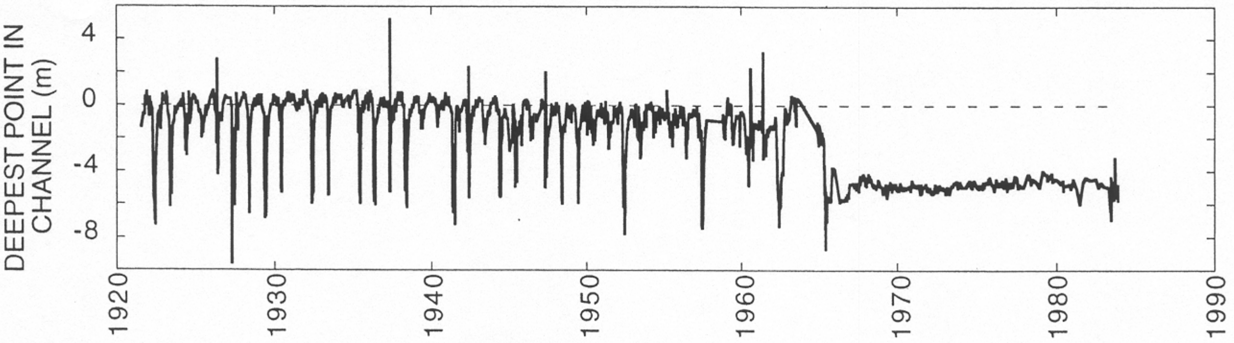

**Figure 5.** Deviation of low point in the channel cross section for the Colorado River at Lees Ferry, Arizona [*Burkham*, 1986].

sand concentrations in diurnally varying flow, 2) wave action [*Bauer and Schmidt*, 1993], 3) seepage erosion during downramping of diurnal fluctuations [*Budhu and Gobin*, 1994], 4) heavy trampling and downslope displacement by river runners [*Valentine and Dolan*, 1979], 5) wind deflation [*Dolan et al.*, 1974], 6) tributary floods and debris flows [*Melis et al.*, 1994], and 7) periodic slump failures [*Cluer*, 1995].

National Park Service concerns prompted the first systematic study of sand bars in 1974 and 1975 [*Howard*, 1975; *Howard and Dolan*, 1976, 1979, 1981]. Their work documented significant sand-bar erosion and encroachment of vegetation onto 20 formerly barren bars. Erosion, which generally reduced bar area and elevation, was greatest upstream from the Little Colorado River, although the trend was pervasive throughout Grand Canyon. *Borden and Weeden* [1973] identified and classified 443 potential camping beaches and began long-term monitoring.

The 1983 flood (Figure 2a) temporarily rebuilt sand bars through much of Grand Canyon. In October 1983, *Brian and Thomas* [1984] examined 227 of the 443 sand bars monitored by *Borden and Weeden* [1973]. Erosion after 1973 but before the 1983 releases had claimed 26 campsites, mostly in narrow reaches. Of the comparable camping beaches, 28% had decreased, 30% had increased, and 42% were unchanged in size. The 1983 flood completely removed 24 beaches, created 50 new ones, and aggraded many others, mostly in western Grand Canyon. Most of the new sand bars were unstable and rapidly eroded during high releases between 1984 and 1986. Generally, sand bars in narrow reaches were more severely eroded while those in wide reaches aggraded.

*Kearsley et al.* [1994] continued the evaluation of campsites begun by *Borden and Weeden* [1973] by directly measuring beach size in the field and in aerial photographs. *Kearsley et al.* [1994] concluded that 52% of campsites were smaller, 46% of campsites were the same size, and only 2% were larger in 1990 than in 1965. They concluded that the "benefit" of sand aggradation from the 1983 flood, noted by *Brian and Thomas* [1984], had not been long lasting. Campsites changed by vegetation encroachment or removal and by deposition or erosion of sand; some of the changes occurred because of tributary floods or debris flows [*Melis et al.*, 1994].

A large amount of research concentrated on measurement of changes in sand bars. Many researchers focused on how Glen Canyon Dam could be operated to minimize sand-bar erosion, ignoring the conclusions of *Dolan et al.* [1974, 1977] that the problem stemmed from lack of replenishment of beaches. Because most studies under GCES I were conducted in the high-release period of 1983-1985, they advised avoidance of intentional and uncontrolled floods from Glen Canyon Dam to minimize sand-bar erosion [*Bureau of Reclamation*, 1988, p. A-21].

Some researchers revisited the original data set established by *Howard* [1975]; others monitored new sites and sand-bar types, creating a mosaic of different sand bars monitored at different times using different methods. For example, *Beus et al.* [1985] remeasured *Howard's* [1975] profile lines; *Ferrari* [1988] reported the resurvey of 20 of these lines with 4 additions made for ecological reasons; *Schmidt and Graf* [1990] remeasured profile lines and began detailed topographic and bathymetric surveys of beaches and eddies; and *Cluer* [1995] used high-frequency repeat photography and photogrammetry to measure sand-bar change at 6 sites. Technological advances improved the analyses, particularly the addition of bathymetric measurements [*Schmidt and Graf*, 1990]. Many of the monitored sand bars differed in morphology, configuration, and location, leading to a complex array of responses to operation of Glen Canyon Dam and conflicting conclusions in reports. Effects of antecedent conditions, particularly during the research flows of 1990-1991, were not adequately considered. In their study of sand-bar response to fluctuating flow, *Beus and Avery* [1993] concluded that "no single test flow affected all sand bars in the same manner."

A hydrodynamic classification of sand bars added an important tool to understanding the dynamics of sand bars. *Schmidt and Rubin* [1995] defined the fan-eddy complex (Figure 6), after preliminary work by *Howard and Dolan* [1981] and following *Schmidt* [1990] and *Schmidt and Graf* [1990]. Later modification resulted in the definition of three types of sand bars: (1) separation bars, which typically occur on the downstream side of debris fans on the upstream side of recirculation zones; (2) reattachment bars, which typically form beneath the primary eddy and extend to the stagnation point on the downstream side of the recirculation zone; and (3) channel-margin deposits, which typically form along channel banks and minor flow obstructions (Figure 6).

The classification of sand bars led to immediate gains in understanding the origins and stability of deposits with respect to operations of Glen Canyon Dam. *Schmidt and Graf* [1990] and *Schmidt* [1990] measured changes in eddy size and tracked changes in the flow reattachment point with respect to sand-bar deposition. *Melis* [1997] distinguished debris fans in terms of the discharge range that submerges them and thereby minimizes or eliminates the eddies downstream [*Schmidt*, 1990]. *Melis* [1997] also evaluated the range of river flood stages under which sand bars would be deposited. *Rubin et al.* [1990] made hydrodynamic interpretations of bedforms that indicated the nature of eddy recirculation that deposits reattachment bars. *Schmidt* [1993] correlated the type, extent, and stage of erosion with general dam-operating regimes; he noted the apparent trade-off between high-stage and low-stage sand bars, and aggradation of separation bars and degradation of reattachment bars during high dam releases. *Schmidt* [1993] stressed the importance of overall spatial and temporal history in understanding short-term changes in sand bars. *Schmidt et al.* [1995] and *Webb* [1996] found that reattachment bars were more unstable than separation or channel-margin bars, but that 60% of all sand bars had eroded between 1890 and the early 1990s. Using repeat photography, these researchers documented the systematic decrease in net sand-bar erosion with increasing distance from Glen Canyon Dam.

Research on changes in sand bars generally established that: (1) all sand bars do not respond in similar ways to operations of Glen Canyon Dam; (2) reattachment bars respond differently than separation and channel-margin bars; (3) steady flows generally erode sand bars and redistribute sand to lower elevations in the eddy; (4) high fluctuating flows aggrade some sand bars while eroding others; and (5) sand-bar response may vary with distance downstream from Glen Canyon Dam. In the course of research, the management paradigm shifted from emphasis on lack of replenishment, to minimizing erosion by minimizing or altering flow fluctuations, to rebuilding sand bars while minimizing erosion in the intervening periods.

Lack of annual flooding, caused by operation of Glen Canyon Dam, allowed colonization by native and nonnative riparian species on sand-mantled banks. Lack of flooding led to concern that trees in the old high-water zone were becoming senescent and not reproducing because of the drought imposed by the dam. Subsequent research indicates that the old high-water zone will survive despite the lack of annual inundation because most of the species are facultative riparian plants that can utilize precipitation, although their growth rates decrease [*Anderson and Ruffner*, 1988]. Seedling establishment of native species is expected to shift downslope from the old high-water zone, which is becoming increasingly fragmented in their new, primarily xeric, environment [*Carothers and Brown*, 1991].

The "new high-water zone" [*Johnson*, 1991], which formed between the 850-2830 $m^3/s$ river stages, is a critical resource that supports extensive vegetation and 5-10 times the number of breeding birds than occurred along the pre-dam river [*Brown et al.*, 1987]. For example, the black-chinned hummingbird (*Archilochus alexandri*), which is common in the southwestern United States, nests almost exclusively in *Tamarix* trees in the river corridor [*Brown*, 1992]. *Turner and Karpiscak* [1980] documented the decreased frequency of river-bank inundation, pre- to post-dam, up to 1977 and used repeat photography to document the increase in riparian vegetation.

In the late 1960s, *Martin* [1971], following the *Clover and Jotter* [1944] survey, found *Tamarix* "abundantly distributed" along the river corridor and was alarmed at its "explosive spread" through Grand Canyon. *Tamarix* along with the native coyote willow (*Salix exigua*), Goodding willow (*Salix gooddingii*), cottonwood (*Populus fremontii*), and several native species of shrubs aggressively colonized the newly available substrate [*Turner and Karpiscak*, 1980]. The large increases, which occurred in both the old and new high-water zones, were significant. The 1983 flood, as well as increases in the beaver population, have destroyed many young *Populus*. *Brown and Trossett* [1989] estimated that 500 ha of new riparian habitat was created in 20 yrs of dam operations. In an analysis of aerial photography taken between 1965 and 1985, *Pucherelli* [1988] found *Prosopis* cover increased in the old high-water zone but at a rate 5 times slower than its increase in the new

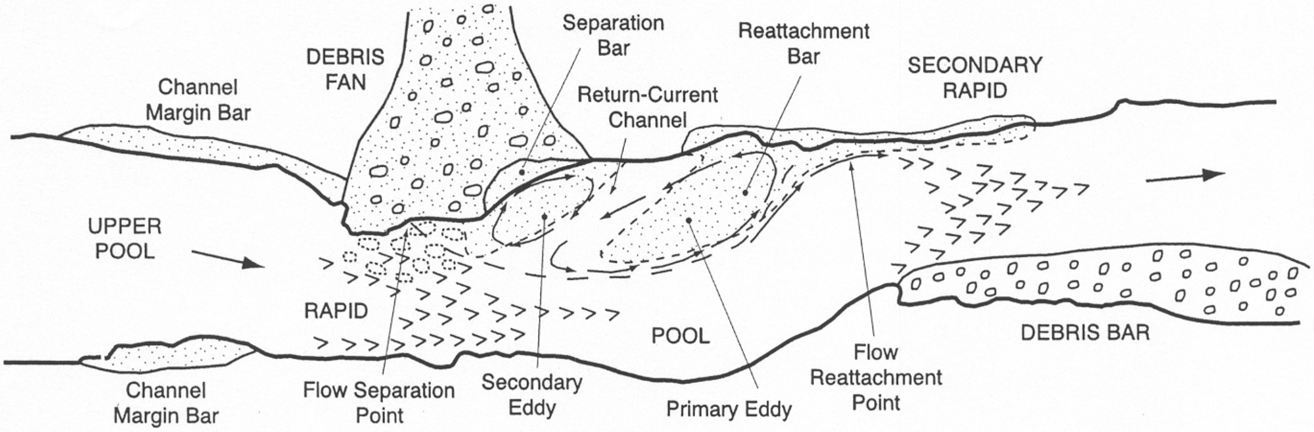

**Figure 6**. Schematic diagram of a typical fan-eddy complex in Grand Canyon [*Schmidt*, 1990].

high-water zone. The rate of the invasion slowed as the new high-water zone filled with plants.

As vegetation becomes denser and senescent, problems emerge as *Tamarix* makes its local environment more saline and less productive and the number of insects it supports declines [*Stevens*, 1989]. *Stevens* [1989] presented a competition model in which self-shading effects may increase the probability of eventual replacement of *Tamarix* with *Salix exigua*. Researchers concluded that the continued recruitment of riparian species requires periodic disturbance (i.e., flooding) to open patches [*Stevens and Ayers*, 1993] and suggested to managers desiring more riparian vegetation that the optimal dam-release scenario included periodic flooding with lower fluctuating and less damaging powerplant releases. The new high-water zone vegetation is highly valued by some managers as wildlife habitat, particularly for the endangered southwestern willow flycatcher [*U.S. Department of the Interior,* 1995] and other neotropical birds [*Brown et al.*, 1987]. The population of this species in Grand Canyon, while relatively small in total numbers, is believed to be the largest population remaining in Arizona [*Unitt*, 1987]; the birds heavily use dense stands of *Tamarix*. Prolonged flooding and inundation damage or kill *Tamarix* as well as native species. The flood of 1983 destroyed large numbers of *Tamarix* [*Stevens and Waring*, 1988]; continued high water in the mid-1980s minimized *Tamarix* reestablishment. Therefore, flooding may help minimize an undesirable, nonnative species while damaging a habitat desirable for endangered species.

Post-dam marshes developed in wide reaches of the Colorado River (Figure 1), particularly between Nankoweap Rapid (river mile 52) and the Little Colorado River; in the Furnace Flats reach of river miles 65-72; and in western Grand Canyon, particularly near Parashant Canyon (river mile 198). Marsh vegetation cannot withstand scouring or lengthy inundation; the 1983 flood, which peaked at 2720 $m^3/s$, killed half of the vegetation below the 1420 $m^3/s$ stage by drowning, burial, or erosion [*Stevens and Waring*, 1988]. *Stevens and Ayers* [1993] documented 65 sites containing 4.8 ha of marsh vegetation; the 1983 flood decreased the number of sites to 17. Despite the damage, seedlings became established within several years of the cessation of the high releases from the dam [*Stevens et al.*, 1995].

Riverine riparian vegetation in Grand Canyon poses a management dilemma [*Schmidt et al.*, 1998]. On the one hand, lack of flooding has created a ribbon of lush riparian vegetation along the Colorado River that is habitat for wildlife, but continued lack of flooding may result in a low-productivity, senescent environment. Restoration of periodic flooding could damage what is considered extremely valuable wildlife habitat, particularly for bird species, and damage marsh habitat, the most biologically productive part of the new high-water zone. One of the primary goals of the 1996 controlled flood was creating some disturbance to the new high-water zone without risking major habitat destruction for endangered species.

### *4.7. Temperature, Clarity, and Aquatic Productivity*

Before completion of Glen Canyon Dam, the Colorado River was thought to be largely heterotrophic with little primary production in the sediment-laden water [*Carothers and Brown*, 1991]. The green algae *Cladophora glomerata* was present but not abundant in the river; numerous algal species were found in tributaries in Glen Canyon, but few studies were conducted in the Colorado River itself [*Blinn and Cole*, 1991]. Aquatic insect populations may have been low in the mainstem [*Blinn and Cole*, 1991], and certain terrestrial insects were likely to have been a part of the diets of native fishes [*Carothers and Brown*, 1991]. Debris fans and associated debris bars in the pre-dam river provided stable substrate for abundant aquatic insects, while shifting sand beds supported little benthic productivity.

The temperature of the Colorado River through Grand Canyon varied seasonally from 0 to 29°C before construction of Glen Canyon Dam [*Rote et al.*, 1997]. The surface of the river froze in the low-velocity reaches near Lees Ferry every 10-20 yrs [*Webb*, 1996]. The annual range in water temperature steadily declined after 1963 as Lake Powell filled. The temperature of water released through the dam has averaged about 8°C, with a range of 7-15°C between 1977 and 1995.

The combination of cold water and low sediment concentrations have dramatically altered the aquatic ecosystem of the Colorado River, converting a historic heterotrophic system to an autotrophic system dependent on autochthonous production. These conditions have resulted in high photosynthetic productivity downstream from the dam, making ideal conditions for a blue-ribbon trout fishery in the tailwaters [*Carothers and Brown*, 1991]. Productivity decreases downstream as sediment input from tributaries increases and reduces light available for photosynthesis. The clear, cold water favored development of an abundant, but moderately diverse trophic structure supported by *Cladophora* and a large assemblage of ephiphytic diatoms. The more upright forms of are more available to grazing macroinvertebrates and fish; higher temperatures favor more sessile diatom forms that presumably are less available as food to the nonnative amphipod, *Gammarus lacustris*, and other consumers. Higher productivity takes place under low to moderate river fluctuations and when the wetted channel perimeter is greatest; *Blinn et al.* [1995] concluded that twice the amount of energy was available at flows of 807 $m^3/s$ than at 142 $m^3/s$. Wetting and drying, caused by wide-ranging fluctuating flows, caused significant loss of *Cladophora* biomass with attendant losses of diatoms and *Gammarus* [*Angradi and Kubly*, 1993].

Although few collections provide details on algal and macroinvertebrate species composition of the pre-dam river, changes in species composition appear to be dramatic, with numerous species disappearing and several new or uncommon species becoming more abundant [*Blinn and Cole*, 1991]. Using Cataract Canyon, upstream from Lake Powell in Utah, as a surrogate for pre-dam conditions in Grand Canyon, *Haden* [1997] found the primary consumers were collector/filterer insects that rely on allochthonous detritus as an energy source. *Haden* [1997] found considerable differences in species composition of benthic invertebrates related to changes in trophic structure and temperature. The primary consumers in Cataract Canyon (and presumably the historic river) were dominated by collector/filterer insects which required a range of temperatures to complete their life cycles and relied on allochthonous detritus as an energy source. The benthic community below Glen Canyon Dam was dominated by *Gammarus*, and nearctic dipterans that are closely associated with *Cladophora* [*Stevens et al.*, 1997]. Although macroinvertebrate composition differed, total macroinvertebrate biomass was similar in Cataract Canyon and below Glen Canyon Dam.

Little is known about the food supply available to native fishes in the heterotrophic, pre-dam river, although most of it likely was supplied in drift. *Vanicek* [1967] found that aquatic and terrestrial insects, plant debris, filamentous algae, and fish were the primary foods of roundtail chub, humpback chub, and bonytail in the Green River prior to completion of Flaming Gorge Dam. *Tyus and Minckley* [1988] reported gorging by humpback chub on migrating Mormon crickets (locusts) in the Green and Yampa rivers, suggesting opportunistic feeding and the importance of terrestrial food sources. In the post-dam river in Grand Canyon, many fish species rely heavily on the abundant macroinvertebrate biomass found in the dam tailwaters that decreases in abundance downstream. In the tailwaters, rainbow trout ate primarily *Gammarus*, filamentous algae, midges, and blackflies [*Carothers and Minckley*, 1981; *Maddux et al.*, 1987; *Leibfried*, 1988]. *Valdez and Ryel* [1997] reported that humpback chub near the Little Colorado River (125 km downstream from the dam) ate primarily *Gammarus* (45%) and blackflies (40%), with some use of midges and terrestrial invertebrates. Further downstream (220 km downstream from the dam), humpback chub ate primarily blackflies (49%) and terrestrial invertebrates (30%), with less use of *Gammarus* and midges. Hence, despite a vastly different trophic structure, native as well as nonnative fishes have to rely heavily on *in situ* primary and secondary production, since upstream sources of organic material have been interrupted by impoundment of the river.

Inherent in all of the research on aquatic productivity is the assumption that high aquatic productivity is a desirable management goal for the post-dam river [*Carothers and Brown*, 1991]. Research on the aquatic community has focused on minimizing productivity losses by minimizing daily fluctuations and implementing large dam releases. Implementation of interim flows and the preferred alternative, low modified fluctuating flows, have benefitted, maintained or increased aquatic productivity and are, therefore, thought to be desirable. Benefits of controlled flooding to biological productivity manifest themselves over a longer time period than, for example, sand-bar deposition, and those benefits can only be determined through long-term monitoring. Because of the high societal value placed on the blue-ribbon trout fishery upstream from Lees Ferry, maximizing productivity of *Cladophora*, and hence *Gammarus*, is considered to be valuable. One of the primary reasons that minimum discharges from Glen Canyon Dam were raised from 85 to 227 $m^3/s$ in summer months was to minimized stranding of trout and loss of incubating eggs and newly hatched fry [*U.S. Department of the Interior*, 1995].

### *4.8. Adaptation of Native Fish Populations to the Post-Dam River*

The native fishes of the Colorado River were in decline as early as the 1950s, primarily as a result of water diversion, degraded water quality, and the invasion of competing and predaceous nonnative fishes [*Miller*, 1961]. By the time Glen Canyon Dam was completed in 1963, fish assemblages were dominated by nonnative carp, channel catfish, and red shiners in the mainstem and rainbow trout and brown trout in the tributaries [*Valdez and Ryel*, 1995]. Of the 8 native mainstem fish species, 3 were extirpated at about the time of, or shortly after, dam completion; roundtail chub and bonytail were last reported in Grand Canyon in the 1950s, and Colorado squawfish were last reported in the mid-1970s. Razorback suckers are now extremely rare, humpback chub are endangered, and flannelmouth suckers, bluehead suckers, and speckled dace are confined to local populations, primarily near seasonally-warmed tributaries. Razorback suckers and Colorado squawfish were probably transient species through Grand Canyon.

By the early 1970s, water temperatures in Grand Canyon had dropped below the range of 16-22°C needed for successful mainstem reproduction by the warmwater native fishes. Successful mainstem reproduction has not been documented for these species, although attempted spawning has been reported in warm springs for humpback chub [*Valdez and Masslich*, 1999]. Humpback chub spawn primarily in the Little Colorado River and flannelmouth suckers, bluehead suckers, and speckled dace spawn in tributaries, including the Little Colorado River [*Robinson et al.*, 1996], Paria River [*Weiss*, 1993], and Bright Angel and Kanab creeks [*Otis*, 1994]. Flannelmouth suckers are also reported spawning in the dam tailwaters, possibly as a result of more stable flows from implementation of interim flows in 1992. The cold water, while appropriate for spawning of nonnative salmonids, suppressed mainstem reproduction by most nonnative warm-water species, as well. Like the native warm-water fishes, these species also ascend seasonally-warmed tributaries for spawning.

Native fishes have faced substantial competition and predation from nonnative fishes since before completion of Glen Canyon Dam. In the post-dam river, nonnative fish predation may account for substantial mortality of a year class [*Valdez and Ryel*, 1997; *Douglas and Marsh*, 1996]. Carp are voracious predators of fish eggs and larvae, and can quickly locate and scavenge newly deposited eggs, particularly in small tributaries. Channel catfish consume large numbers of young native fishes when they are most active, at night and during high turbidity. Rainbow and brown trout consume large numbers of juvenile native fishes descending from natal streams, and fathead minnows and red shiners consume newly-hatched larvae in shallow-nursery habitats, such as backwaters.

The cold clear riverine conditions have influenced fish distribution and habitat use. *Maddux et al.* [1987] and *Valdez and Ryel* [1995] demonstrated that mainstem fishes in Grand Canyon are distributed primarily near seasonally warmed tributary mouths. Habitat use, particularly for humpback chub, reflects a combination of canyon geomorphology, local cover, and food supply. Preferred channel reaches have abundant debris fans and are typically in proximity to warm springs or perennial tributaries [*Valdez and Ryel*, 1995]. Young-of-year and juveniles (generally <200 mm long) prefer backwaters (i.e., eddy return channels), river banks with vegetation overhanging from the new high-water zone, or shorelines of talus or debris fans [*Converse et al.*, 1998]. Adults prefer offshore habitats, especially large recirculating eddies associated with debris fans. The quality of these shoreline habitats is affected by flow stage changes, and high fluctuating flows can destabilize these habitats, forcing fish to relocate at great risk of predation, excessive energy expenditure, and starvation. High water clarity significantly reduces movement by humpback chub, possibly affecting feeding and suggesting use of turbidity as cover [*Valdez and Ryel*, 1995]. This underscores another negative effect of lowered suspended sediment in Grand Canyon.

Backwaters in Grand Canyon are used extensively as nurseries by young of both native and nonnative fishes, and as rearing and holding areas by small forms such as native speckled dace and nonnative fathead minnows and red shiners [*Arizona Game and Fish Department*, 1997]. Backwaters are not extensively used as nurseries by young humpback chub, flannelmouth suckers, and bluehead suckers in less regulated reaches of the upper basin [*Valdez* *and Wick*, 1983], primarily because the fish are hatched shortly after the peak of runoff, before sand bars that form these backwaters are exposed by receding flows. The strong interdependence of Colorado squawfish and backwaters in the upper basin results from fish hatching in late summer when backwaters are available. Backwaters in Grand Canyon, however, are important because their temperatures are slightly higher than water moving downstream. Because the mainstem is consistently cold and backwaters are available under most interim flows, backwaters serve as thermal refugia for fish by entraining water and allowing warming from solar radiation. Although the warm, sheltered water attracts fish and results in high primary and macroinvertebrate production, high water clarity in the presence of predators often precludes daytime use by many fishes. Hence, except when turbidity is high, many fish use backwaters transiently. During periods of high sediment input and low fluctuating flows, however, backwaters can become filled with sediment. Periodic high controlled releases can increase water velocities through eddy return channels and flush these sediments, restoring capacity and reinitiating productivity in backwaters.

Humpback chub evolved in an environment of exceptionally large floods with high sediment concentrations. Controlled high releases from Glen Canyon Dam are not expected to significantly affect their survival, behavior, or status. Floods may improve the habitat of native fishes by increasing turbidity, restoring backwater space and productivity, redistributing nutrients, and importing a large mass of terrestrial organisms and debris used as food by these fishes. In the post-dam river, floods will temporarily scour large amounts of moribund *Cladophora* and possibly reduce available food supplies for a short time to both native fishes and nonnative trout in the dam tailwaters. *Cladophora* has proven to be resilient and the associated macroinvertebrate assemblages recover quickly, often exceeding pre-flood densities, following floods.

## 5. CONCLUSIONS FROM THE GLEN CANYON ENVIRONMENTAL STUDIES PROGRAM

The following conclusions were drawn from scientific studies completed under the GCES program:

1. Despite blockage of most sediment that formerly entered Grand Canyon by Glen Canyon Dam, most researchers concluded that sediment input from tributaries downstream from the dam was being stored on the channel bed or in eddies by most dam releases because of the reduced sediment-transport capacity.
2. *De facto* flood control resulting from dam operations prevents deposition of sand on high-stage bars and reworking of debris fans. The absence of floods, therefore, is a disturbance to pre-dam geomorphic processes.
3. The results of sand-bar monitoring during the research flows, designed to determine the effects of various fluctuating releases, were inconclusive, in part because antecedent conditions were not properly analyzed.
4. Encroachment of riparian vegetation on sand bars used as campsites was almost as important as erosion in reducing usable campsite size.
5. Some debris fans have aggraded because of continuing tributary debris flows and reduced flood frequency in the Colorado River. Debris flows erode or bury existing sand bars, and aggradation affects navigability of rapids and minimizes deposition of replacement sand bars.
6. Riparian vegetation, much of it nonnative but valued as wildlife habitat, was encroaching and filling backwaters and marsh areas that support dam-related biota.
7. During many flows, sand moved from emergent sand bars to the eddies, thereby filling backwater aquatic habitats.
8. Clear, cold water changed the trophic structure of the aquatic ecosystem from a heterotrophic to an autotrophic system dominated by *Cladophora*, which supports *Gammarus*, now a major food source for native and nonnative fishes.
9. Native fish populations, already seriously threatened or endangered by introductions of nonnative species and blockages of migration routes, can no longer spawn in most of the mainstem, placing increasing dependence on seasonally warmed tributaries.
10. Maximizing the rainbow trout fishery and the endangered populations of humpback chub may be mutually exclusive because of their strongly contrasting life-history strategies and reproduction requirements.

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R.H. Webb, U.S. Geological Survey, 1675 W. Anklam Road, Tucson, AZ 85745; email: rhwebb@usgs.gov

D.L. Wegner, Ecosystem Management International, P.O. Box 23369, Flagstaff, AZ 86002

E.D. Andrews, U. S. Geological Survey, 3215 Marine St., MS-458, Boulder, CO 80303-1060

R.A. Valdez, SWCA, Inc., 172 W. 1275 S., Logan, UT 84321

D.T. Patten, Department of Plant Biology, Box 871601, Arizona State University, Tempe, AZ 85287-1601