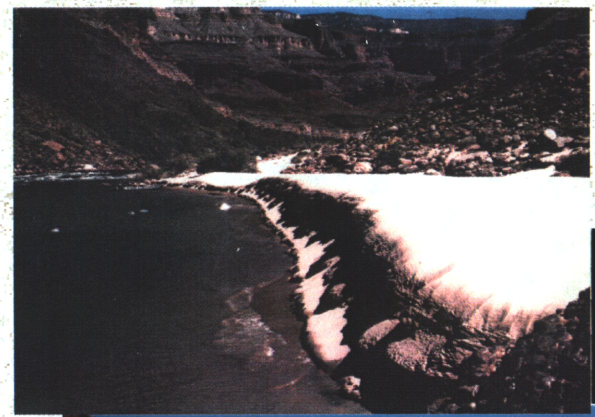
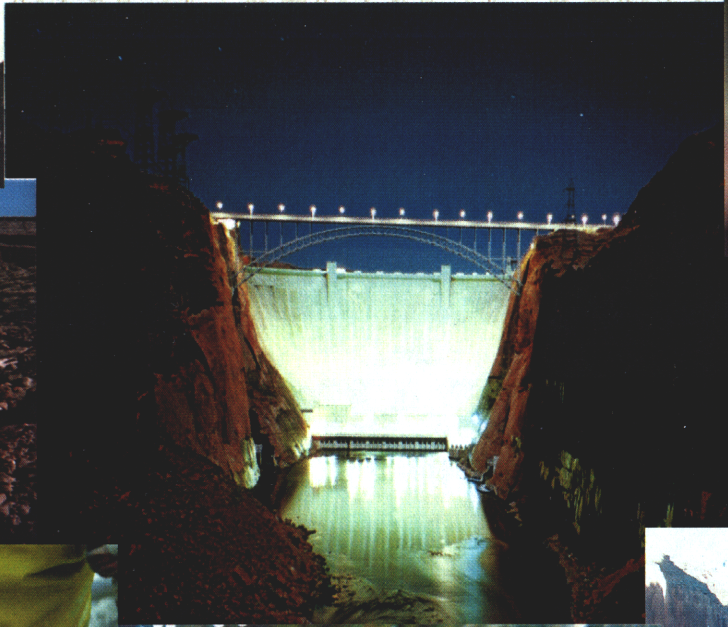
Grand Canyon Monitoring and Research Center

Science Advisors River Trip

Briefing Book

Sept. 29 – Oct. 8, 2001





USGS
science for a changing world

Note: River trip was originally scheduled for Sept/Oct 2001. Postponed due to 9/11/01 event.
This trip actually took place April 6-13, 2002 (same briefing book used.)

Purpose and Layout of this Booklet

The intent of this booklet is to provide an overview of the programs currently funded through Grand Canyon Monitoring and Research Center (GCMRC), the mechanisms at hand at GCMRC to facilitate data collection, management and delivery, and an idea of the processes involved in data collection associated with resource monitoring.

As you travel downstream, you will be exposed to sites that are associated with different monitoring or research projects. The staff from GCMRC will be on hand to provide you information about the research, but you are encouraged to read the summary documents for a better understanding of the overall goals of the monitoring or research projects. By doing so, you will gain a better understanding of why particular areas in the Grand Canyon may be monitored more intensively than others.

As you float down the river, you should also remember to have fun, relax and enjoy yourself, and remember that the AMP was established as a consensus-based program to study the "...effects of the Secretary's actions" on the downstream resources. The intent is that managers could use this information to recommend appropriate changes in dam operations, if needed.

Acknowledgements

Many thanks to Carol "Fritz" Fritzinger (GCMRC Logistics Coordinator), and Jacob "Jake" Tiegs (GCMRC Warehouse Tech) for handling the logistics and gear needs of this trip. Also, thanks in advance to the Humphrey Summit Support crew: Jeff Behan, Kirk Burnett, Steve Jones, Lynn Roeder, Rachel Schmidt, and Harlan Taney for getting us down the river safely and cooking up some great meals.

Photo credits include: Helen Yard (Flycatcher), Bill Vernieu (Anasazi Granary), Larry Stevens (Kanab Ambersnail), Lisa Kearsley (beaches). Other photographs were obtained from GCMRC holdings.

Science Advisors River Trip
Briefing Book

Table of Contents

Cover Photos (clockwise from top left): Owl Eyes – before 1996 BHBF (RM 134.6L); Southwestern Willow Flycatcher; Humpback Chub; Anasazi Granary; Kanab Ambersnail; Rainbow Trout; Owl Eyes – after 1996 BHBF; Glen Canyon Dam

Section 1
Trip Agenda and Overview

PARTICIPANT LIST

GCMRC SCIENCE ADVISORS – 2001

DR. JILL S. BARON (Riparian Ecology) – US GEOLOGICAL SURVEY, BRD

DR. VIRGINIA H. DALE (Statistics) – OAK RIDGE NATIONAL LABORATORY

DR. LANCE H. GUNDERSON (Adaptive Management) – EMORY UNIVERSITY

DR. DAVID HULSE (Geographic Information Systems) – UNIVERSITY OF OREGON

DR. JAMES F. KITCHELL (Fisheries) – UNIVERSITY OF WISCONSIN

DR. JOHN B. LOOMIS (Socio-Economics) – COLORADO STATE UNIVERSITY

DR. RANDOLPH S. PARKER (Hydrology) – U.S. GEOLOGICAL SURVEY, WRD

DR. DALE M. ROBERTSON (Limnology) – U.S. GEOLOGICAL SURVEY, WRD

DR. DOUGLAS W. SCHWARTZ (Archaeology) – SCHOOL OF AMERICAN RESEARCH

DR. JOE WATKINS (Anthropology) – BUREAU OF INDIAN AFFAIRS

Currently Unassigned Resource Areas:

Aquatic Ecology

Geomorphology

Science Advisors Resource Orientation River Trip
September 26 - October 8, 2001

Daily Agenda

Tuesday, 9/25

A.M. - 8:00:	Crew loads gear at GCMRC warehouse
P.M. - 12:00:	Truck departs for Lee's Ferry to rig boats

*(Participants starting the trip at Lee's Ferry arrive in Flagstaff, spend the night at Amerisuites)

Wednesday, 9/26

A.M. - *6:00:	Participants starting the trip at Lee's Ferry leave Flagstaff in van (pick-up at Amerisuites)
*8:30:	Van arrives at Lee's Ferry, finish loading boats
9:00:	Boats depart downriver
P.M. - 12:00:	Lunch
5:30:	Arrive at camp (North Canyon - 24 ½ Mile)
6:30:	Dinner
7:30:	Evening discussion around the campfire

Thursday, 9/27

A.M. - 6:00:	Coffee
6:30:	Breakfast
7:30:	Boats depart downriver
P.M. - 12:00:	Lunch
5:30:	Arrive at camp (Buck Farm - Saddle Canyon)
6:30:	Dinner
7:30:	Evening discussion around the campfire

*schedule for participants starting trip at Lee's Ferry
**schedule for participants starting trip at LCR

Friday, 9/28

A.M. - 6:00:	Coffee
6:30:	Breakfast
7:30:	Boats depart downriver
P.M. - 12:00:	Lunch
5:30:	Arrive at camp (LCR - 60 Mile)
6:30	Dinner
7:30:	Evening discussion around the campfire

**(participants starting the trip at LCR arrive in Flagstaff, dinner on your own, spend the night at Amerisuites)

Saturday, 9/29

A.M. - 6:00:	Coffee
**6:00:	Vans pick up participants starting the trip at LCR at Amerisuites Drive to Salt Trailhead (continental breakfast in vans)
6:30:	Breakfast
7:30:	Boats depart downriver (to LCR)
**8:00:	Helicopter meets vans at Salt Trailhead for shuttle to Boulders Camp on LCR
**10:00:	All participants shuttled to Boulders Camp, hike to confluence to meet boats
10:00:	Discussions at LCR: Native Fish, Tribal Perspectives, Tributary Debris Flows in LCR and Access to Spawning Habitat
P.M. - 12:00:	Lunch at LCR
12:30:	Continue Discussions at LCR if more time is needed
2:00:	Depart downriver for Palisades
2:30-4:30	Discussions at Palisades: Erosion and Mitigation, Arroyo Cutting, Cultural Sites and the Possible Effects of a BHBF
4:30:	Depart downriver
5:00:	Arrive at camp (Palisades -Tanner)
5:30:	River/Camp Orientation
6:30:	Dinner
7:30:	Evening discussion around the campfire: Sediment Storage and Budget

*schedule for participants starting trip at Lee's Ferry
**schedule for participants starting trip at LCR

Tuesday 10/2

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	8:00:	Morning discussion (optional)
	10:00:	Depart Downstream
	10:15-11:00:	Shinumo Creek
P.M. -	12-12:30:	Lunch
	2:00-3:30:	Elves Chasm, discuss Kanab Ambersnail
	5:00-5:30:	Arrive at camp (Forester)
	6:30:	Dinner
	7:30:	Evening Discussion around the campfire: Vegetation/Integrated Terrestrial Resource Monitoring, Channel Margin Surveys

Wednesday, 10/3

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	8:00:	Morning discussion (optional)
	10:00:	Depart downstream
	10:30:	Randy's Rock, Discussion: Humpback Chub Issues
P.M. -	12-12:30:	Lunch at Stone Creek
	1:00-3:00:	Tapeats Creek
	5:00-5:30:	Arrive at camp (Owl Eyes)
	6:30:	Dinner
	7:30:	Evening discussion around the campfire: Experimental Flows

Thursday 10/4

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	8:00:	Morning discussion (optional)
	10:00:	Depart downstream
P.M. -	12:00-3:30:	Lunch at Kanab Creek, discussion: Native Fish and Aquatic Foodbase
	3:30:	Depart downstream
	5:00-5:30:	Arrive at camp (Ledges)
	6:30:	Dinner
	7:30:	Evening discussion around the campfire: Native Fish

Sunday, 9/30

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	8:00:	Morning discussion (optional)
	10:00:	Depart downstream
	10:30-11:00	Discussion at Cardenas: Remote Sensing
	11:00:	Depart downstream
	11:30-2:30:	Lunch and Tour of Unkar Delta
P.M. -	2:30:	Depart downriver
	5:00-5:30:	Arrive at camp (Grapevine - Cremation)
	6:30:	Dinner
	7:30:	Evening Discussion around the campfire: Remote Sensing

Monday, 10/1

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	7:30:	Early departure for Phantom Ranch
	9:00:	Arrive Phantom Ranch
	9-11:30:	Discussion: Brown Trout and Native vs. Non-native Issues at Bright Angel Creek
	11:30:	Depart downstream
P.M. -	12-12:30:	Lunch
	5:00-5:30:	Arrive camp (Bass - 110 Mile)
	6:30:	Dinner
	7:30:	Evening Discussion around the campfire: Camping Beaches and Recreational Issues

Friday 10/5

A.M. - 6:00:	Coffee
6:30:	Breakfast (packed black bags required)
8:00:	Morning discussion (optional)
10:00:	Depart downstream
11:30-2:30:	Lunch and hiking at Havasu
P.M. - 2:30:	Depart downstream
5:00-5:30:	Arrive at camp (Fern Glen)
6:30:	Dinner
7:30:	Free social evening around the campfire

Saturday, 10/6

A.M. - 6:00:	Coffee
6:30:	Breakfast (packed black bags required)
8:00:	Morning discussion (optional)
10:00:	Depart downstream
P.M. - 12:00-1:00:	Scout, run, pictures at Lava Falls
1:00-2:00:	Lunch below Lava Falls
2:00:	Depart downstream
5:00-5:30:	Arrive camp (194 Mile)
6:30:	Dinner
7:30:	Evening discussion around the campfire: Debris Flows, Integration and Ecosystem Science Perspectives

Sunday, 10/7

A.M. - 6:00:	Coffee
6:30:	Breakfast (packed black bags required)
8:00:	Morning discussion (optional)
10:00:	Depart downstream
P.M. - 12-12:30:	Lunch (Goodding's Willow, 209 Mile) Discussion: Traditional Cultural Properties (TCPs); Co-management of Resources
5:30:	Arrive camp (220 Mile)
6:30:	Dinner
7:30:	Closing Comments and discussion around the campfire: AMP Process, Strategic and Science Planning, Adaptive Management

Monday, 10/8

A.M. -	6:00:	Coffee
	6:30:	Breakfast (packed black bags required)
	7:30:	Depart for Diamond Creek
	9:00:	Arrive at Diamond Creek, Take-out vehicles meet trip, unload and de-rig Boats, load trucks
	11:30-12:00:	Lunch @ Diamond Creek
P.M. -	12:00:	Depart Diamond Creek
	3:00:	Arrive Flagstaff, clean-up trip at GCMRC Warehouse

VISITING ARCHAEOLOGICAL SITES
at Grand Canyon National Park

As you hike in the Grand Canyon you may be lucky enough to come across remnants of cultures from long ago. You may see evidence left by people early in this century, miners perhaps, or remnants of prehistoric and historic Native American inhabitants, dwellings for example, or pictographs, petroglyphs, and potsherds.

These ruins and artifacts are a precious legacy. It is the mission of the National Park Service to preserve these special places. You can help us by observing our House Rules.

Thank you! The Management

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1. Keep your feet off the furniture.

Due to their age, archaeological sites are very fragile. Walls crumble and topple easily. Walk carefully and avoid stepping on walls, artifacts, and easily eroded slopes.

2. Don't eat in the living room.

Avoid picnicking in archaeological sites. Crumbs attract rodents who may then nest in the site. Pick up and carry out all of your trash and garbage.

3. No slumber parties.

Do not camp in ruins or on archaeological sites. These sites are extremely fragile. Your inadvertant activities will damage these wondrous places.

4. Don't touch the paintings.

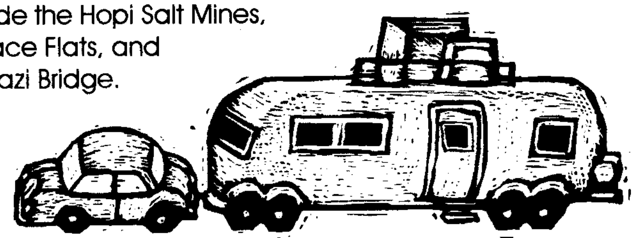
Oils from human skin damage pictographs and petroglyphs. Never deface this artwork by adding your own. These irreplaceable masterpieces are easily destroyed. (And besides that, it's illegal!).

5. Don't pee in the parlor—or any other room.

Pa-leese! I mean really! Why would anyone think this was acceptable behavoir? Your mom would be REALLY mad if you did this at home.

6. Don't go if you're not invited.

Due to their extreme fragility and their importance to Native Americans, a number of archaeological sites along the Colorado River are closed to visitation. These include the Hopi Salt Mines, Furnace Flats, and Anasazi Bridge.



7. Don't rearrange the furniture or mess with the knicknacks.

Leave everything right where you found it. Out of context, artifacts mean little to archaeologists. Leave artifacts for others to enjoy just as you have. (Remember, it's illegal to collect any artifact or natural object from a National Park. And we wouldn't want you to get in trouble with your mom.)

8. Tell mom if you see anything wrong.

Contact a ranger if you find archaeological sites defaced or if you witness someone removing artifacts. Call (520)-638-7767 to report an incident.

NOTES ON CULTURE AND HISTORY ALONG THE COLORADO RIVER THROUGH GRAND CANYON

Mile	Comments
0	Lees Ferry Historic District; site of original ferry crossing - 2 sites, upriver during high water, downriver during low water (winter). Numerous buildings reflect many different uses from a trading post (referred to as Lees Fort) to USGS buildings (mainly from the 1920's). Upstream and underwater are the remains of the Charles Spencer, the only boat in Arizona listed on the National Register. This area is administered by Glen Canyon NRA. GRCA begins at the confluence of the Colorado River and the Paria.
	Just downstream of the launch ramp, note the cable across the river. It marks the official dividing line between the Upper and Lower basins for water allocations.
	River left, at the rim, is Navajo Nation land (DOI and Navajo have ongoing dispute as to the location of the boundary).
12	Just below Soap Creek on the left, at Salt Water Wash, is a small inscription pecked into the rock face just above the river in a small eddy. The inscription reads: FMBrown, Pres DCC&PRR was drowned, July 10 1889 opposite this point. Frank Mason Brown, President, Denver Colorado Canyon and Pacific Railroad Company, ... Brown was the financier for an ill-fated expedition directed by Robert Brewster Stanton who was surveying for the construction of a railroad along the river. The man who carved the epitaph, Peter Hansbrough, drowned 2 days later, with Henry Richards, in 25-Mile rapid.
31.5	South Canyon: Series of Puebloan ruins on terrace above river. Rooms first noted in 1953 by Walter Taylor. Occupation ca. A.D. 800 - 1050. One large ss boulder containing numerous petroglyphs adjacent to largest habitation room. Many of the glyphs are recognizable as Hopi clan symbols. Trails lead visitors to most of the rooms. Access onto limestone terrace is through notches in 2 separate locations. Just look for footprints up through the sand (or mud). The skeleton shown in the river guide was likely an Anglo. The skull was taken in 1934; other parts taken over the years so that virtually nothing remains.

Just downstream of South Canyon is Stanton's Cave, famous for considerable research conducted on the split-twig figurines. The figurines, dates ca. 2500 B.C., were found in this cave, and many others in the Redwall limestone throughout the park. Excavations in the 1960's by RC Euler recover over 100 figurines, primarily on the surface of the cave. Under the surface, however, were the remains of driftwood and extinct animal bones dated to 43,000 BP. The cave is called Stanton's Cave because Stanton purportedly hauled his boats and equipment up into the cave after the first 3 men died on his 1889 trip. He returned to the canyon in early 1890 to resume his survey efforts.

32 Vasey's Paradise, a spring which flows out from the Redwall. Watch out for poison ivy. Also an endangered snail lives here so stay at river level. Vasey's shows up in Hopi history as the place the Spanish priests forced some Hopi men to travel to for fresh water.

40 Marble Canyon Dam site: the beginning of the modern environmental movement after the loss of Glen Canyon and the saving of Echo Park. One of the few places Reclamation planned to build a dam and didn't. Everything you have come through would have been underwater had the dam been built.

43 Look high up on the right for the remains of a wooden bridge across a crevice in the limestone. Part of a cross-canyon route. The bridge is made of driftwood logs of cottonwood, C-14 dates 770/850 AD. Sites located across from the bridge on river left at the talus top and above the bridge along the route to the top of the Redwall. The route on the other side of the river is through Eminence Break, located just downstream on river left.

43.8 Two Anglo graves located on beach just below rapid on left; Peter Hansbrough of the Stanton survey and a boy scout, David Quigley, who drowned in Glen Canyon in 1951. Why both bodies washed up here is a mystery.

52 Nankoweap, one of the most beautiful places along the river. Considerable Puebloan occupation, PI-PII, both on the delta and up the canyon all the way to the North Rim. The view from the granaries is spectacular. They have been stabilized; one room rebuilt after visitors destroyed the front wall in 1980.

56 Kwagunt, another lovely place. A fault, the Butte fault, connects Nanko and Kwagunt up the drainage. Great place to live 1000 years ago. Both places named for Paiutes by John Wesley Powell.

61.5 Little Colorado; TCP for Hopi, Zuni and Navajo for various reasons. The Hopi place of emergence, the Sipapu, is located 5 miles up the LCR. They believe that not only did they as a people emerge from the Sipapu, but their spirits return there upon death. Also, part of the migration path to the Salt Mines, located just downstream on river left.

For the Navajo, the confluence represents the joining of the sacred male and female beings that mark the boundary of Navajo ancestral lands.

For Zuni, the rivers, along with the Zuni River, form an umbilical cord which connects them to their place of origin.

Just upstream on the leftbank of the LCR is a stone cabin attributed to a miner named Ben Beamer. The cabin is built of materials from an earlier dwelling, which is built on a midden which dates back to the Archaic. Over 2 meters of midden exist underneath the cabin. You'll note considerable manipulation of the trails and erosion channels in an attempt to preserve the deposits. Faint pictographs visible on cliff/overhang on downstream side of cabin.

64.5-65.5 Carbon Creek to Lava Canyon; really nice hike up one canyon and down the other. Connected by the Butte fault. Really interesting geology.

65.5 Palisades Delta; Remains of the Tanner-McCormick mine visible from the river (tailings); old cabin site also. Very fragile sediment deposits.

71 Cardenas Creek/Camp; high on the ridge above the camp is a structure referred to as Stanton's Fort or Cardenas Fort (AZ C:13:2). First photographed by Stanton in 1890, the structure has been interpreted by Hopi as a men's society room. No archeo-astronomy at the site (we've checked). The few sherds located suggest A.D.1175 date.

72.5 Unkar Delta (see brochure)

76.5 Hance! Big ride and the beginning of the gorge. Note the fire damage on the terrace above the river from a campers fire this past May. We lost most of the original Hance camp. Hance also had an asbestos mine just downstream and up; you can see the tailings from the river.

87.5 Just above the boat beach at Phantom, Bright Angel Site, excavated by School of American Research in late 1960's. See wayside exhibit. Lots of archaeology up Bright Angel Canyon up to the North Rim, primarily Puebloan (PII).

107.4 On river left, remains of metal boat, the Ross Wheeler, abandoned in 1915. We had to chain it to the rocks after someone tried to steal it about 8 years ago. Downstream, on river left, you can see the remains of the original cable car Bass had across the river which delivered his tourists from the south side to the north side. See photo of the hanging horse in the Belknap guide.

108.5 Shinumo Creek enters just downstream of the camp. The terraces above the camp contain numerous archaeological sites, all probably connected with the occupation sites in the creek and up to the North Rim. Additionally, the terrace above the river was to be the switchyard for Stanton's railroad. Also, Wm Wallace Bass had a tourist camp up the drainage, most of the remnants are still visible a few miles up Shinumo Creek. Great place for a layover so you can dayhike in Shinumo (the North Bass trail). Trails lead from the camp up and over the ridgeline into the drainage. Bass also had an asbestos mine in the next canyon downstream (Hakatai).

116.5 Elves Chasm; beautiful waterfall and pools

120 Blacktail; beautiful, quiet slot style canyon

132 Stone Creek, just below Deubendorf rapid on the right. Lovely side canyon with 4 main water falls. Great place for a layover.

133.8 Tapeats Creek; nice hike up to Thunder River. Lots of water and you can hike all the way to Deer Creek if you want across Suprise Valley.

136.3 Deer Creek; great hike up above the falls; watch out for the poison ivy (you'll see it). Once on top of the Tapeats ss, the trail will take you into Deer Creek narrows. Watch for hand-prints, both positives and negatives, along the cliff on both sides of the drainage. Once the canyon opens up above the "jacuzzi", no more prints. Nice hike up to the spring also.

148	Matkatamiba Canyon; if you can get in, well worth it. Quiet, fluted, etc...
156.5	Havasu. Worth the stop even if lots of boats there.
178	Vulcan's Anvil; basalt plug that sticks up from the river is considered to be sacred to Hualapai and Southern Paiute. Just above Lava Falls
188	River right, pictographs at talus top just above river along with historic graffiti from the dam building era (Bridge Canyon Dam).

Culture and History Notes courtesy of: Jan R. Balsom
Cultural Resource Manager
Grand Canyon National Park

Section 2
Background

A BRIEF HISTORY OF THE COLORADO RIVER ECOSYSTEM

Lawrence E. Stevens

Geography and Impoundment History

The Colorado River is the primary river system in the American Southwest, draining one twelfth of the coterminous United States. It has the highest ratio of reservoir storage to mean annual flow of any large river basin in North America, making it one of the most thoroughly controlled American rivers. It is dammed by more than 40 large flow regulation structures. The river flows 472 km through northern Arizona between Glen Canyon Dam and Lake Mead, including lower Glen Canyon and all of Grand Canyon. River locations are designated by distance from Lees Ferry, Arizona (river kilometer, km 0), which lies 24.5 km downstream from the dam. The river descends from an elevation of 947 m at Lees Ferry to 404 m elevation at Diamond Creek (km 363), with a mean gradient of 1.52 m/km and with most of its descent occurring in more than 165 whitewater rapids. The river is deeply incised into the uplifted Colorado Plateau, and it flows through Sonoran and Mohave desert scrub vegetation. Mean annual precipitation on the canyon floor is 215 mm/yr, bimodally distributed between winter and summer.

Geomorphology

The Colorado River is a debris fan-dominated river constrained by talus slopes and cliffs of Proterozoic and Paleozoic bedrock strata, including resistant sandstones, limestones, igneous and crystalline strata, as well as softer shales and siltstones. Variation in bedrock hardness causes variation in channel width-to-depth ratio, channel slope, and valley width. These characteristics allowed Schmidt and Graf (1990) to divide the Grand Canyon into 11 geomorphic reaches. The characteristic channel unit in eddy-dominated rivers is the debris-fan eddy complex.

Channel width is intermittently narrowed by debris fans, rockfall or landslides, and most of the river's drop in elevation occurs in these sections. Immediately downstream from constrictions, channel width abruptly increases and large recirculating eddies exist. Downstream from this expansion, the channel narrows slightly and depth decreases over a gravel or cobble bar creating distinctive wide-shallow and narrow-deep geomorphic reaches. The uppermost Glen Canyon reach is wide (mean width >85 m); 2 wide and 2 narrow (<85 m wide) reaches occur in Marble Canyon between the Paria River (km 1) and the Little Colorado River (km 98) confluences; and the Grand Canyon section between km 98 and Lake Mead contains 3 wide and 5 narrow reaches. The number of sandbar deposits and fluvial marshes, and the percent cover of soft *versus* firm substrata on the channel bed, are positively correlated with reach width. Debris-fan eddy complexes exist at more than 530 tributary confluences, each creating spatially fixed and geomorphically distinctive pool, riffle and sometimes *return current channel* (RCC; backwater) habitats.

Fine-grained Alluvial Deposits in Eddy-dominated Rivers

Fine-grained (less than 2 mm) alluvial deposits develop at sites where velocity is lowest, particularly in eddies and at channel margins adjacent to wide, low-gradient reaches. Channel constrictions, especially tributary debris fans, control flow separation and thereby control velocity and fine-grained sediment deposition. As a result, sand bars and other intermittent patches of fine sediment in eddy-dominated rivers do not migrate in the Colorado River as they do in alluvial rivers.

Fine-grained eddy deposits include *separation bars* that form near the upstream end of an eddy, *reattachment bars* that form beneath the primary recirculating eddy cell, and *channel-margin deposits* distributed along through-flowing reaches. The reattachment bar, which is commonly colonized by marsh vegetation, is a sand platform that projects upstream as a spit. The upstream portion of the reattachment bar is separated from the bank by an RCC, a scour feature formed by concentrated, recirculating flow when the bar is inundated. Many reattachment bar platforms are emergent after flood recession, and the RCC becomes an area of stagnant flow. Under normal flows, suspended fine sand and silt derived from tributary flows aggrade in RCC's and are deposited as veneers over coarser mainstream flood deposits. The distribution and characteristics of fine-grained deposits are greatly affected by flow regulation, and sediment transport--including suspended sediment concentrations and particle size distribution.

The Pre-dam Colorado River

The unregulated Colorado River was flood-prone, turbid, and warmed during summer. The mean daily pre-dam flow from 1922 through 1962 was 470.4 m^3/s, with a mean annual flood peak of 2,450 m^3/s, a 10-yr flow return frequency of 3,540 m^3/s, an historic peak flow of 8,500 m^3/s, and a paleoflood peak flow of 14,000 m^3/s. The river transported a highly variable mean sediment load of 6.0×10^{10} kg/yr past Lees Ferry and was virtually always turbid. Pre-dam water temperature ranged from freezing in winter to 29.4°C in the summer at Lees Ferry, and the river supported a largely endemic, warm-water fish assemblage. Numerous pre-dam photographs reveal little riparian vegetation and little benthic algal cover on rocks during low flows, suggesting that scouring floods limited the colonization and growth of shoreline vegetation and benthic macroalgae. Virtually no data are available on the fish community structure or benthos in the river prior to impoundment.

The Post-dam Colorado River

The 200 m-high Glen Canyon Dam was completed in 1963, creating Lake Powell reservoir and regulating the Colorado River. Lake Powell reservoir is the second largest reservoir in the United States. It is estimated that the reservoir with be filled with sediment in 640 years. Construction of this hypolimnetic release dam did not greatly alter the mean daily flow (412.2 m^3/s), but impoundment greatly reduced flood frequency and magnitude, increased hourly varying flow, decreased sediment transport, and created cold-stenothermic conditions. Post-dam river flows from 1965 to 1991 fluctuated widely on an hourly basis but little seasonally. During normal inflow years, the maximum range of daily flows exceeded 750 m^3/s every month of the year. This large range in daily flow approximated the post-dam annual discharge range, and exposed the benthos along the shoreline to daily desiccation. However, flood control has stabilized the river's shorelines, allowing profuse riparian vegetation to develop. This vegetation supports a great diversity of terrestrial vertebrates and invertebrates.

The regulated Colorado River is characterized by "normal flow years" with mean annual flood peaks less than 892 $m^3 \cdot s^{-1}$ and annual flow volumes less than $1.22 \times 10^{10} \cdot m^3$. In "normal flow" years from 1963 to 1991, the range of daily flows sometimes exceeded 790 $m^3 \cdot s^{-1}$ in response to hydroelectric peak power generation, equalling the annual discharge range. Extreme daily discharge fluctuations created "tides" of more than 3 m. Flows two to three times greater than powerplant capacity, and larger annual flow volumes, have occurred during occasional "high flow" years. In high flow years, instantaneous peak discharge at Lees Ferry typically exceeded powerplant capacity but daily discharge variability decreased. High releases occurred in 1965 and during 5 years after Lake Powell filled (1980), but only in 1983 has an annual post-dam flood peak reached mean pre-dam stage. Flows from 1991 through the present have a daily range restricted to between 6,000 and 8,000 cfs/d, and prescribed annual range of 5,000 to 25,000 cfs.

Impoundment reduced sediment transport at Lees Ferry to <1% of pre-dam levels, and mainstream turbidity is now largely determined by tributary-derived suspended sediment contributions. More than 290 ephemeral and 40 perennial tributaries join the Colorado River in Grand Canyon, but only 6 perennial tributaries have mean flows >1 m^3/s. Although the base flow of the Paria River (the most upstream perennial tributary) is only 0.2 m^3/s (<0.002% of the mean mainstream flow), it contributes an average of 2.75 x 10^6 metric tons of suspended sediment/yr, with concentrations of up to 780,000 mg/L. The Little Colorado River annually supplies 3 times more suspended sediment than the Paria River, and Kanab Creek (km 230) provides additional sediment in the lower Canyon. Turbid inflow from the Paria River reduces maximum benthic light availability between km 1 and 98 approximately 70% of the time on an erratic, seasonal basis. Cumulatively, the Paria River, Little Colorado River and subsequent tributaries reduce maximum light availability in the middle and lower Grand Canyon 80% of the time.

Sediment retention by Glen Canyon Dam and the locations of sediment-contributing tributaries have created 3 mainstream turbidity segments: the clearwater segment (the Glen Canyon reach) lies between Glen Canyon Dam and the Paria River confluence; the variably turbid segment includes the 4 reaches between the Paria River and the Little Colorado River in Marble Canyon; and 3) the usually turbid middle and lower Grand Canyon segment includes the seven reaches between the Little Colorado River and Diamond Creek.

The mean and annual variability of Colorado River water temperature at Lees Ferry was reduced from a pre-dam annual range of 0 to 29.4°C to 8 to 12 °C today, through hypolimnetic releases.

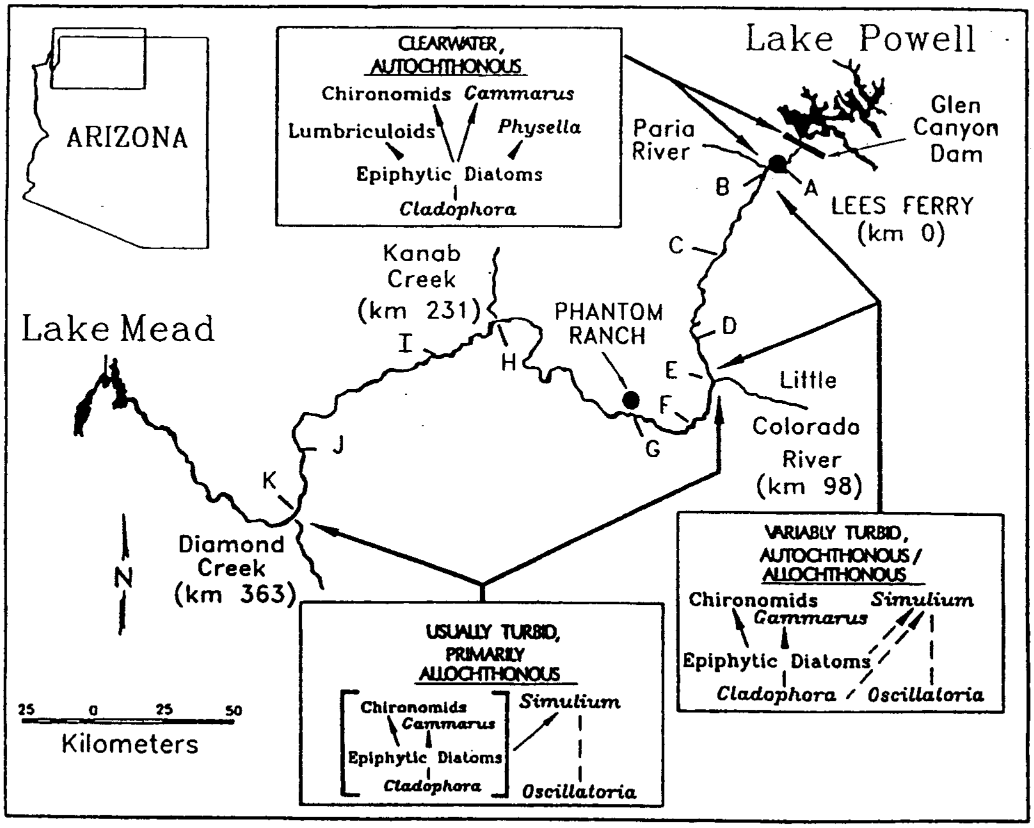
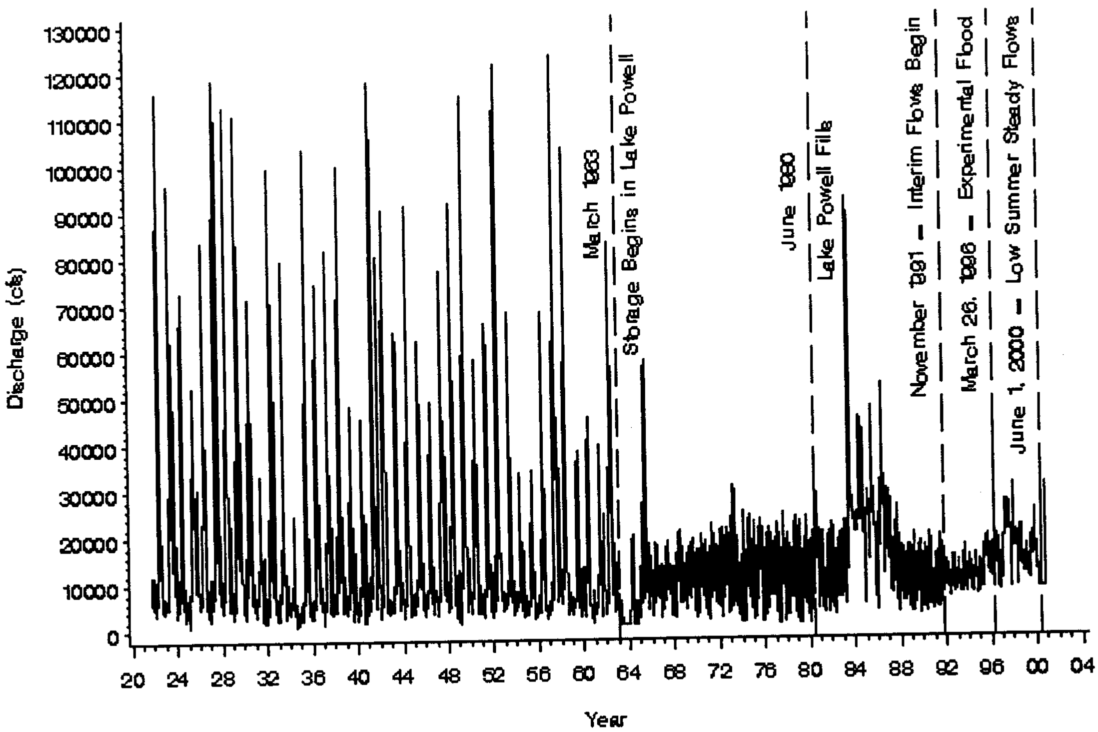


Table I. Study sites in the Colorado River in the Grand Canyon. Study site letters pertain to Figures 1 and 8. Distance (km) is measured from Lees Ferry, Arizona which lies 24·6 km downstream from Glen Canyon Dam. Turbidity segments include the clear water (CW), variably turbid (VT) and usually turbid (UT) segments. Reach names have been modified from Schmidt and Graf (1990) and reach width was measured at 680 m^3/s by Schmidt and Graf (1990). Sample size is six for all water quality parameters at each site

Site	Distance from Lees Ferry (km)	Turbidity segment	Reach number (Figure 8) and name	Mean reach width (m)	Elevation (m AMSL)	Mean DO (mg/l) (mg/l; SD)	Mean specific conductivity (μS; SD)	Mean temp. (°C; SD)	Mean pH (SD)	Mean Secchi depth (m; SD)
A	0	CW	1. Glen Canyon	85·3	947	8·1 (1·16)	0·91 (0·02)	9·2 (2·20)	7·7 (0·19)	5·35 (1·01)
B	3	VT	2. Permian Gorge	70·0	940	8·3 (1·38)	0·90 (0·04)	9·6 (2·17)	7·8 (0·34)	4·30 (2·12)
C	50	VT	4. Redwall Gorge	67·1	871	10·2 (1·18)	0·79 (0·35)	10·0 (2·92)	7·6 (0·47)	1·02 (1·01)
D	83	VT	5. Marble Canyon	106·7	842	10·7 (0·66)	0·92 (0·04)	10·5 (2·38)	8·0 (0·26)	1·05 (1·15)
E	98	VT	5. Marble Canyon	106·7	821	10·5 (0·42)	0·94 (0·05)	10·8 (2·07)	7·9 (0·28)	1·38 (1·04)
F	110	UT	6. Furnace Flats	118·9	810	10·6 (0·82)	1·00 (0·06)	10·5 (2·37)	7·9 (0·21)	0·97 (1·36)
G	142	UT	7. Upper Granite Gorge	57·9	734	10·9 (0·20)	1·02 (0·05)	10·8 (2·34)	8·1 (0·13)	1·15 (1·80)
H	232	UT	10. Muav Gorge	54·9	568	10·7 (0·77)	1·01 (0·06)	11·4 (2·42)	8·1 (0·13)	0·37 (0·42)
I	240	UT	11. Lower Canyon Reach	54·9	540	11·0 (0·77)	0·99 (0·05)	10·2 (1·97)	8·2 (0·12)	0·15 (0·03)
J	329	UT	11. Lower Canyon Reach	94·5	450	10·8 (0·28)	0·98 (0·03)	11·6 (3·03)	7·9 (0·30)	0·85 (0·77)
K	352	UT	12. Lower Granite Gorge	73·2	409	11·2 (0·37)	1·00 (0·05)	12·7 (3·97)	8·0 (0·23)	0·20 (0·10)

Historical Flows at Lees Ferry



Recent Glen Canyon Dam Releases

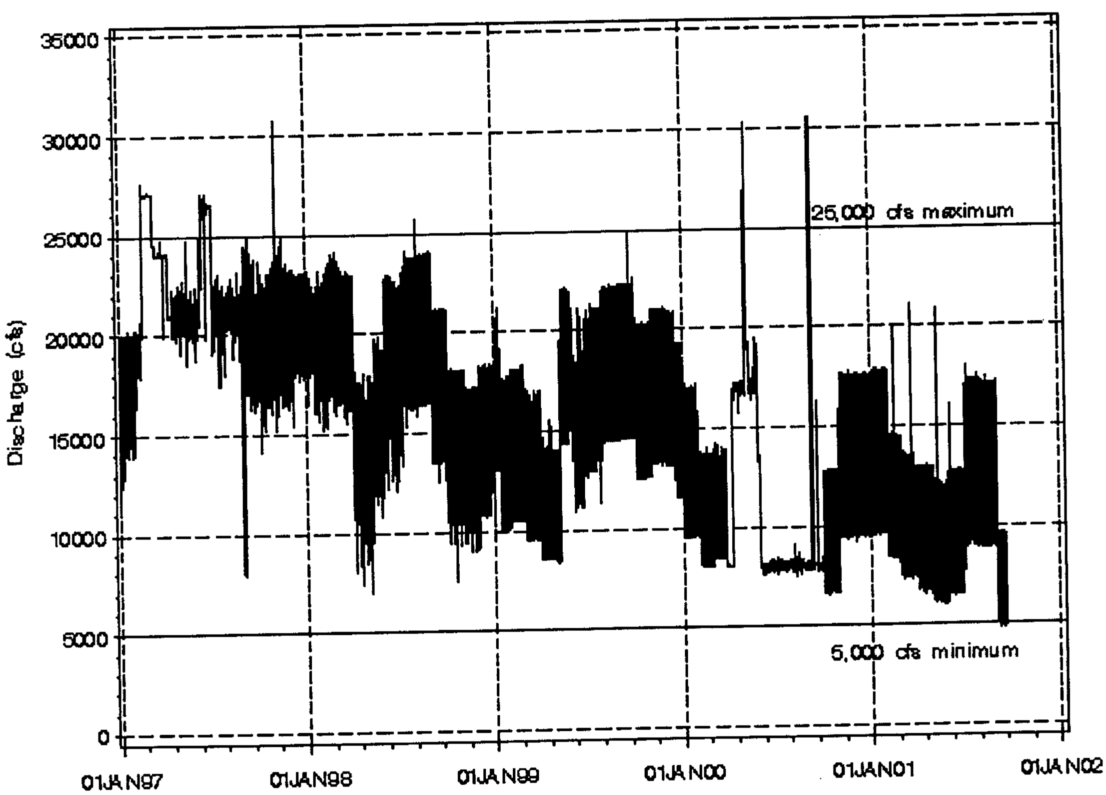


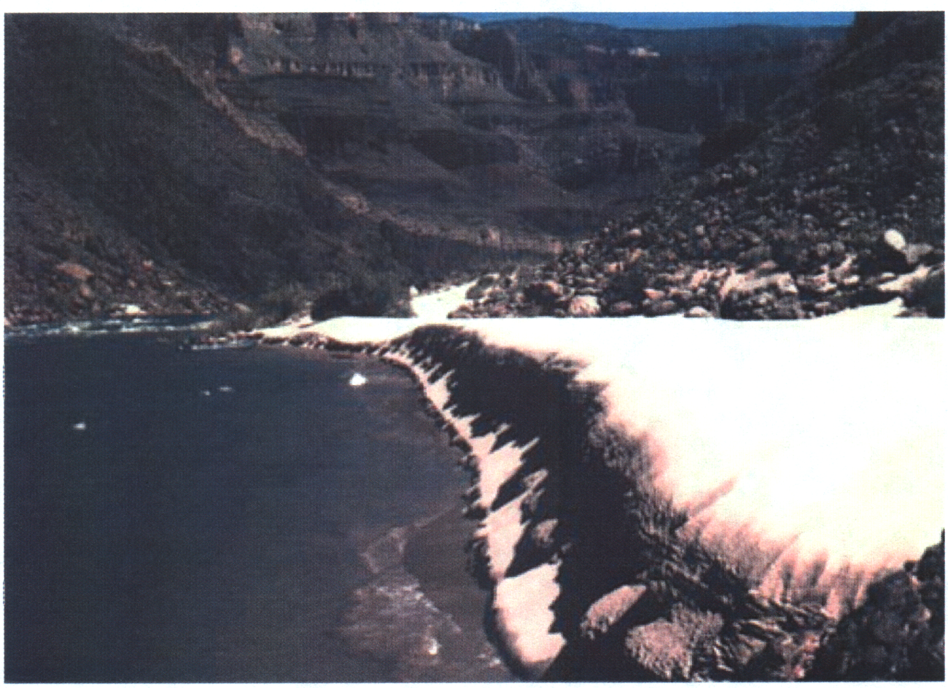
Figure 1. Side canyon flashfloods replenish some of the sediment in the Colorado River through Grand Canyon. (RM14.5.)

Figure 2. Flashflood at 6-Mile Wash.

Figure 3. Flashflood at 6-Mile Wash reaches mainstem Colorado.

Figure 4. Debris fan from flashflood (RM158).

Figures 5 and 6. Owl Eyes camp **before** (3/10/96, above) and **after** (4/28/96, below) the Beach/Habitat Building Flow (BHBF) of 1996.



HISTORY OF DAM-RELATED SCIENCE IN GRAND CANYON

The Colorado River ecosystem that exists within the scope of monitoring and research for the Grand Canyon Monitoring and Research Center (GCMRC) covers approximately 300 river miles and extends from the fore bay of Glen Canyon Dam to the upper reach of Lake Mead. The environments covered include the aquatic environment, the marsh and riparian communities and the terrestrial communities up to the 300,000 cfs stage line. It is a treasury of unique biological and cultural resources and physical processes.

The ecosystem is known to support more than 200 plant and animal species, including 4 fish species that are endemic to the Colorado River, resident and migratory raptors and waterfowl. The corridor also represents the longest undeveloped stretch of riparian habitat in the United States, further adding to the uniqueness of the river corridor. Historic and cultural sites are found in association with biotic communities and geomorphic structures representing past occupation sites, sites of ceremonial importance, or that represent biological or physical resources traditionally used by the tribes.

Since 1983, the Colorado River ecosystem has been the focus of study relating ecosystem change to the operations of Glen Canyon Dam. The principle concern has been dam operations, and specifically, the effects of high fluctuating daily releases to downstream resources including sediment supply, habitat stability, and cultural resource preservation. The Glen Canyon Environmental Studies Phase I found significant impact on the downstream resources as a result of the high daily fluctuations (up to 25,000 cfs) associated with dam releases.

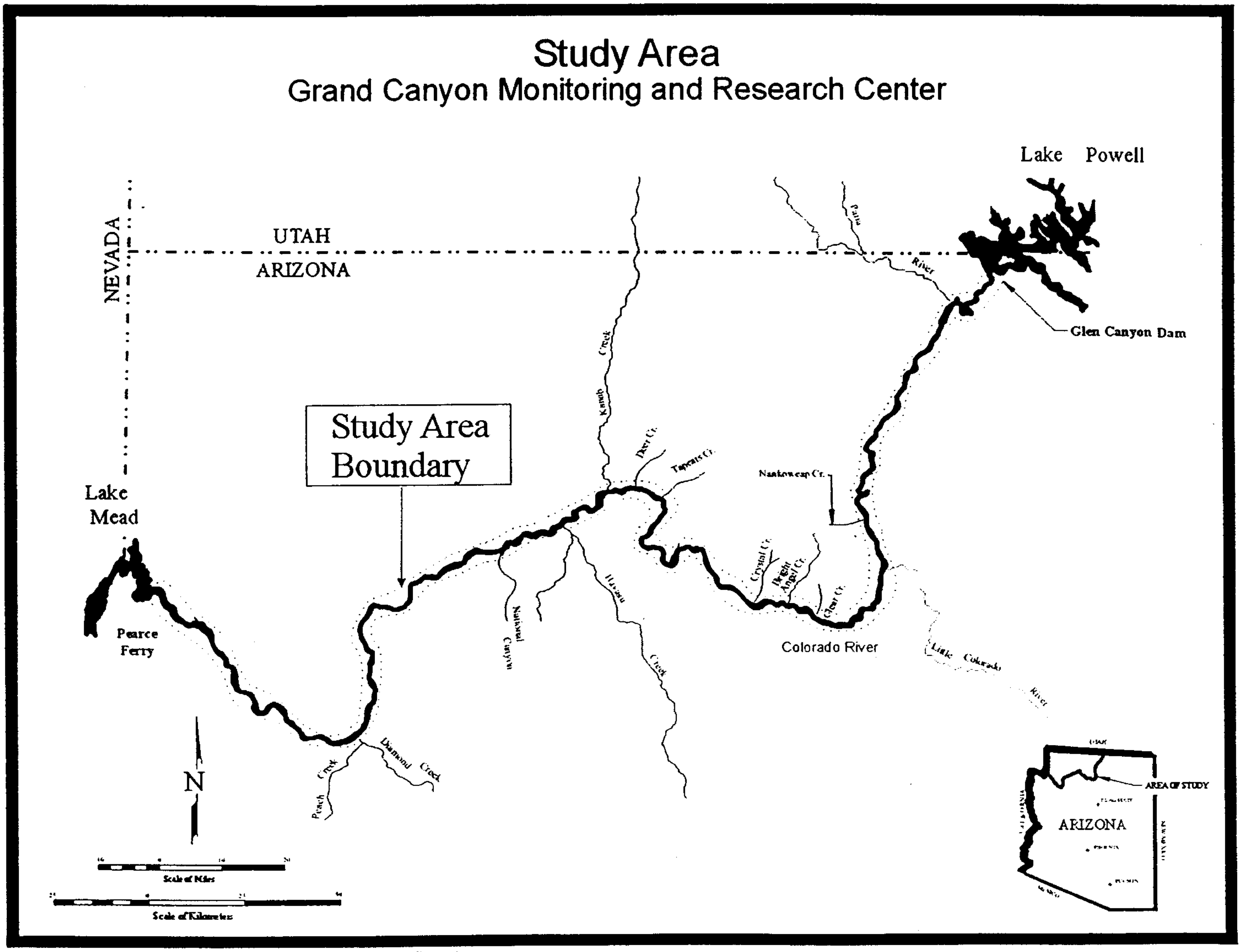
Glen Canyon Environmental Studies (GCES) Phase II (1989-1995) efforts were focused on determining the effects of alternative flow criteria on downstream resources. Associated with this phase was the implementation of research flows in 1990-1991, the signing of the Grand Canyon Protection Act (1992), and the initiation and completion of the Glen Canyon Dam Environmental Impact Statement (1995), and the Beach/Habitat Building Flow in March 1996. These research efforts resulted in the implementation of the modified low fluctuating flow alternative when the Record of Decision was signed by the Secretary of the Interior in May 1996.

Both GCES Phase I and II were programs that were administered by the Bureau of Reclamation. The program was multi-agency in scope, involving tribal, state, federal, university and private interests and investigators. The GCES initiated efforts to develop an integrative science program including geomorphic reach based monitoring sites that included multiple resource monitoring, the development of a GIS database, and the establishment of a library and database to house tabular and hardcopy data.

The record of decision and the GCD-EIS also implemented an Adaptive Management Program for the Colorado River Ecosystem. Included in this program was the institution of a long-term monitoring and research center, called the Grand Canyon Monitoring and Research

Center (GCMRC). The purpose of the GCMRC is to monitor the downstream resources and determine how changes in the quality of these resources may be affected by dam operations. GCMRC is an independent Department of Interior unit that reports directly to the Assistant Secretary for Water and Science. Monitoring and research is funded by the GCMRC through a competitive, peer-reviewed process, with the objective for monitoring projects developed from the stakeholder's management objectives and the Grand Canyon Protection Act. The GCMRC was established in May 1996.

The GCMRC provides information obtained from monitoring and research projects to the Adaptive Management Work Group (AMWG). The AMWG consists of federally appointed representatives of "stakeholders." This "body" uses information provided by the recommendations concerning operations of Glen Canyon Dam to the Secretary for consideration and possible implementation.



Map of Grand Canyon Monitoring and Research Center Study Area.

GLEN CANYON DAM ADAPTIVE MANAGEMENT PROGRAM AND THE GRAND CANYON MONITORING AND RESEARCH CENTER

Barry Gold

Introduction

The Grand Canyon Protection Act of 1992 (GCPA) and the Operation of Glen Canyon Dam – Final Environmental Impact Statement (GCDEIS) directed the Secretary of the Interior to establish and implement long-term monitoring programs and related research and scientific activities that will ensure that GCD is operated in a manner consistent with Section 1802 of the GCPA. The Grand Canyon Monitoring and Research Center was established to facilitate these activities. The mission of the GCMRC is to develop monitoring and research programs and related scientific activities that evaluate short- and long-term impacts of "... the effects of the Secretary's actions ..."[1] on the biological, cultural, and physical resources of the Colorado River ecosystem. The GCMRC is guided in its scientific efforts by the management objectives and information needs specified by the Adaptive Management Work Group (AMWG).

Long-term monitoring of resources of concern has been implemented to detect and quantify changes related to dam operations. Research efforts focus on interpreting and explaining trends, determining causal relationships, and defining inter-relationships among physical, biological and cultural processes. In addition to monitoring and research activities, the GCMRC has developed an information management program to ensure information archiving and transfer to managers, stakeholders, and science organizations.

The physical scope of the research area investigated by the GCMRC is the Colorado River ecosystem, defined as the Colorado River mainstem corridor and associated riparian and terrace zones, located primarily from the forebay of GCD to the western boundary of Grand Canyon National Park, a distance of 293 river miles. The research scope includes limited investigations into some tributaries (e.g., the Little Colorado and Paria Rivers). All projects supported or implemented by GCMRC address determined or potential resource impacts primarily in the Colorado River ecosystem related to dam operations. It also includes, in general, cultural resource impacts of dam operations for inundation levels associated primarily with flows up to approximately 300,000 cubic feet per second (cfs) as addressed in the Programmatic Agreement,[2] and for physical, biological, recreational and other resources, impacts of dam operations for inundation levels associated primarily with flows up to 100,000 cfs. In between these levels, stakeholder concerns with respect to relict vegetation, endangered species, and cultural resources may require activities by the GCMRC.

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[1] As specified in the 1992 Grand Canyon Protection Act, the GCD Environmental Impact Statement (1995), and the Record of Decision (1996). The "Secretary's actions" include dam operations or alternative dam operating criteria as well as other authorized actions; and will be referred to in this document as "dam operations."

[2] The Programmatic Agreement is a legal agreement between federal and state agencies and tribal groups that specifies the responsibilities of the parties to comply with federal historic preservation legislation.

GRAND CANYON MONITORING AND RESEARCH CENTER (GCMRC)

MISSION

To provide credible, objective scientific information to the Adaptive Management Program on the effects of opening Glen Canyon Dam on the downstream resources of the Colorado River ecosystem, utilizing an ecosystem science approach.

ROLES AND RESPONSIBILITIES OF GCMRC

1. Advocate quality, objective science and the use of that science in the adaptive management decision process.
2. Provide scientific information for all resources of concern identified in the "Operation of Glen Canyon Dam Final Environmental Impact Statement."
3. Support the Secretary's designee and the Adaptive Management Work Group in a technical advisory role.
4. Develop research designs and proposals for implementing, by GCMRC and/or its contractors, monitoring and research activities in support of information needs identified by the Adaptive Management Work Group.
5. Coordinate review of the monitoring and research program with independent review panel(s).
6. Coordinate, prepare, and distribute technical reports and documentation for review and as final products.
7. Prepare and forward technical management recommendations and annual reports, as specified in Section 1804 of the Grand Canyon Protection Act to the Technical Work Group.
8. Manage all data collected as part of the Adaptive Management Program. Serve as a repository (source of information) for others (stakeholders, students, public, etc.) in various formats (paper, electronic, etc.) about the effects of operating Glen Canyon Dam on the downstream resources of the Colorado River ecosystem and the Adaptive Management Program.
9. Administer research proposals through a competitive contract process, as appropriate.
10. Manage GCMRC finances and personnel efficiently and effectively.

GCMRC MONITORING AND SCIENCE PROGRAMS

Monitoring and research activities are grouped into terrestrial, aquatic and integrated activities. Remote sensing and information technologies are programs intended to support monitoring and research efforts. Information is provided for resources that have long-term monitoring projects associated with them.

I. TERRESTRIAL ECOSYSTEM ACTIVITIES – terrestrial ecosystem activities include biological and cultural resources, and to some extent, physical resources along the Colorado River ecosystem. For the most part, physical resource data are collected simultaneously for both terrestrial and aquatic resources and appear as integrated activities. Resources of concern with the terrestrial ecosystem are archaeological sites, habitat (vegetation), invertebrates and vertebrates, including socio-cultural components. Long-term goals are to integrate data from these resources with data from sediment budget and transport to understand these interactions.

- Monitoring and inventory of terrestrial resources
- Monitoring Kanab ambersnail populations and habitat at Vaseys Paradise
- Evaluation of cultural resource monitoring and mitigation strategies
- Development of a river corridor research design to evaluate the significance of cultural resource data

II. AQUATIC ECOSYSTEM ACTIVITIES – aquatic ecosystem activities involve primarily biological resources. Many of the programs are undergoing review and long-term monitoring programs are not fully implemented for this area of the research and monitoring program.

- Monitoring the phyto-benthic community
- Monitoring the status and trends of downstream fish community
- Monitoring the status and trends of Lees Ferry trout
- Integrated water quality monitoring

III. INTEGRATED TERRESTRIAL AND AQUATIC ECOSYSTEM ACTIVITIES – integrated activities primarily involve data collection associated with physical components of the Colorado River ecosystem. These activities provide data to other areas with respect to habitat availability and habitat change as it relates to silt, clay, sand, gravel and larger grain sizes.

- Long-term monitoring of fine-grained sediment storage throughout the main channel
- Long-term monitoring of streamflow and fine-sediment transport in the main channel Colorado, Paria and Little Colorado Rivers
- Long-term monitoring of coarse-grained sediment inputs, storage and impacts to physical habitats
- Long-term monitoring of recreational camping beaches

IV. INFORMATION TECHNOLOGY ACTIVITIES – Extensive data and information currently exist in the GCMRC collections relating to the Colorado River ecosystem, resource conditions, quality, and relationships to other resources. Potential equal amounts of data and information exist within museums, universities, agencies, etc. However, much of this information has not been organized, managed or integrated into an analysis of the interrelationship among various resources and dam operations.

The following areas will be implemented in the Information Management Program:

- Development of metadata elements for data collection, processing and use.
- Continued development of extensive multidisciplinary databases and a database management system.
- Development of a geographic information system (GIS) to accommodate multiple layers associated with all resources of interest to stakeholders, including river base map development.
- Development of databases associated with remotely sensed data not presently incorporated in the Glen Canyon Environmental Studies (GCES) database system.
- Development of selected stakeholder interface mechanisms to access data and information in the database management system and GIS.
- Development of an outreach program, including identification and quantification of user needs, to transfer GIS data and information to stakeholders.
- Evaluate remote sensing technologies relative to less intensive and more cost effective methods of monitoring Canyon resources.

The following areas are included in the Information Management Program:

TECHNICAL SUPPORT SERVICES – REMOTE SENSING

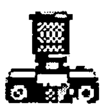
- Data Base Management
- Geographic Information System
- Remotely Sensed Data Collection

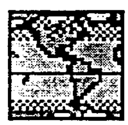
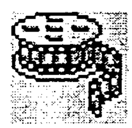
GRAND CANYON MONITORING AND RESEARCH CENTER LIBRARY OVERVIEW

The purpose of the Grand Canyon Monitoring and Research Library is to collect, archive and deliver materials collected on the Glen Canyon Dam and its effects on the surrounding environment. These efforts assist the center in its charge to administer long-term monitoring and research. This information could very well be the template and comparative data that will aid in the protection and management of river systems around the world.

The primary purpose of the library is to ensure that these materials are available to researchers funded through GCMRC. The secondary purpose is to provide non-funded researchers and the general public access to documents that are unique to GCMRC. Incorporated with this second purpose is the education and promotion of the use of materials unique to the GCMRC. An underlying management goal associated with the library is to consolidate, preserve, and organize materials to facilitate effective information delivery.

The GCMRC library holdings include information about resources associated with Glen and Grand Canyons. All of this information is contained in a variety of media types ranging from documents to videotapes to slides. All of this information, no matter what media type, is an invaluable resource to the researchers who work in Glen and Grand Canyons, as well as the general public.




Holdings
Hard copies and electronic copies of final funded research reports.
Reprints of articles resulting from funded research.
Books resulting from research efforts associated with GCMRC.
Books and articles related to Grand and Glen Canyons.
Books and articles related to natural and controlled rivers and environments.
Photographs and slides developed by GCMRC staff (aerial and field documentation).
CD-ROM versions of aerial photographs and slides.
Videotapes (over-flights, and programs related to Glen and Grand Canyons).
Maps (topographic, flight-line maps, Arc/Info Coverages, orthophotographgy).

Section 3
Briefing Papers

Terrestrial Ecosystem Activities

Kanab Ambersnail at Vaseys Paradise, Grand Canyon National Park: 1998 Monitoring and Research

Dr. Vicky Meretsky, Indiana University, and Dave Wegner, Ecosystem Management International, Inc.

History and Conceptual Basis

Kanab Ambersnail (KAS) is a federally endangered terrestrial snail. Two extant populations are known to occur: one on private land in Three Lakes, near Kanab, Utah, and the other at Vaseys Paradise in Grand Canyon National Park. The species was proposed for emergency listing as an endangered species in 1991 and was listed in 1992. Of the two remaining populations, only the Vaseys Paradise population can be studied easily as the other one exists on private land.

The Endangered Species Act of 1973 (ESA) requires federal agencies whose activities affect endangered species to make protection of existing populations and recovery of the species primary management goals. Since discovery of the snails through the Glen Canyon Environmental Studies (GCES) program (1991), the KAS at Vaseys Paradise have been the subject of extensive study of the snails' habitat, population size, predation and impacts related to the operations of Glen Canyon Dam. The primary habitat utilized by the snails is directly impacted by the operations of Glen Canyon Dam.

Through a Section 7 consultation process, the Bureau of Reclamation and the U.S. Fish and Wildlife Service (USFWS) have included the KAS in both the Glen Canyon Dam EIS (1996) and the ongoing Grand Canyon Monitoring and Research Center program. A Kanab Ambersnail Working Group, consisting of members of the USFWS, Reclamation, Arizona Game and Fish Department, National Park Service, academia (Indiana University) and private consultants (previous GCES associate) are presently coordinating related to the research and monitoring.

Habitat Data Collection

Data are collected at Vaseys Paradise with respect to vegetation area and composition. Habitat is divided into patches that are composed of dominant species (e.g., *Mimulus cardinalis, Nasturtium officanale, Carex aquatilus*). Habitat is mapped for all patches up to 100k cfs. Surveys are conducted in Spring and Fall and coincide with surveys for snails in these patches.

Habitat Data Collection (continued)

Habitat patches are influenced by the discharge of the springs, rainfall events and river discharge. The spring's discharge define upper wetted areas and influence the extent of plant growth and distribution. Drier years may result in reduced patches over the growing season or may provide an opportunity for plant species adapted to drier environments to become more representative in a patch for some period of time. Warm winters may also affect growth at the springs particularly with respect to *Nasturtium*, an annual plant. The species may go through several reproductive cycles given warmer conditions and expand in area covered. Patches immediately near the spring discharge show the most change in area covered (6, and 8U) as well as patch 7L which is likely most influenced by mainstem volumes.

Snail Population Estimates

Population estimates for Kanab Ambersnail at Vaseys Paradise based on extrapolations from samples, vary from calculated means of 6,300-7,100 individuals in April/May to 18,000-34,000 in October. Snail numbers increase over the season representing reproductive effort for that year, while spring numbers represent over-winter survival. Snail length is more equally spread out by October with higher frequencies of occurrence, while April lengths are recorded at lower frequencies and for numbers in snail length between 3.5-9.5mm.

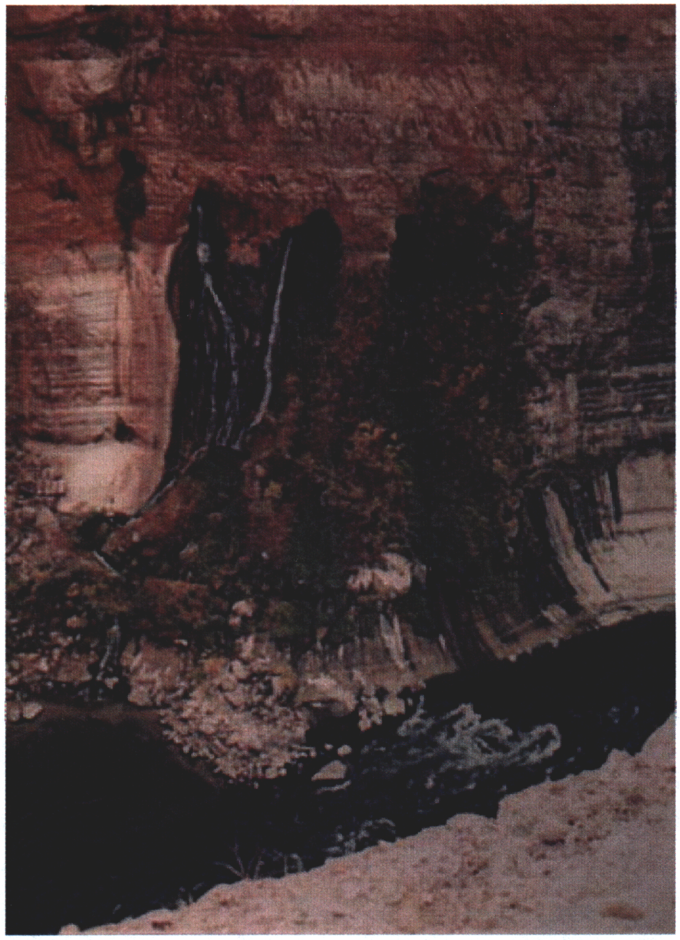


Figure 1. Vasey's Paradise- home of the only population in Grand Canyon of the endangered Kanab Ambersnail.

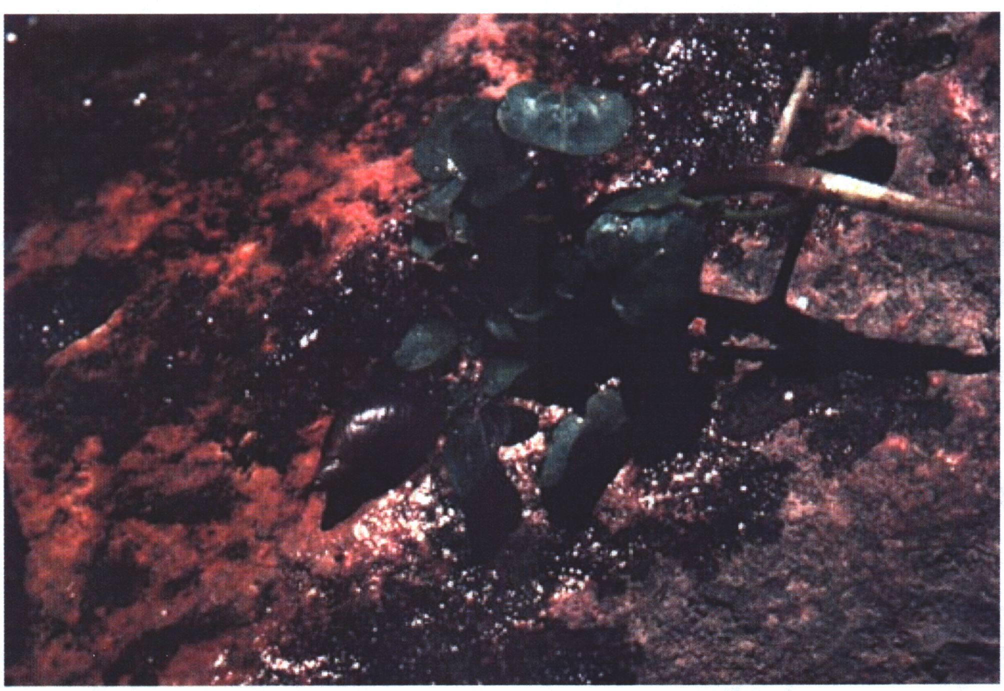
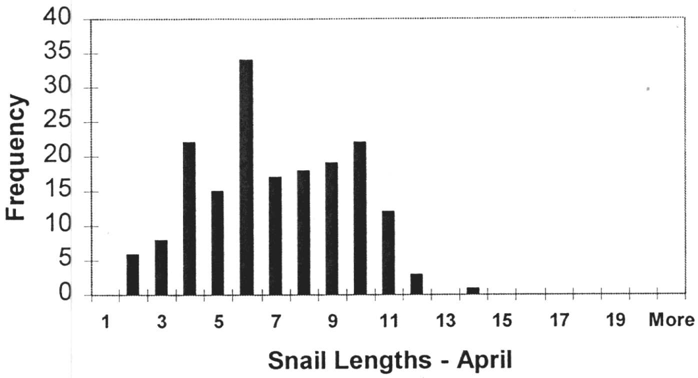
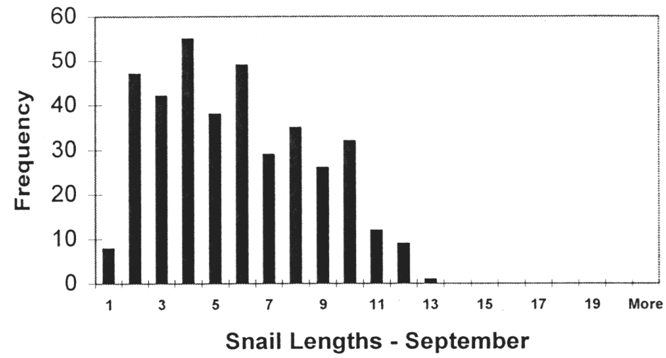


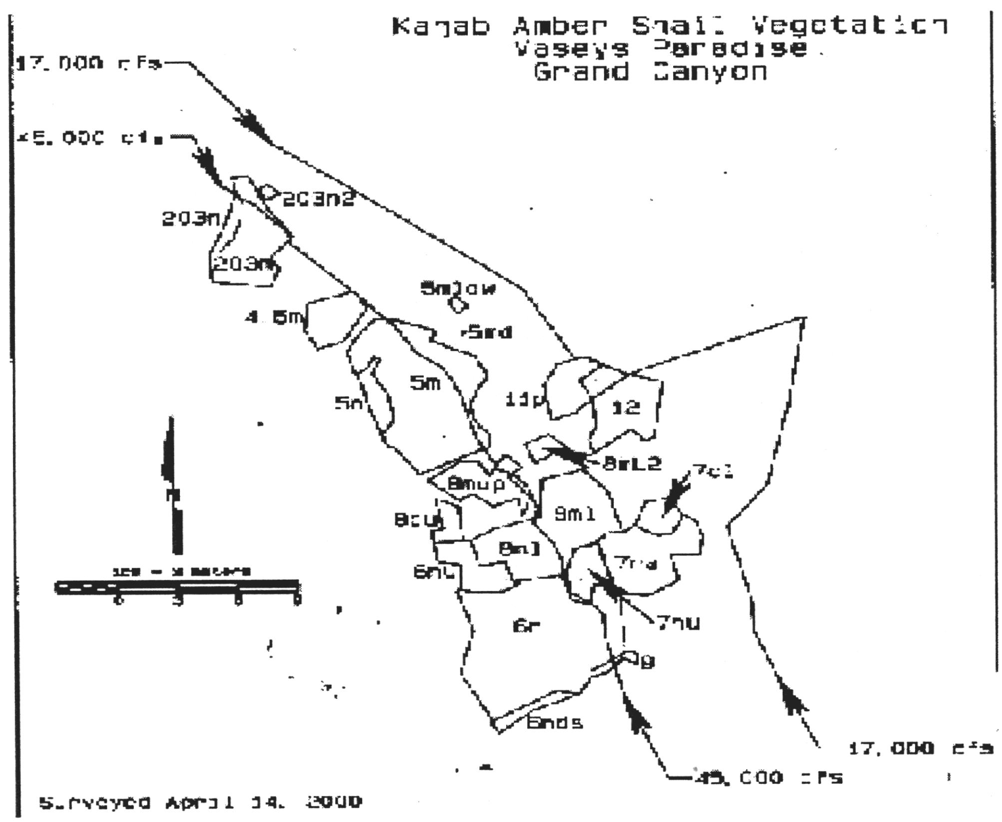
Figure 2. The Kanab Ambersnail, a relict Pleistocene species.

Figure 1. Comparison of snail lengths and frequencies between the months of April and September





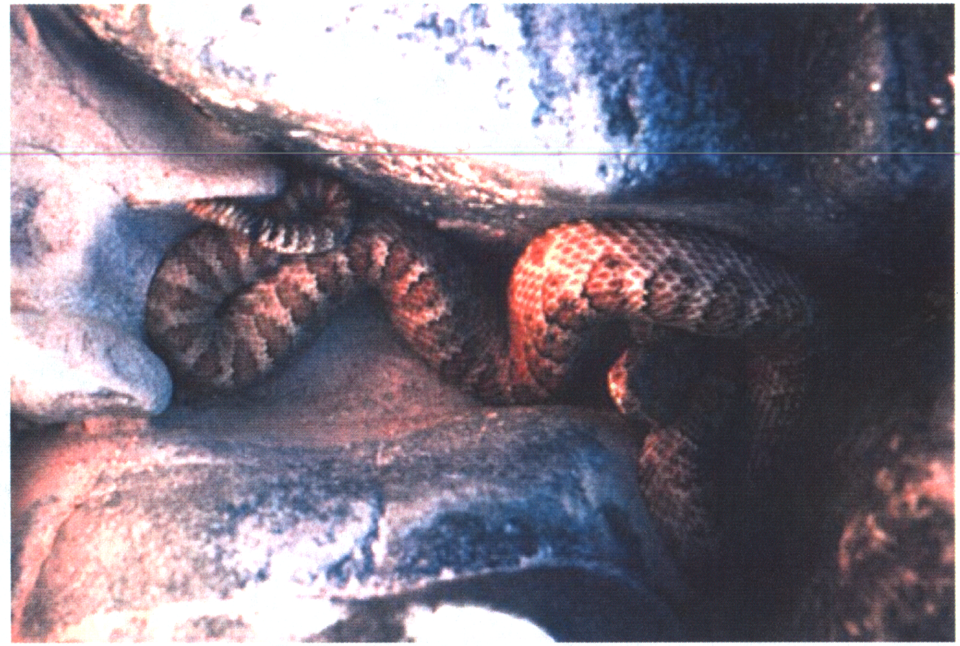
(Figures from SWCA report October, 2000. Meretsky, V. J. and D. Wegner. 2000. Kanab Ambersnail at Vaseys Paradise, Grand Canyon National Park. 1989-99 Monitoring and Research. SWCA, Inc. Environmental Consultants, Flagstaff, AZ.)



Area of habitat above and below 45K cfs and total area of habitat surveyed in April 2000.

Above 45K cfs 161.67 m^2 **Below 45K cfs** 93.82 m^2 **Total area** 255.49 m^2

Figure 1. Desert Bighorn sheep (the smallest and least common of the 4 North American species) inhabit steep canyon slopes.



Figures 2. Grand Canyon Pink Rattlesnake, a subspecies of the Western Rattlesnake.

Figure 3. The Grand Canyon is a *refugium* for one of the largest populations of peregrine falcons in North America.

Riparian Vegetation

Riparian vegetation represents a range of plant species that exists along the river corridor and in the tributaries. In general, riparian communities or associations are dominated by perennial woody species. Germination requirements for plant species influences their occurrence and the present, post-dam assemblage is reflective of the changes in the hydrology. Pre-dam riparian vegetation like mesquite and acacia require scour for germination and a receding hydrograph typical of the pre-dam Colorado River. The Sonoran Desert plants have long tap roots that withstand long periods of dryness on the upper surface of the soil. Other species associated with pre-dam river include Gooddings willows and some cottonwoods. These species are more often found along alluvial floodplains or in large areas susceptible to flooding, sedimentation and slow hydrologic recession like the area around Lees Ferry, Cardenas or in the western portion of Grand Canyon (RM 209) and river reaches further south near Yuma. The roots of these plants are shallower than those of mesquite and acacia, so the plants are more dependent on water being more consistently available. Taking these variables into account, one can begin to predict where and what types of riparian vegetation will be encountered along the river corridor.

The spatial pattern of plant species distribution is dependent on time since disturbance, magnitude of disturbance and availability of water and seed bank availability. Riparian plants able to withstand high scour velocities and whose seeds need to be scarified are likely to be deposited in high velocity environments (like mesquite in the old high water zone) and elevations higher than most beach faces (e.g., channel margins or debris fans), while species that germinate in lower velocity, high sediment accumulation habitats may be found along the lower end of reattachment bars and closer to the zone where water is available on a daily basis rather than periodically available. The lower elevation sandbars are currently colonized by coyote willow, seep willow, tamarisk, desert broom, and arrowweed. Most of these are resistant to burial, where those species associated with the old high water dynamics are more susceptible to burial effects, primarily because they have reduced abilities for vegetative propagation (cloning).

Monitoring Riparian Vegetation

Riparian vegetation serves as habitat for riparian breeding birds and other faunal elements (insects, herps mammals) and is a concern for encroachment on camping beaches. Rather than measuring vegetation in and of itself, the monitoring program has taken an approach that collects data across trophic levels at sites that are initially linked to that resource for which we have the most continuous data set: birds. With respect to riparian vegetation, structure and composition are measured at each bird patch (64/year: 57 downstream and 7 upstream of Lees Ferry). Linkages between hydrology and vegetation density take place independent of bird surveys and involves random transects along the river corridor. Measurements are made from the river's edge to stage discharge levels of 60k cfs.

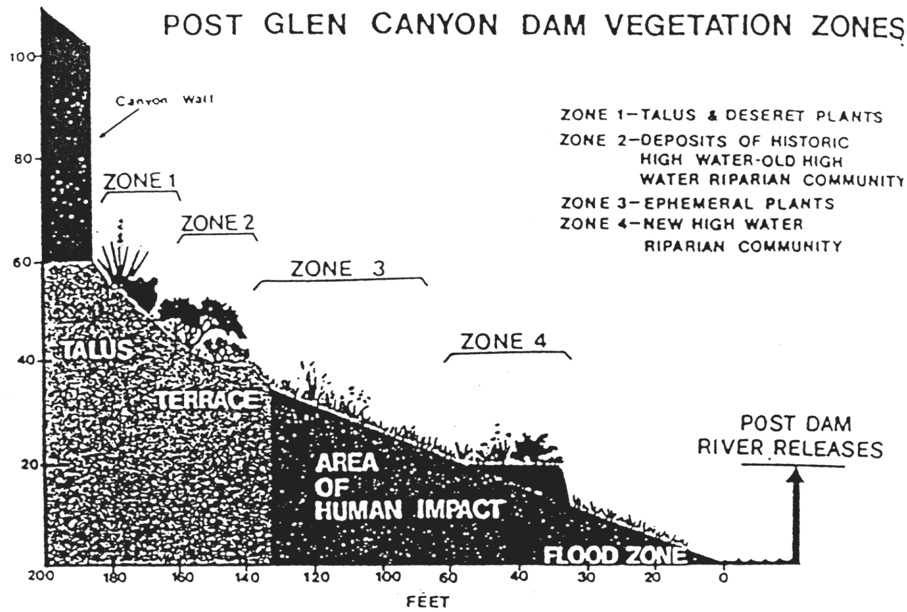


Diagram of Post-Dam vegetation zones. Zone 4 includes marsh, beach and woody riparian plant communities.

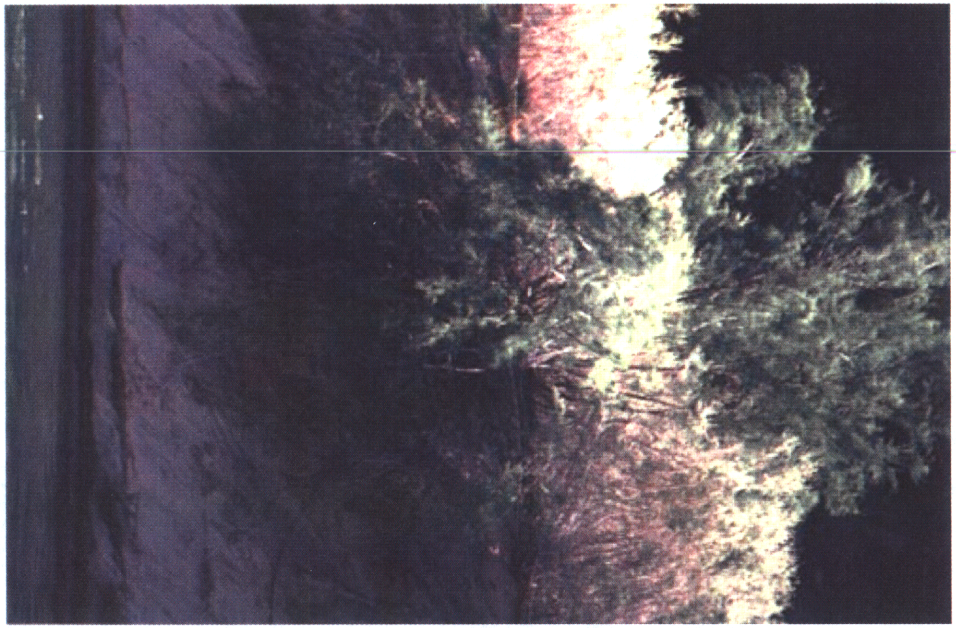


Figure 1. Arroyo cutting can expose cultural resources, causing archaeological information to be lost.

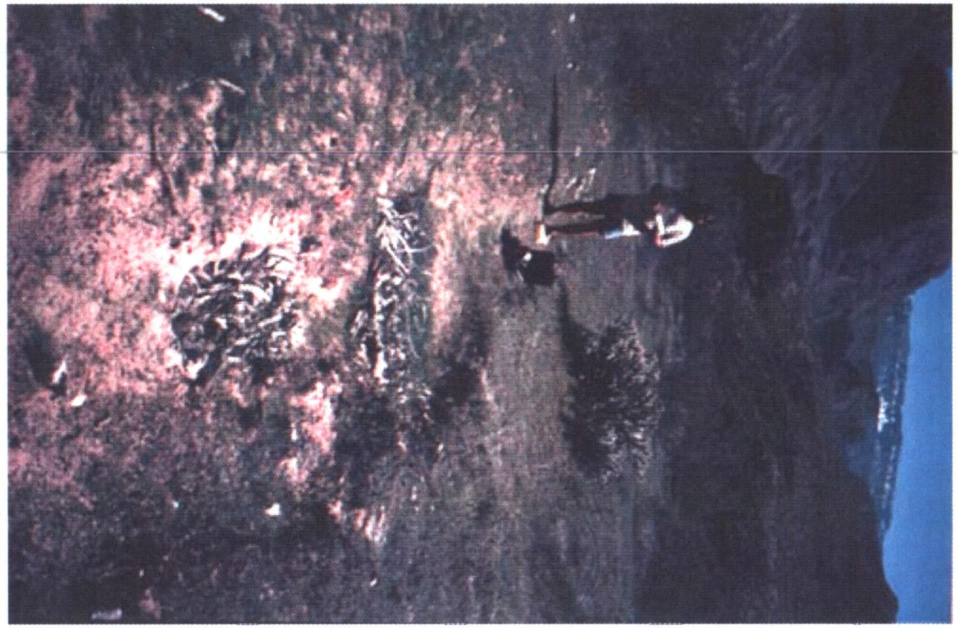


Figure 2. Non-intrusive brush checks capture sediment and help stabilize the drainage.

Figure 3. Prehistoric fire-pit eroding from cutbank. Valuable cultural information would have been lost without excavation actions.

Figure 4. Ceramic vessels recovered from an eroding terrace slope.

CULTURAL RESOURCE RESEARCH DESIGN IN THE COLORADO RIVER CORRIDOR

Introduction

Cultural resource investigations have been on-going in the Colorado River corridor for the last four decades. Beginning in 1990, efforts to monitor cultural resources have become more systematic and detailed. In 1994, the Bureau of Reclamation, the National Park Service (Grand Canyon National Park and Glen Canyon National Recreation Area) and several tribal groups executed a Programmatic Agreement to assess the effects of Glen Canyon Dam operations on important cultural resources. While efforts to assess resources have been considerable, a research design has not been completed to direct the overall efforts.

Long-term research goals and domains form a framework that determines the types of data that should routinely be collected through monitoring, data recovery, and remedial actions. Research domains also determine how these data should be collected in order to address specific questions. All archaeological work must be done in an overall research framework that complies with the minimum requirements set forth in the Secretary of the Interior's Standards for Archaeology and Historic Preservation. The research design addresses areas of research potential, treatment, and application for cultural resources along the Colorado River from Glen Canyon Dam to the to the western boundary of GCNP for preservation decision making.

Project Objectives

The objectives of this project are to: 1) Provide research domains and research questions that are relevant to river specific research with links to larger regional contexts. Research domains may include theoretical and methodological concerns. Issue areas may include archeology, history, ethnography, engineering, architecture, and geomorphology, paleoclimate, and geoarcheology; and 2) Provide a framework for treatment of all cultural resources. The treatment framework should include: 1) evaluation of NR eligible and other resources for purposes of property type evaluation and treatment; and 2) prioritization criteria that includes property type and significance, condition and integrity, and threats. Provide recommendations for incorporating new resource discoveries within this framework.

This project was awarded in September 2001. An orientation with the cultural representatives will be held by November 2001 to outline work tasks and schedules. The project is expected to be completed about December 2002.

EVALUATION OF CULTURAL RESOURCE MONITORING AND MITIGATION STRATEGIES

General Project Description

Numerous cultural resources have been identified within the Colorado River ecosystem. These resources are defined as archaeological resources (prehistoric and historic) and traditional cultural resources of importance to Native American groups and other stakeholders. The cultural resources extend from Glen Canyon Dam to the western boundary of Grand Canyon National Park, approximately 293 river miles. The lateral extent of the area is approximately 256,000 cubic feet per second (cfs) stage level which generally approximates the extent of terrace deposits containing cultural materials.

Monitoring data on cultural resources within the area have been collected by the National Park Service (NPS) and tribal groups for several years. These monitoring efforts have identified areas where erosion and gullying have damaged archaeological sites. In an effort to mitigate loss to archaeological sites, the NPS and the Zuni Conservation Program have installed numerous rock and brush check dams at approximately 29 archaeological sites. These dams have been in place for varying lengths of time with differing amounts of maintenance. The purpose of the dams is to slow or arrest erosion through the accumulation of sediments behind the dams. The utility of these measures has not been thoroughly investigated to date.

Project Goals and Objectives

The goal of this project is to employ remote sensing technologies utilized by GCMRC to study check dam mitigation measures. Additional goals include 1) the evaluation of these technologies for long-term monitoring efforts, and 2) the evaluation of the effectiveness of the check dam mitigation strategies at selected archaeological sites along the Colorado River corridor. Specific objectives of the project are: 1) investigate check dams installed at archaeological sites along the river corridor using existing and on-going remotely sensed data (such as photogrammetric applications to aerial photography and other technologies currently being utilized by GCMRC), Evaluate these technologies for the study of these mitigation measures; 2) evaluate the effectiveness of the check dams and identify geomorphic and other processes that operate at the sites to promote or hamper their utility; 3) provide recommendations on the utility of the remote sensing techniques to study these mitigation measures for long-term monitoring efforts and; 4) provide recommendations on the utility of these mitigation measures and suggest modifications to these efforts, if necessary.

Twelve sites have been selected to be investigated during this study. Eight of the sites have erosion control features in place and four of the sites will serve as controls. The work is in the preliminary stages with field visits for ground checks scheduled in Spring and Fall of 2002.

Erosional Effects on Cultural Resources at Terrace Locations

Major Questions:

1) Are the erosional processes identified at cultural sites related to dam operations or are they natural? Can this be determined?
2) What can be done to help protect cultural sites that are experiencing erosional effects?

Past studies (Hereford, 1993; Thompson & Potochnik, 2000) argue that erosion has increased in the post-dam period and that this is due to: (1) the presence of the dam which withholds sediment and eliminates high flood events, and (2) the operations of the dam which regulate flows within a narrow range relative to pre-dam unregulated conditions. This situation results in a lower main stem base level that has changed the equilibrium conditions at the mouths of gullies and arroyos, resulting in the accelerated rates of gully erosion. The erosion along channel margins and the headward cutting gullies impact deposits that contain cultural materials causing loss of cultural materials and their context. Recent work (Thompson& Potochnik, 2000) concludes that, (1) gully erosion of terraces has been severe during the past 20 years due to unusually high precipitation, (2) sediment deprivation coupled with a lack of large annual floods has caused a reduction in restorative (depositional) factors, (3) beach-habitat-building flows (BHBF) are essential for initiating natural restorative processes, (4) aeolian reworking of newly deposited flood sands onto higher terraces may be one of the most important gully mitigation processes and, (5) gully-deepening and river/wind depositional processes were in dynamic equilibrium prior to dam construction allowing preservation of cultural sites. At selected gully sites, sediments were deposited in arroyo mouths following the 1996 spike flood (Yeatts, 1996) suggesting that BHBFs maybe used as a management tool to temporarily stabilize cultural resources. The duration that deposits remain in arroyos may vary with subsequent flow regimes, climatic conditions, geomorphic setting, and amount of deposit. A modeling project (Wiele, 2001) predicts certain channel margin deposits, given selected flow levels and sediment availability.

In contrast, a recent program evaluation (PEP Report 2000) recommended addressing broader geomorphic questions and less emphasis on distinguishing dam effects from natural processes. They argue that erosional processes are long-term and will continue to affect the cultural resources. Attempts to quantify dam related versus natural effects is not a cost-effective research endeavor. A new suite of geomorphic questions that are tied to the future research design should be developed for the corridor resources. These questions should link the prehistoric fluvial and sedimentary environment to the resources and provide a basis for understanding site location and occupation and site preservation processes.

Managing a Limited Sediment Supply to Achieve In-Situ Preservation of Cultural Sites Within Pre-Dam River Terraces

Closure of Glen Canyon Dam reduced the available fine-sediment supply of Glen, Marble and Grand Canyons by about 90 percent. This highly limited sediment-supply condition, combined with the drastically reduced annual flood frequency, makes the challenge of achieving in-situ preservation of cultural resources within pre-dam river terraces great. Unless active nickpoints within terrace gullies are buried, and remain isolated from rainfall-runoff processes, active head-ward erosion of the gullies will continue upstream. Gullies with nickpoints that have already migrated upstream to terrace elevations above the maximum stage of controlled floods (BHBF's) will continue to erode through terraces. Burial of gully reaches below the nickpoint elevation can temporarily isolate sites from environmental processes, but such deposits will not arrest rapid head-ward advancement of active gullies.

Where terrace gullies can be completely inundated and buried with fine-sediment by the maximum stage of controlled floods, terrace erosion might be arrested for longer periods; assuming that site burial can be maintained through repeated managed bar-building floods. The overall effectiveness of such strategies is limited by the degree to which controlled-flood magnitude is constrained by dam operations, and by the limitations of the post-dam fine-sediment supply within the river channel. Temptation on the part of managers to increase the magnitude of controlled floods to achieve in-situ preservation must be balanced with the fact that multi-year accumulation of tributary fine-sediment is not occurring under current dam operations. If multi-year inputs of fine-sediment are not able to accumulate throughout the channel at lower elevations, then implementation of controlled floods needs to capitalize on periods when the channel is newly recharged with fine-sediment. Higher fine-sediment supply conditions result in higher suspended-sediment concentrations, and higher sand-bar deposition rates. By timing controlled floods of any magnitude with periods when the channel is recharged with new fine-sediment inputs, the potential for bar-building success is increased.

Recently obtained suspended-sediment data (see Attachment 1) collected during summer 1999 through spring 2000, support the fact that most ROD operations do not allow annual fine-sediment inputs to accumulate within the Colorado River ecosystem. The preliminary conclusion of sediment researchers is that most recent, new sand inputs to Marble Canyon were transported past Phantom Ranch within several months, and that erosion of sand from the upper reaches of the ecosystem occurred once the new inputs were exported. The latest paradigm for fine-sediment resources related to the impact of dam operations is more complex than originally thought during completion of the Glen Canyon EIS. Perhaps more important than near-elimination of the spring snowmelt-runoff flood, is the fact that regulation has now limited the frequency of flows below 8,000 cfs from about 50 percent of the time (pre-dam), to less than 15 percent of the time during the 1990's. Raising the base of lower flows has created nearly optimal sand export conditions most of the year (see Attachment 1), relative to the average grain-size of sands input from Marble and Grand Canyon tributaries.

The potential for achieving in-situ preservation of cultural resources within Glen Canyon terraces is likely nil without drastic measures, such as sediment augmentation. Achieving such a goal in reaches below the Paria and Little Colorado Rivers may be feasible without sediment augmentation, but may still require additional flexibility in dam operations beyond that which is allowed under the current ROD.

Assessment and Treatment of Gullies
Andres Cheama, Zuni Conservation Program

Purpose

The purpose of the treatment is to help stabilize a gullies within the vicinity of archeology sites and to reduce the velocities through the affected site by placing check dams and other structural treatments, such as a "rocks lining" to provide roughness to the channel.

Assessment

The Archeology Section of the Park Service does the initial assessment of the sites. Once a site is identified, a determination is made to either treat the site or not and if it is to be treated, how? If structural treatment is needed, then staff from the Zuni Conservation Program will accompany the Park Service to assess the site for the proposed treatment.

In assessing the site, there are several variables that are looked at in determining the feasibility of treatment. The first parameter is the size of the gully. Since the work is limited due to manpower and time constraints, any work that will require an extensive amount of time and movement of a large volume of rock is deemed unfeasible. The second is the developmental stage of the gully. It makes little sense to treat a gully that is stabilizing. More benefit can be gained by concentrating on gullies that are in the incision stage of development. The last two parameters are the gradient at the proposed location, and the soils. In areas where the slope is steep and the soils are loose, other variables are looked to determine if treatment will work; i.e., a solid control and a chance of vegetation to get established. In areas where the soil deposits are coarse fluvial sediment or wind blown deposits, one problem is sub-surface flow that undermines the structure through piping and de-stabilization of the soil due to saturation. Another form of treatment is vegetative, and if it can be used to either augment the structural treatment or as a stand-alone treatment.

Treatment

Structural treatment will consist of check dams, rock lining, headcut treatment, and bank protection. The spacing of the checks is done to allow the built up sediment to reach the next check. Structures can be rock and brush, basket weave, or log jams. Rock lining of the channel is done to prevent scouring of the channel bed. Bank protection consists of armoring the banks with rock, and in some sites deflectors were put in to help keep the water away from the banks and promote deposition on the downstream side of the structure. The construction of these checks and any type of structural treatment is labor intensive because rocks must be carried from nearby slopes in five-gallon buckets. For example, in 1995, seventy-three structures were built in two days at Palisades using buckets and rock litters.

Monitoring and Maintenance

The Park Service and the Zuni Conservation Program do monitoring. If maintenance is required, then the Park Service and the Conservation Program will perform the work. Most of the work involves the installation of a low flow channel and re-enforcement of the banks. This type of maintenance was done at Palisades in 1998, and at other sites, using the same procedure.

Aquatic Ecosystem Activities

GCMRC Water Quality Monitoring Program

Bill Vernieu
Susan Hueftle
Nick Voichick

Introduction

Water quality monitoring conducted by the Grand Canyon Monitoring and Research Center is focused on defining the physical, chemical, and biological characteristics of the water in Lake Powell and the Colorado River in Grand Canyon. This information is used to develop an understanding of how natural processes and dam operations affect trends and variability in these parameters and in linkages with other downstream resources. The program is designed to address established information needs and management objectives related to Lake Powell and downstream resources affected by water quality.

Inflow hydrology and composition, internal mixing processes, and operational effects of Glen Canyon Dam determine the water quality released downstream to the Colorado River in Grand Canyon. Downstream changes are due to the effects of instream processes, tributary inputs, and biological effects of the aquatic ecosystem.

Program Components

The GCMRC Integrated Water Quality Monitoring Program is undergoing revision following external panel review. In it present form, it consists of four components: (1) quarterly lake-wide reservoir monitoring on Lake Powell, (2) monthly forebay monitoring in Lake Powell; (3) continuous monitoring of the Glen Canyon Dam tailwater below the dam and at Lees Ferry; and (4) thermal monitoring at a network of mainstem and tributary sites in Grand Canyon.

The reservoir-wide and forebay monitoring on Lake Powell was established in 1991 and continued to the present. Information from this program is integrated with the twenty-five-year period of record (1965-1990) from the Bureau of Reclamation's previous Lake Powell water quality monitoring program to provide a continuous coverage of Lake Powell's water quality history.

Susan Hueftle

Results of Lake Powell-Tailwater monitoring:

The Hydrograph:

The August water quality monitoring trip found the reservoir at a steady elevation of 3680 ± 0.1 ft (1121 m). The hydrograph reflects the drought conditions that pervaded the Colorado river basin for water year 2000 (WY00-Oct. 1999-Sept. 2000). By September, the basin was still 83% of normal precipitation. Lake Powell inflows totaled 8,134,423 af or about 71% of dam-era average, while releases totaled 9,378,000 af or about 96% of post dam releases (USBR Hydromet database).

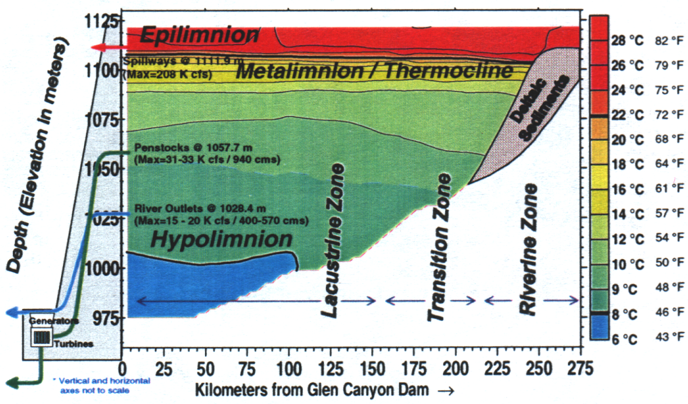
Typically the spring inflow begins in February and peaks in early June. This year inflows didn't increase significantly until May and the bi-modal peak was on May 12th and June 3rd (30,600 cfs and 40,600 cfs, respectively, figure 1).

The Profiles:

Figure 2 provides orientation for some of the terminology and general characteristics of the reservoir. There, and in the main channel isopleths for the reservoir (figure 3), the effect of the depressed inflows is apparent. These profiles demonstrate physical conditions (temperature, conductivity (or salinity), pH, etc.) along the thalweg of the Colorado river in the reservoir. The dimensions of the spring flood plume, as observed by the fresher water extending across the top of the lake (figs. 3c & 3d) in the conductivity plots, is less extensive than in past years which had greater inflow. Further, the specific conductance of the base inflow near Hite Marina was over 1100 µS, as opposed to the low of 470 µS at the peak of the spring runoff last May '00. By contrast, May of 1997, reflecting one of the highest inflow years in the last 14 years, had a minimum conductance of 356 µS, and the fall of that year had a maximum inflow conductance of 960 µS. The conductance of the inflow is dictated by the volume of runoff combined with other seasonal characteristics including irrigation runoff and temperature. Long-term trends near the dam are demonstrated in figure 4.

Winter mixing drove the thermo-/ chemo-cline (zones of steepest change gradient) to the depth of the penstocks (~50-60 m from the lake's surface) in January. By the peak of summer warming in August, the upper boundary of the thermocline started at 10-12 m and extended to the depth of 30-40 m throughout the lake (figures 2, 3a-3d, 4). Because of the reduced inflow volume, this year's thermocline is shallower than in recent years' (fig.4).

Figure 2: Temperature profile for the main channel of Lake Powell, Aug. '00, including some terminology.



Lake-wide dissolved oxygen content is decreasing after last spring's lake-wide enrichment which reached a 15 year high. This was a result of 2 processes last spring and winter. For the 2nd consecutive winter Lake Powell experienced a late winter oxygenated underflow plume (figures 3a-3c). As a result of high inflows since 1993 and continuing dilution of overall ion concentrations, the density gradient separating the epilimnion from the hypolimnion has weakened, allowing the penetration of cold, well-oxygenated water into the deepest layers of the lake. This process was significantly enhanced by the use of the jet-tubes in 1996 for

Figure 1: Hydrograph for Lake Powell elevation, inflow and outflow for Oct 1, 1999 to September 30, 2000.

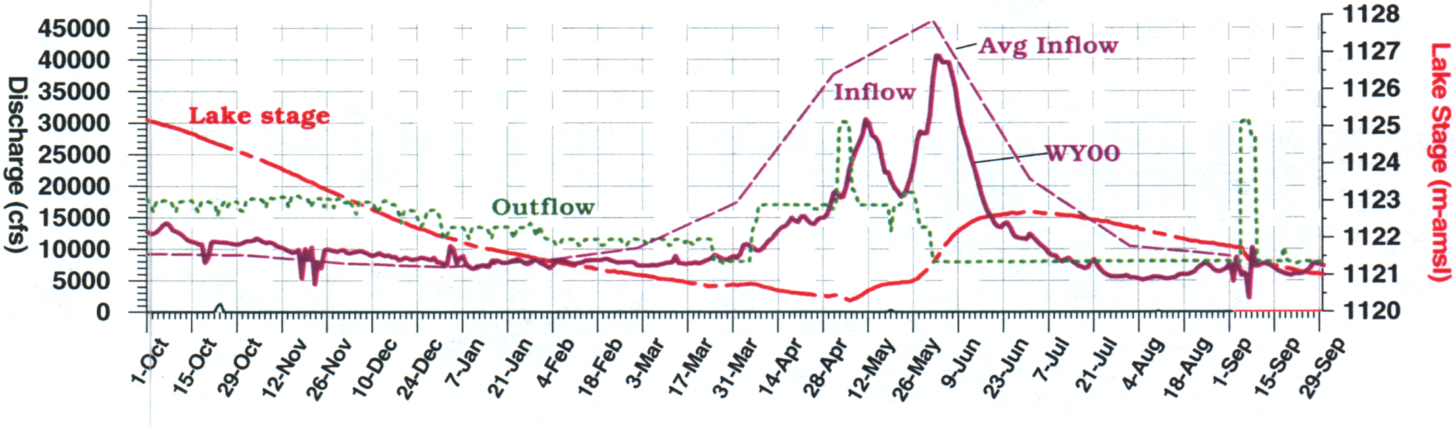
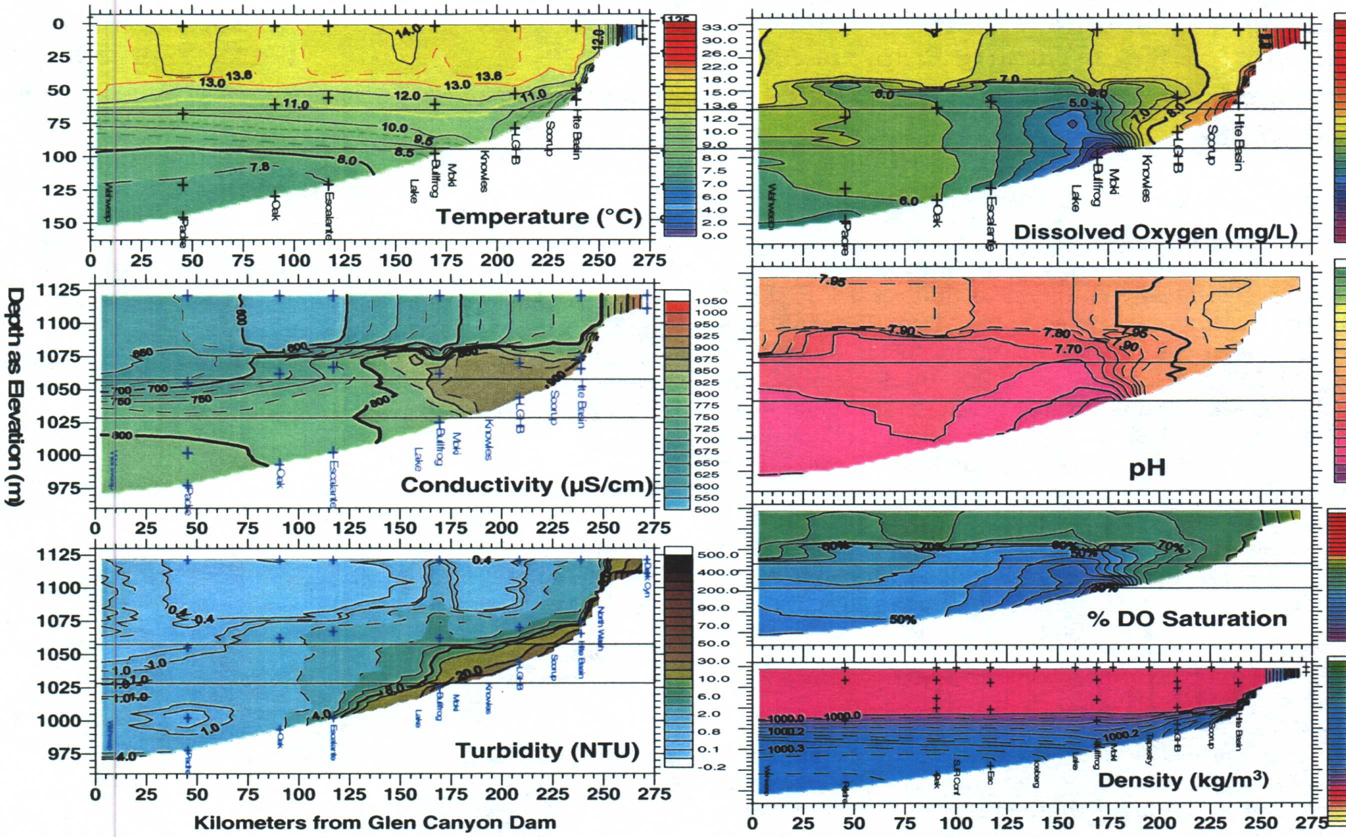
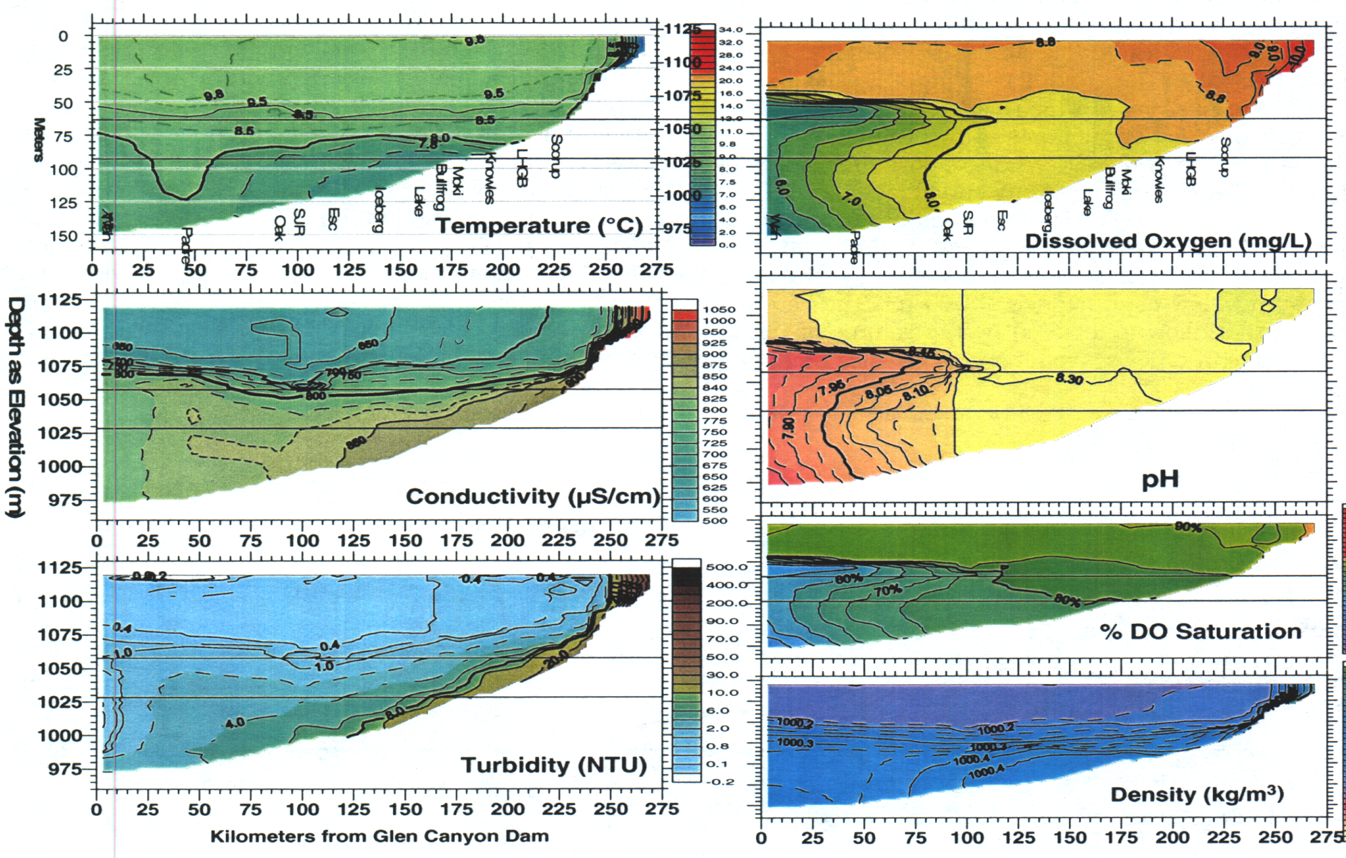


Figure 3. Isopleths of the Colorado channel of Lake Powell.

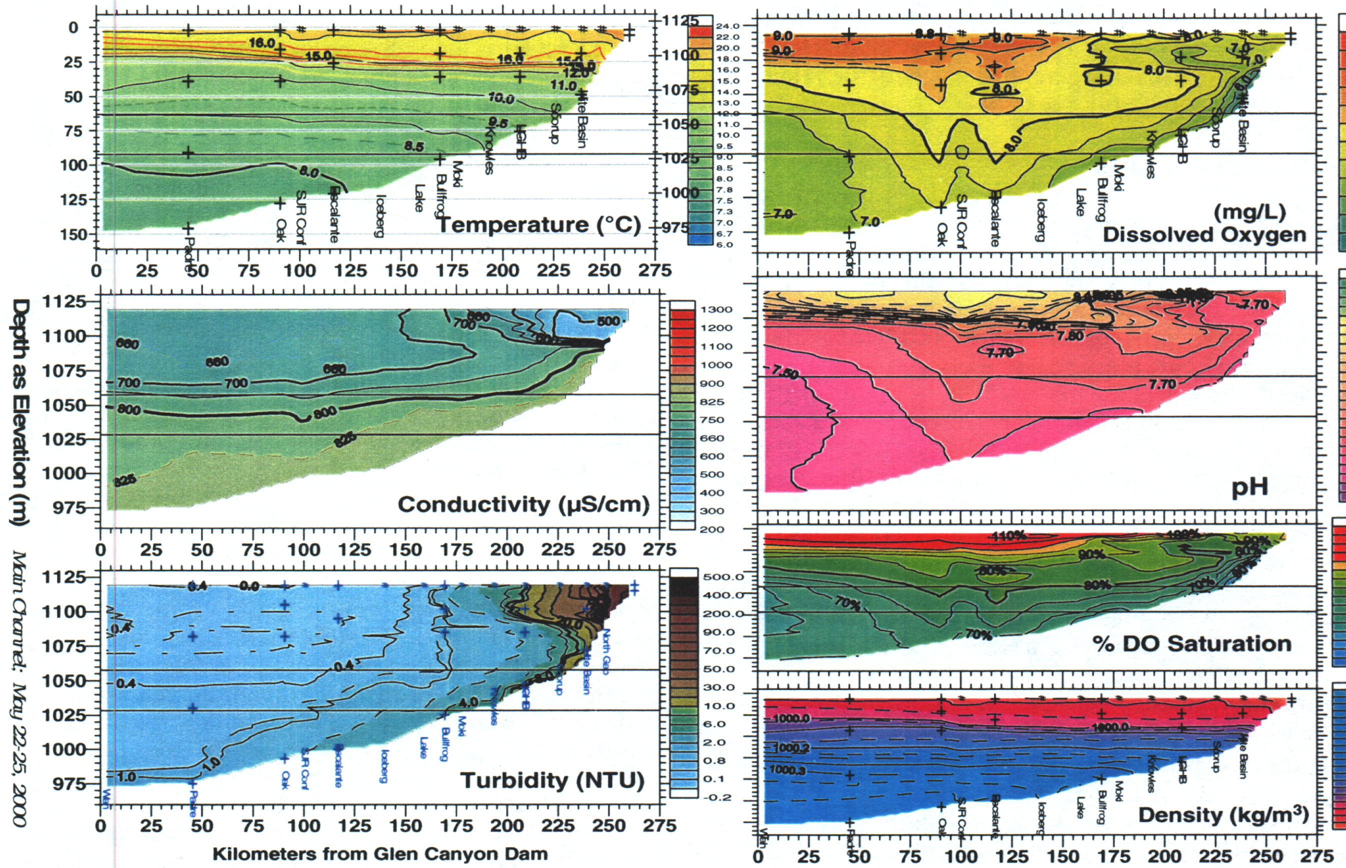
3 A. December 6-11, 1999, Lake elevation 1122.9 m (3684 ft)



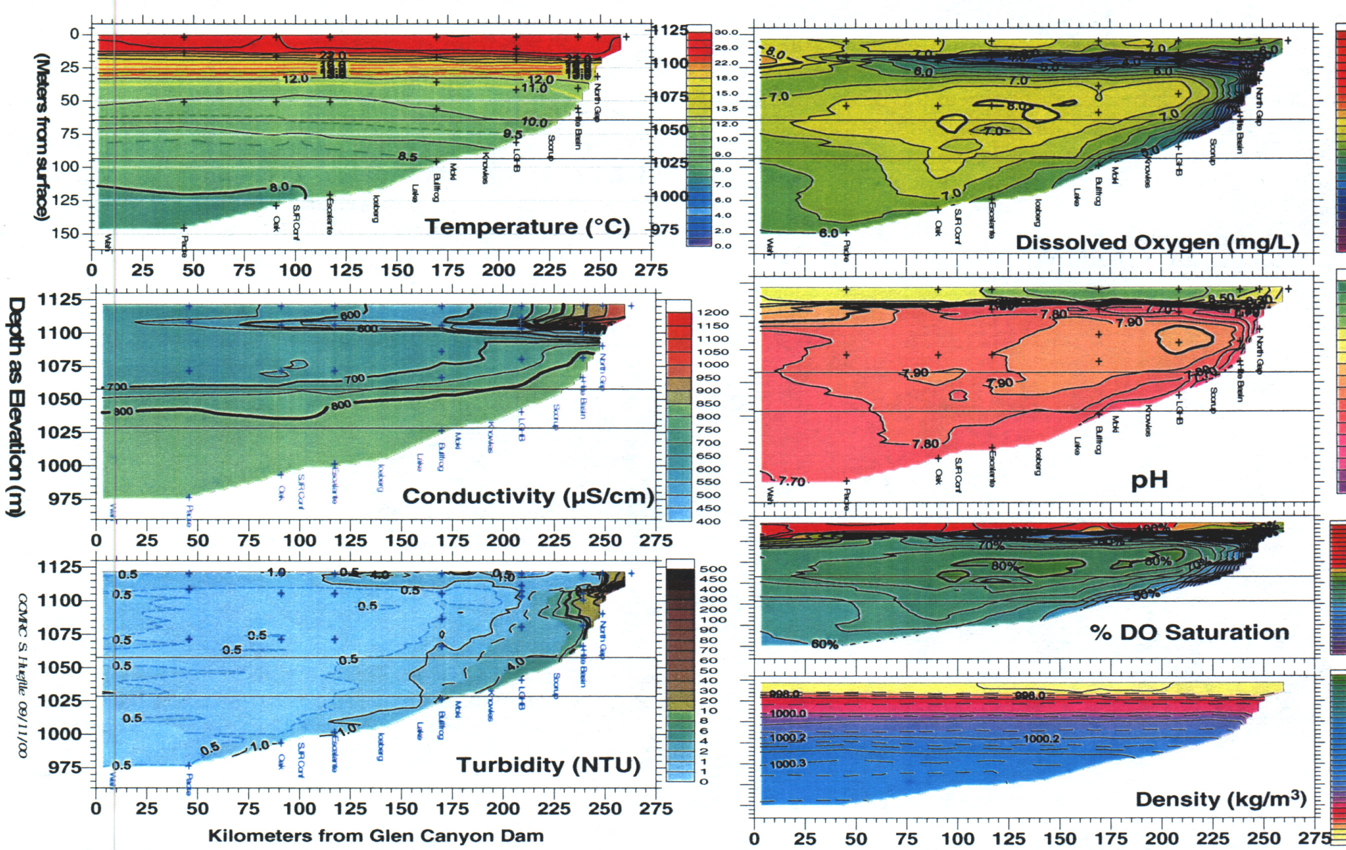
3 B. February 25-29, 2000, lake elevation: 1121.1 m (3678 ft)



3 C. Main Channel; May 22-25, 2000. Lake elevation =1120.8 m (3677.1 ft)



3.D. Main Channel; August 25-28, 2000. Lake elevation = 1121.8 m (3680.5 ft)



the experimental flood, as well as high steady discharges that followed. Given the low levels of hypolimnetic dissolved oxygen that existed prior to 1997 and the hazards of discharging low oxygen, this may offer a tool for managing hypoxia (low O_2) levels in the future.

Nutrient results:

Although results are provisional, nutrient levels throughout Powell demonstrate a response to recent climatic trends. Figure 7 displays surface nutrient values from Lees Ferry to the Colorado inflow stations, and generally represents or even exaggerates trends throughout depths of the reservoir. Across the lake and in the tailwaters, phosphorus values have increased since 1993. This could be a result of the increased inflows in recent years, or could be associated with biotic interactions, and will receive extensive study in the future. Ortho-phosphate, though often near detection limits, shows similar results. Nitrate-nitrite nitrogen alone demonstrates consistently decreasing concentrations paralleling conductance trends on the reservoir. As would be expected, nutrient levels are highest at the inflow and decrease toward the dam. Seasonal trends produce the highest concentrations associated with the inflow event, with nutrients metabolized, mixed and diluted through fall and winter.

Biological results:

Much of the plankton data is in the early stages of analysis. Figure 7 summarizes the data from an aerial perspective, showing the levels of phytoplankton biovolume and zooplankton biomass present in the reservoir and tailwaters for the last year. It shows that productivity for both peak in spring and summer. Primary productivity increases as early as February resulting in the high spring saturation levels of oxygen in the lake. Blooms of algae and zooplankton often follow winter turn-over. Increasing nutrients and warmer temperatures continue to favor productivity until predation and excessive heat drive productivity lower in the water column by late summer and fall.

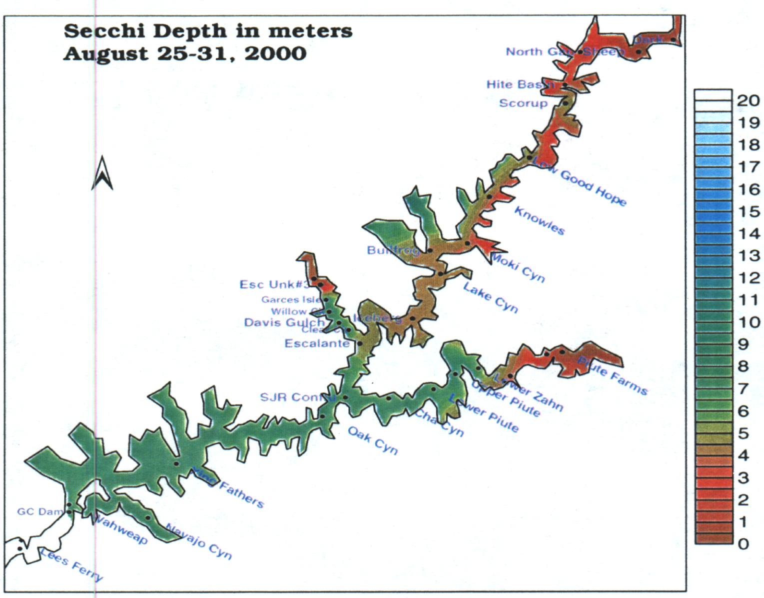
For August, secchi depths (table I, map 1) reflected heightened productivity from phytoplankton (see chlorophyll levels, table I, fig.6), suspension of sediments from the spring flood (a minor contributor this year with lower inflows), as well as some "whiting" of the lake in the lacustrine zones from super-saturation of calcium carbonate, a fairly common occurrence in late summer. Chlorophyll values ranged from 0.5 to 3 mg/m^3 in the down-lake portions of the reservoir, 2 to 10 mg/m^3 in the transitional portions, and 5-10 mg/m^3 in the inflows, reflecting seasonal peaks.

The ranges of nutrients and primary productivity are indicative of a large reservoir system with distinct zones (riverine to lacustrine) and this generally demonstrates a system which transitions from moderate or mesotrophic productivity in the transition zone to primarily oligotrophic (low nutrient, low productivity) in the lower reaches of the lake.

Findings on the reservoir included some unusual events on-shore. In May, the appearance of mosquitoes in two bays at the lower end of the lake was experienced for the first time in many years. This may be an effect of the fairly stable lake elevation during this spring. On the first night of the August trip, Mark Anderson of Glen Canyon National Recreation Area had a misadventure with a rattlesnake. "I thought I kicked a cactus". A sound bite on the toe lead to a midnight helicopter out, but he returned to the trip in a day and a half, gaining the Trooper Award. Other unusual wildlife included an impressive but fairly benign giant hairy scorpion *Hadrurus spadix*, and the rarest sighting, a freshwater jellyfish, *Craspedacusta sowerbyi*. The jellyfish was found by a park visitor in Oak Canyon. This is the only known species of freshwater jellyfish in the U.S., but though seen on rare occasions, it appears not to be documented in Lake Powell.

Acknowledgments:

The Integrated Water Quality Program wishes to thank Glen Canyon National Recreation Area for assistance of personnel and equipment. Appreciation is extended to GCMRC staff and the many supporters of the IWQP and volunteers who assisted in collections.



For further information, please contact:

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Map 1: August '00 secchi depths across Lake Powell with map of stations sampled in WY2000. Lake length along the main channel is 272 km (154 miles) from dam to Dark Canyon.

Figure 4: Wahweap (forebay station above dam) profiles from Jan 1993 to September 13, 2000. Penstock and jet tube depths indicated.

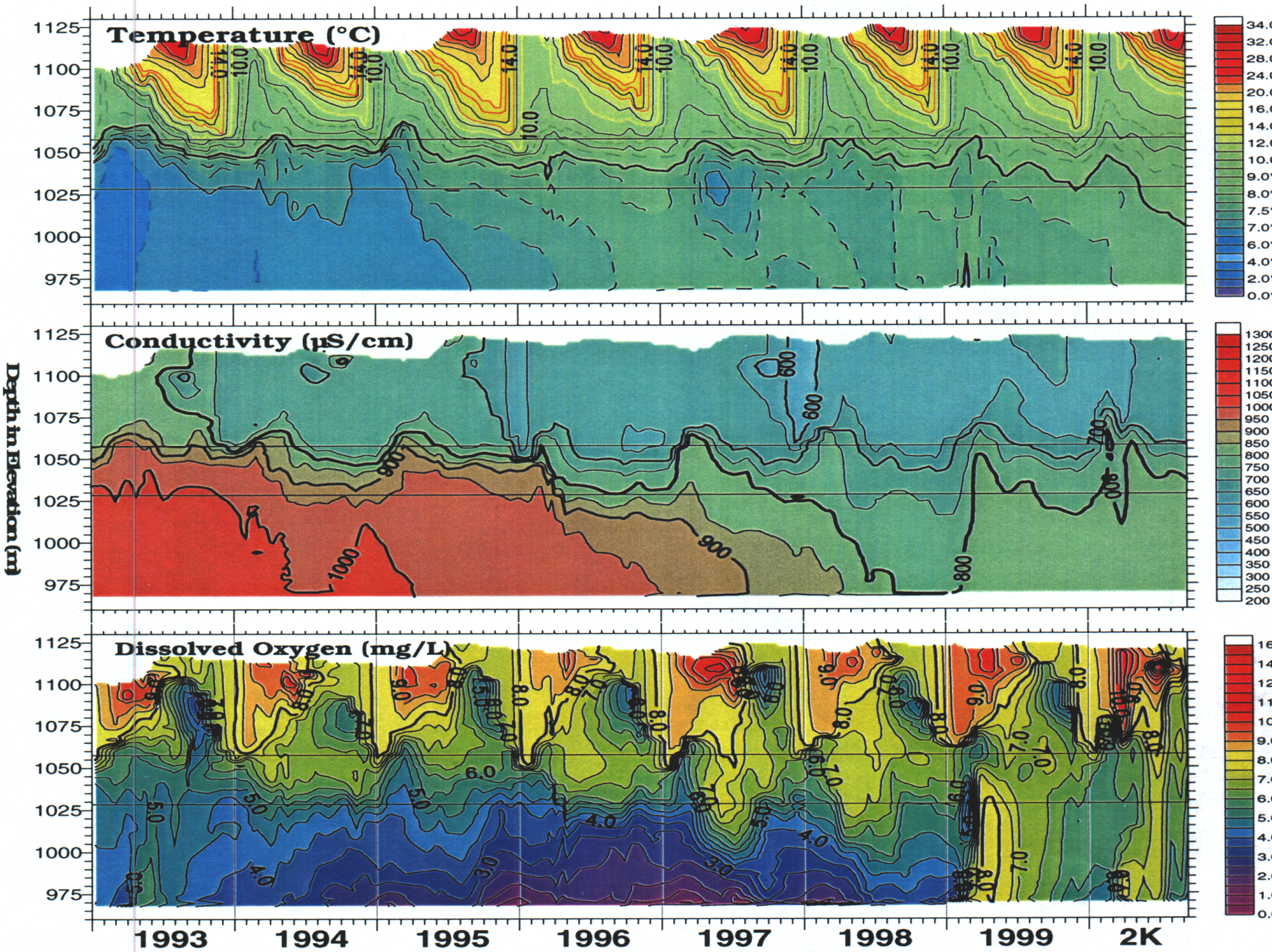


Table 1: Secchi depth (m) and surface chlorophyll-a (mg/m3) values for Feb '92 through August 2000. Storet numbers refer to Lake Powell stations, reach (CR= Colorado River, ESC=Escalante, SJR= San Juan, NVC= Navajo Cyn.; and river kilometer from Glen Canyon Dam.

Site Name	Storet# ↓	Maximum Secchi Disk readings (m) for Feb '99 to August '00							Surface Chlorophyll-a (mg/m^3) for WY99-00						
	Quarter →	9902	9906	9909	9912	2K02	2K05	2K08	9902	9906	9909	9912	2K02	2K05	2K08
Lees Ferry	LPCR-249								2.16	1.43	1.13	1.24	0.66	0.69	0.41
GC Dam	LPCR-001								0.15	0.06	0.14	0.31	0.03	0.04	0.10
Wahweap	LPCR0024	16.7	11.2	10.8	7.9	15.5	12.7	7.6	0.46	0.45	0.98	0.40	0.31	0.44	0.91
Xing Fathers	LPCR0453	15	9.3	8.3	16.1	18.3	10.25	7.9	0.96	0.37	0.89	0.42	0.41	0.28	1.08
Oak Cyn	LPCR0905	12.95	9.4	7.9	15.5	15.7	12.5	7.9	0.49	0.46	1.68	0.28	0.51	0.12	1.29
SJR Confluence	LPCR1001	13.5	8.6	6.5		14.15	11	7.4	0.45		1.86		0.46	0.70	1.67
Escalante Confluence	LPCR1169	15.1	7.9	7.4	15.1	15.8	12.1	4.7	1.47	0.86	1.6	0.95	0.41	0.26	1.81
Iceberg	LPCR1395	14.9	6.5	6.7		15.8	11.4	4.1	1.43	0.909	1.64		0.44	0.40	3.40
Lake Cyn	LPCR1587	13	7.3	6.7	11.1	16.2	9.7	4.3	2.49	2.064	1.98	0.39	0.39	0.18	2.95
Bullfrog	LPCR1692	10.8	5.4	6	8.3	13.5	6.8	4.15	1.45	1.94	2.83	0.75	0.32	0.41	1.84
Moki Cyn	LPCR1772	8.6	4	8	8.8	11.8	4.2	3.95	2.55	1.84	2.39	0.54	0.62	0.61	1.72
Knowles	LPCR1933	12.3	3.2	7.3	9.5	12.5	2.5	4.2	1.56	1.22	3.69	0.18	0.75	0.30	4.15
Low Good Hope	LPCR2085	12.9	2.3	7.4	7.4	12.3	2.7	5	1.53	1.15	4.43	1.21	0.70	1.04	3.29
Scorup	LPCR2255	10	3.2	6	4.4	7.8	0.55	4.8	1.44	1.53	4.285	0.70	0.40	2.25	3.41
Hite Basin	LPCR2387	10.4	0.9	2.73	3.9	9	0.35	3.4	2.14	2.75	6.97	1.17	0.52	2.31	4.94
North Gap	LPCR2483	10.45	0.34	3.8	3.1	7.2	0.25	3.4	0.81	2.16	6.88	0.11	0.12	3.95	9.57
Sheep	LPCR2626e	0.45	0.2				0.2	0.35	1.31	0.81				3.08	5.27
Dark Canyon	LPCR2713e			0.28	0.47	0.28					2.6	0.93	1.02		
Clear Ck	LPESC072e	7.95		5.2		14.2	12.1	6.4	1.08		1.61		0.26	0.69	1.48
Davis Gulch	LPESC119	9.6	10.4	6.1		14.15	12.1	6.5	1.1	0.24	1.13		0.21	0.21	1.20
Willow Ck	LPESC200	12	10.6			7.6	11	7.5	0.55		1.13		0.20	0.27	0.97
Garces Isle	LPESC273e		10.5	5.15		4.8	8.8	7.1	0.4		2.42		0.24	0.43	1.00
Esc Unk#3	LPESC347e		0.9	0.08		0.48	0.35	0.28	1.18	0.32	3.67		7.11	2.22	6.10
Navajo Cyn	LPNVC124	5.8		10.1		9.7	12.7	7.5	5.84		0.89		0.66	0.16	0.30
Cha Cyn	LPSJR193	11.6	7.7	7.3	10.35	10.3	10.8	6.9	1.009	0.55	1.28	0.97	0.84	0.53	1.16
Lower Piute	LPSJR329	12	9.7	6.9	6.7	11.3	10.8	7.2	0.91		1.48	0.77	0.55	0.40	1.25
Upper Piute	LPSJR431	13.3	7.5	4.7	6.3	10.3	8.7	9.2	0.87	0.39	3.755	0.46	0.30	0.51	0.52
Lower Zahn	LPSJR625	11.4		2.45	5.5	8.3	5.5	6.6	1.49		4.46	1.56	0.71	1.07	0.50
Mid Zahn	LPSJR686		0.25			2.05	5.8		0.91	2.135			1.47		4.37
Piute Farms	LPSJR850e			0.45	0.8	0.4	0.15	0.12			3.82	1.00	0.96	3.64	5.94

Figure 5: Chlorophyll values (mg/m³) for WY00 for Lake Powell and tailwaters. Samples were collected at 1m depth.

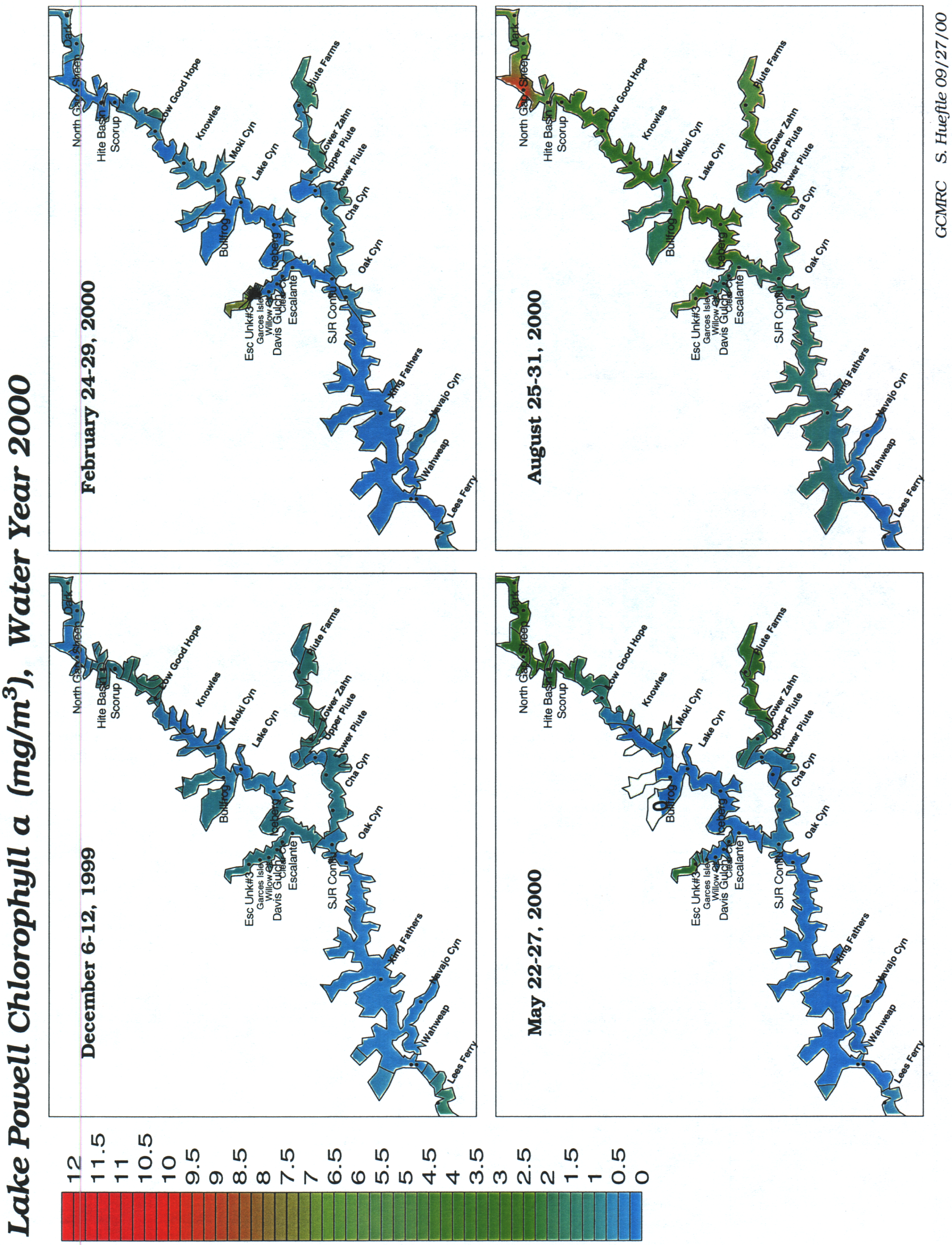


Figure 6: Phytoplankton biovolume (µm³/L) and Zooplankton biomass (µg DW/cm² —analogous to µg/L) estimates for Sept '99 to May '00 quarterly trips. Zoop samples compiled for 0-30m & 30-60m tows.

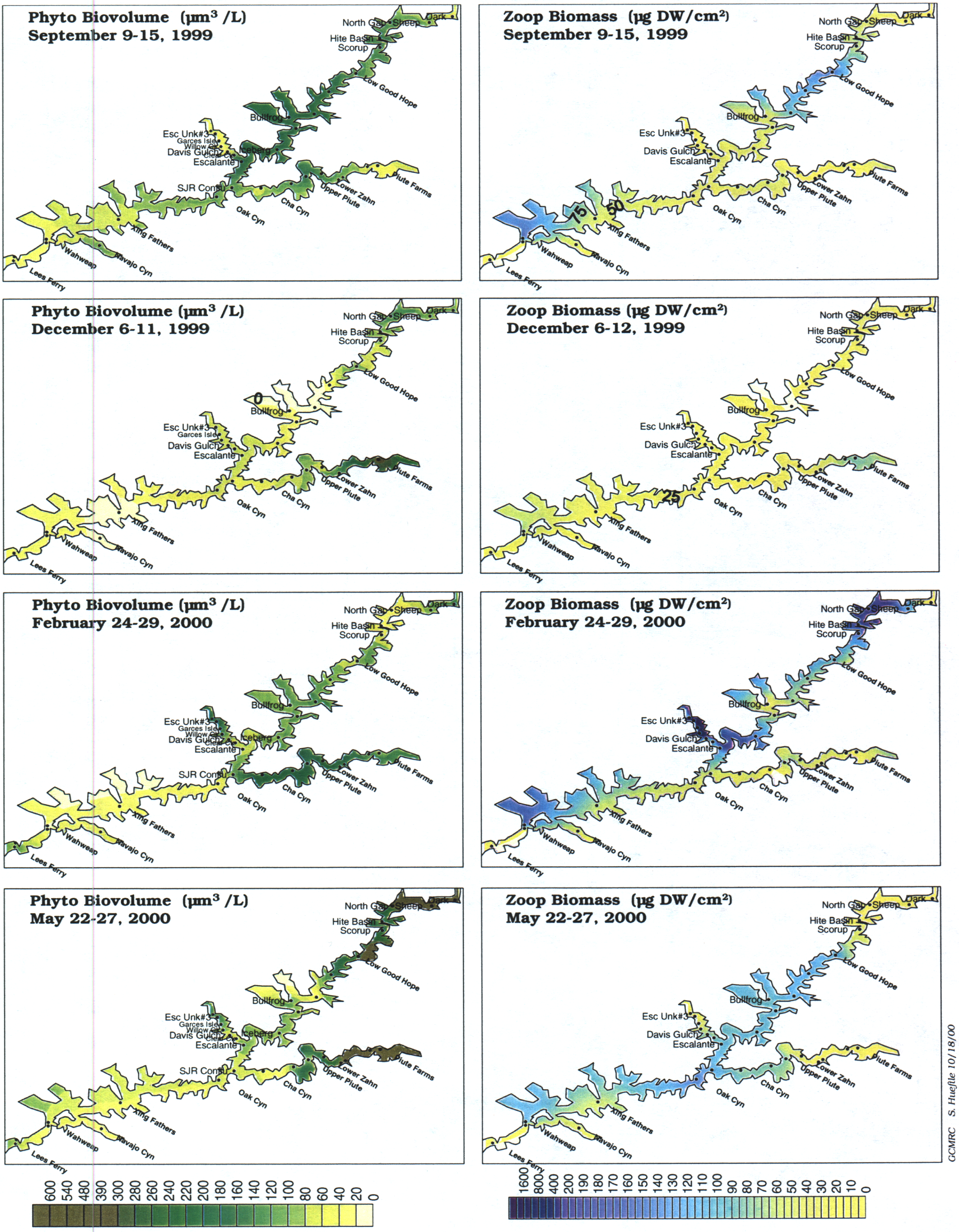
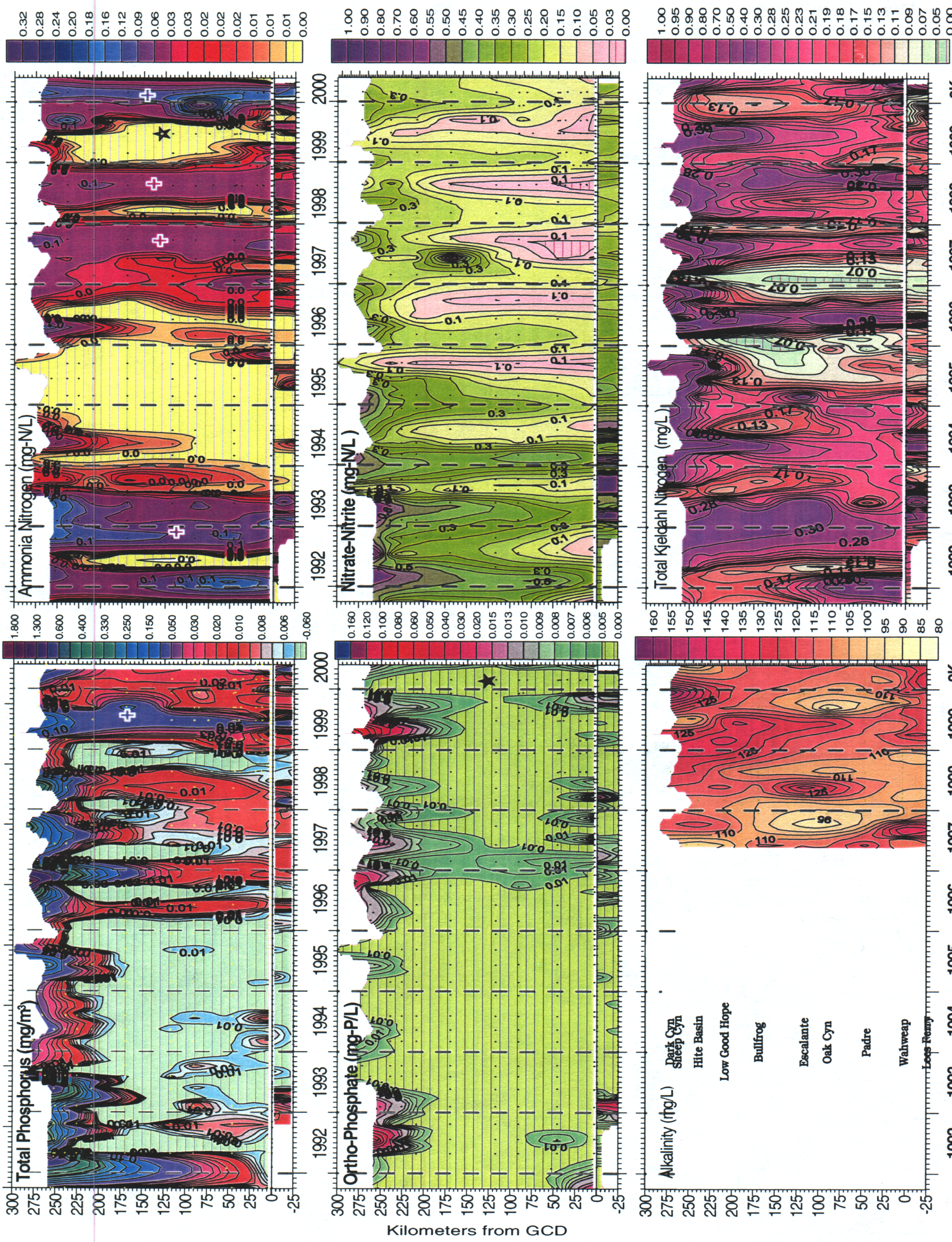


Figure 7: Surface Nutrient Values in the Main Channel and tailwaters of Lake Powell, Sept. 1991 to May 2000 (0 to -2m). Values below detection levels indicated by striped areas. PROVISIONAL DATA: Stars indicate low suspect values; crosses indicate high suspected values. Ammonia values are particularly variable.



Salmonid Population Size in the Colorado River, Grand Canyon, Arizona

Fishery Fact Sheet
Arizona Game and Fish Department
Grand Canyon Monitoring and Research Center
June 2001

INTRODUCTION

Over the past decade, considerable research and monitoring has been conducted on the effects of varied flow regimes on aquatic biota of the Colorado River below Glen Canyon Dam (GCD). Management recommendations for native fish assume that physical habitat features (seasonality of flow, habitat morphometry, temperature) are the primary limiting factors for native fish populations. However, much less is known of population size and dynamics of exotic fish and, in particular, the risk of predation that salmonid populations pose to native fish. The objective of this study was to estimate population size and distribution of non-native salmonids rainbow trout (*Oncorhynchus mykiss;* RBT) and brown trout (*Salmo trutta;* BNT) in Grand Canyon for use in assessing predation risks to native fishes.

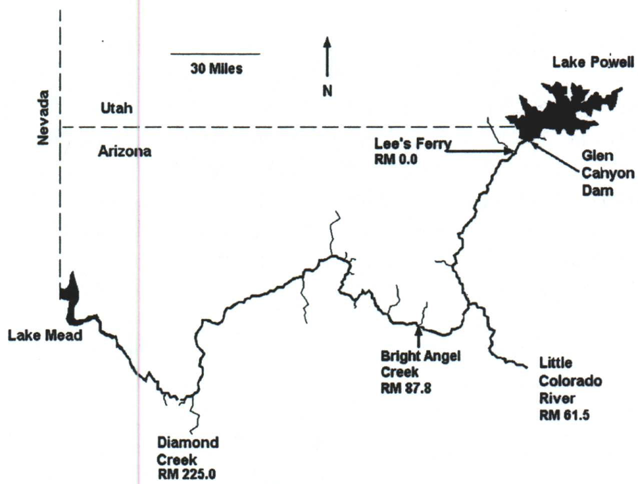


Figure 1. Study area.

METHODS

Population Estimate Approach and Assumptions

We estimated system-wide (RM 18-225) population size for rainbow and brown trout by calibrating single-pass electrofishing (EF) catch-per-effort (CPE) values to absolute, local estimates of fish density (N_o). The latter were obtained by a series of spatially and temporally discrete depletion and/or mark-recapture (M/R) electrofishing experiments conducted over a range of fish densities. The focus of this report is on results from depletion experiments. We have no observational model for M/R data at this time, but hope to evaluate them using mark-rate techniques in the coming year.

Relation of depletion estimates to index samples (single-pass CPE) was made assuming

$$CPE = q\,(N_o)$$

where catchability coefficient q is some fraction of absolute fish abundance removed per unit of effort (Hilborn and Walters 1992). In this manner, single-pass index EF samples collected throughout the river system can be "translated" into absolute fish numbers, which are then expanded and plotted longitudinally against river mileage. The resulting curve is then integrated to provide a system-wide population estimate.

The theory behind depletion electrofishing is illustrated in Figure 2, whereby increases in cumulative numbers (K) of fish over a consecutive series of electrofishing passes is plotted against the accompanying decline in CPE with each pass (Leslie and Davis 1939). The value of the x-axis intercept of the regression line in figure 2 (98, or estimated K at CPE = 0 after multiple passes) is the estimate of fish present prior to electrofishing. In our analysis, we used a maximum binomial likelihood routine to search for N_o estimates (Walters, unpublished; Hilborn and Walters 1992) while also accommodating occurrences of zero CPE values.

We treated all depletion data as originating from closed populations (see *Field Methods*). We restricted our inferences on N_o to areas effectively sampled by EF (within ca. 15 m of the shoreline; AGFD, unpublished March 2001 data). Fish with capture probability (q) of near zero (fish inhabiting deep, offshore areas) were modeled indirectly by extrapolating near shore estimates across river length and width.

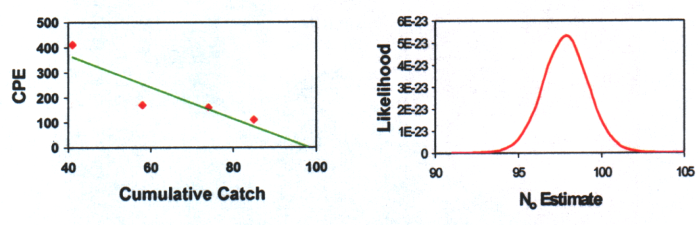


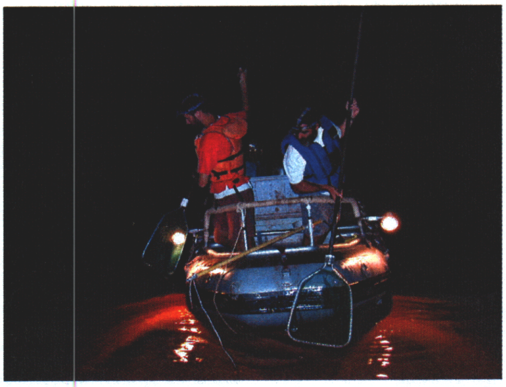
Figure 2. A typical RBT depletion sample (left, RM 22.3, 6/2/2000) and associated likelihood profile on N_o = 98 fish (right).

Field Methods

We collected electrofishing data during five mainstem Colorado River trips in Grand Canyon National Park during 2000 (table 1). Samples were collected by Arizona Game and Fish Department (AGFD) and SWCA, Inc., Environmental Services (SWCA). Discharge from GCD was relatively constant at 8,000 cfs during the entire study period. An additional mainstem trip was conducted during December

2001, but mark-rate and distributional data from that trip are pending analysis.

All data used in population estimates were collected by electrofishing at night. We used a 16' Achilles inflatable sport boat outfitted for electrofishing, applying an average output of 310 volts and 14 amps to a 35 cm spherical electrode. All salmonids were measured (maximum total length, mm). We clipped adipose fins of all fish larger than 100 mm. As relatively little is known of brown trout population parameters (growth rates, survival, movement), we implanted all BNT >120 mm with passive internal transponder (PIT) tags. We also clipped adipose fins of all PIT tagged brown trout to allow evaluation of tag loss.



We selected experimental depletion electrofishing transects according to availability of shoreline structural features to minimize immigration and/or emigration from the study area between multiple EF passes (Figure 3). We found that sandbars usually provided the best barrier to immigration and emigration from the transect, because trout generally do not utilize such areas. Debris fans, rapids and rock outcrops also served as barriers, but they were not as effective as sandbars (Speas and Rogers, personal observations). In most cases, few fish were captured at the extremities of the EF transects, and we believe effects of immigration and emigration were minimal. Transects averaged 0.13 miles in length.

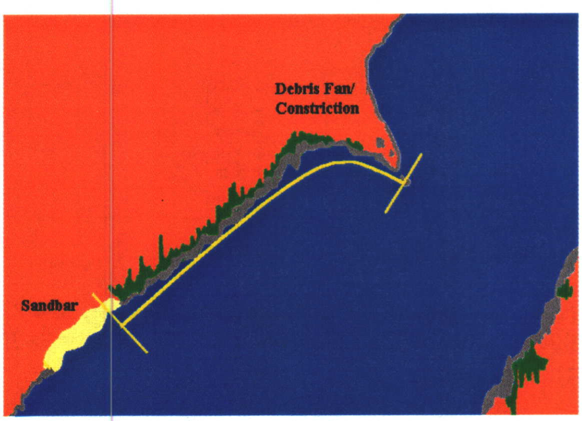


Figure 3. Schematic of a typical depletion/mark-recapture experimental transect.

Each depletion experiment was conducted over a period of 2-3 hours each night. We electrofished depletion transects repeatedly until the catch was reduced to about 20% of the first-pass catch. Fish were processed between passes and retained in a mesh live well until the experiment was concluded. At select locations, depletion transects were revisited 24 h later to collect recapture observations using the same amount of effort applied during the previous night.

Results and Discussion

Combined efforts between AGFD and SWCA resulted in over 500 EF samples collected between river miles (RM) 0 and 225 during June-September, 2000 (table 1). AGFD conducted 77 depletion experiments. Gastrointestinal tracts were collected from almost 900 fish and are currently being analyzed by Grand Canyon Monitoring and Research Center (GCMRC).

Table 1. Size and type of electrofishing samples collected on the Colorado River in Grand Canyon, 2000

Agency	Trip Dates (2000)	N Index CPE	N Depletion[1]
AGFD	6/4-5/18	83	21
AGFD	7/21-8/3	53	37
AGFD	8/25-9/6	26	19
SWCA	6/7-6/23	174[2]	-
SWCA	8/7-8/22	50	-
SWCA	9/14-9/28	43	-
Total	-	429	77

[1]First pass from these samples also functioned as index CPE
[2]Not included in population estimate due to EF power output differences

Catchability coefficients

Estimates of q did not vary by fish density for rainbow trout (slope of q was 0) (Figure 4, left). Catchability may be positively related to density for brown trout, but this bias did not preclude calibration of CPE to absolute density (Figure 5, right). There was little evidence that q varied with successive electrofishing passes. Mean q for RBT including first depletion passes (0.52) was nearly identical to second and later passes (0.51), but q for BNT from first pass inclusion (0.16) was slightly greater than for second pass (0.11).

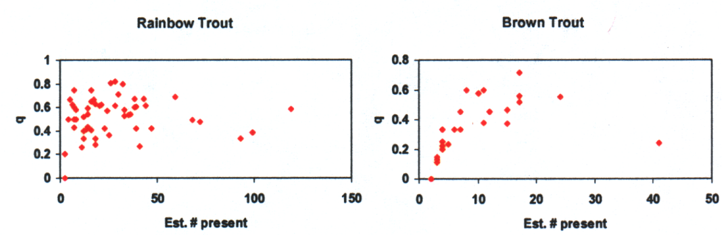


Figure 4. Catchability coefficient (q) in relation to estimated fish density for RBT (left) and BNT (right).

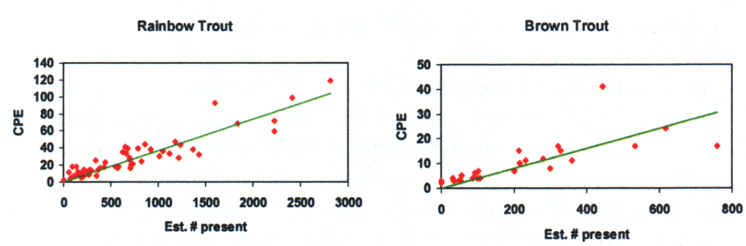


Figure 5. Calibration of local fish density (RBT, left, and BNT, right) estimates to observed first pass CPE from depletion experiments.

The usefulness of CPE calibration for long-term monitoring will depend on variability of q with water clarity and seasons, because such variation will affect the slopes of CPE on N_o (Figure 5). Catchability for RBT in samples collected from turbid water conditions was 0.58, compared with 0.51 from clear water. Catchability of brown trout, by contrast, was only 0.10 in turbid water, compared to 0.18 from clear water. Only 13 depletion experiments were conducted under turbid water conditions, and we consider variance of q with water clarity an information need to further refine the monitoring program.

Also, preliminary observations from samples collected during December 2000 and March 2001 (analysis in progress) suggest that behavioral changes in fish distribution associated with reproduction may also result in different estimates of q (Walters, personal communication).

Salmonid population estimates and longitudinal distribution

For both rainbow (figure 6) and brown trout (figure 7), mean fish/RM were modeled longitudinally by a cubic polynomial regression, in which all terms were significant (RBT R^2 = 0.60; BNT R^2 = 0.24; $P<0.0001$ for each) except for 2nd and 3rd order coefficients for RBT. These terms were retained, however, to obtain the best approximation of longitudinal variation and minimize negative fish density estimates.

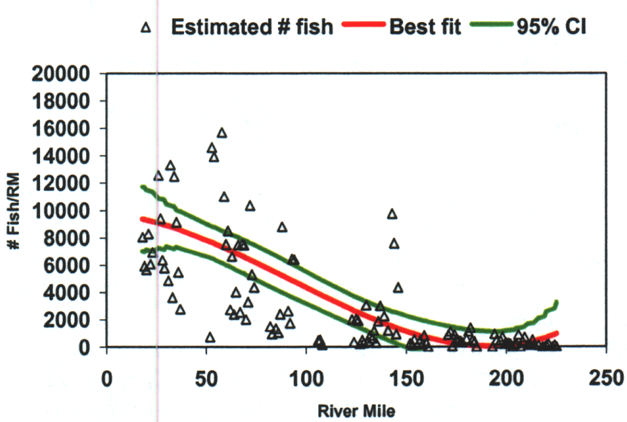


Figure 6. Estimated rainbow trout/river mile, best fitting line and 95% confidence intervals.

$RBT/RM = 0.0025(RM)^3 - 0.6929(RM)^2 - 9.6464(RM) + 9744.1$

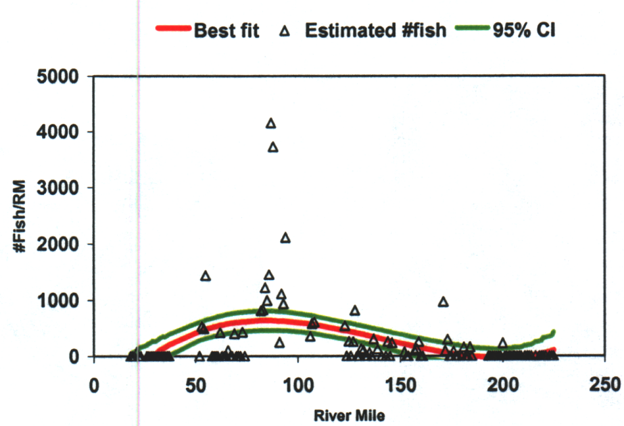


Figure 7. Estimated brown trout/river mile, best fitting line and 95% confidence intervals.

$BNT/RM = 0.0009(RM)^3 - 0.3786(RM)^2 + 44.767(RM) + -990.38$

Integration of the polynomial curves yield an estimated 743,000 RBT (95% CI: 500,000-1,000,000 RBT) occurring in the Colorado River between RM 18 and 225 (figure 6). Estimated brown trout population size was 56,000 (95% CI: 20,000-100,000 BNT). Rainbow trout occurred predominantly in the first 100 river miles below Lees Ferry, whereas maximum brown trout numbers occurred between RM 50 and 150, especially in the vicinity of Bright Angel Creek (figure 7).

Length Frequencies

Modal length frequencies for adult RBT and BNT were 315 and 282 mm, respectively (figure 8). Juvenile model length frequency for RBT was 160 mm, and 120 mm for BNT. Given these distributions, it is likely that at least a portion of the salmonid populations exert predation pressure on small-bodied fish, but frequency of occurrence and composition of fish in salmonid diets are unknown at this time.

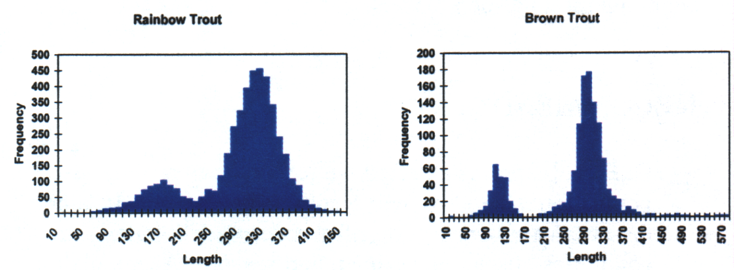


Figure 8. Length frequencies of rainbow trout (left) and brown trout (right) in the Colorado River, Grand Canyon during 2000.

Error Sources

We feel that depletion samples were conducted on highly discrete spatial (delimited transects ca. 0.1 mile in length) and temporal (consecutive EF removal passes) scales. Error associated with immigration, emigration, and within-experiment variance in capture probabilities is likely negligible in comparison to error introduced by cross-sectional extrapolation from the local to the system-wide level. While variance in fish numbers along the longitudinal axis of the river is captured by our method, very little is currently known of fish density gradients along the cross-section of the channel.

Fish in areas inaccessible to electrofishing—primarily deep (ca. > 2 m), offshore areas--are effectively invulnerable to depletion estimators in that their catchability approaches zero. Theoretically, however, such fish should be at least partially accounted for in mark-recapture estimates. For comparative purposes, we calculated M/R estimates for RBT and BNT using the same assumptions as we used with depletion estimates[3].

---

[3] M/R estimates of N_o were calculated by maximizing the binomial likelihood for N_o in the formula

$$\Pr\{m|n,n/N_o\} = [n!/m!(n-m)!](n/N_o)^m(1-(n/N_o))^{(n-m)}$$

where n is total fish marked and m is total fish recaptured in an experimental transect 24 h after marking (Hilborn and Walters 1992).

For rainbow trout, estimates of absolute fish numbers (N_o) from fish recaptured 24 h after marking in depletion transects were about 2.9 times larger than depletion estimates. Brown trout M/R estimates of N_o were only 1.5 times larger than depletion estimates. While these estimates of bias are admittedly crude, they do suggest that depletion estimates of local fish abundance are negatively biased. In practice, biases of 30-50% in depletion estimates are not uncommon (Hilborn and Walters 1992). It is very possible, however, that such negative biases may be overwhelmed by positive biases introduced by extrapolation.

We are confident that depletion-derived estimates will be useful in evaluating relative risk of predation for native fish because they are relatively precise estimates of population orders of magnitude. Use of such estimates in conjunction with estimates being developed for native fish in a predator-prey model framework should reveal the degree of relative risk salmonids pose to native fish at the population level. Evaluation of stomach samples from summer 2000 should also aid in interpreting such models.

Recommendations

- CPE calibration is an effective technique to rapidly assess population size, but we recommend continued—albeit opportunistic—estimation of q under varied water clarity conditions, discharge regimen and seasons. Accumulation of such data should facilitate future population estimates despite effects of diverse sampling conditions.

- To facilitate independent estimators of population size, we recommend continued tagging of all salmonids on all mainstem Colorado River fish monitoring trips.

- The primary source of uncertainty in generating population estimates at the system level is making inferences of fish density in areas inaccessible to electrofishing. We recommend research on the cross sectional distribution of fish density in the Colorado River in Grand Canyon. At present, we are investigating use of snorkel surveys to quantify cross-sectional distribution in the Glen Canyon reach (Lees Ferry), and these data may prove useful in estimating fish densities downstream as well.

- Mark-recapture information is at present distributed over both diel and seasonal time scales. We feel that there is more information in the M/R data than just estimates of q, which warrants more comprehensive assessments than we can provide at this time.

Acknowledgements

Grand Canyon Monitoring and Research Center funded the present study under Cooperative Agreement No. 1425-98-FC-40-22690 and provided logistical support. We are grateful to Dr. Carl Walters for his invaluable input in developing the longitudinal population size approach, and his authorship of the maximum likelihood routine for depletion experiments. We also thank the personnel of SWCA for obtaining considerable amounts of longitudinal trout CPE data during 2001.

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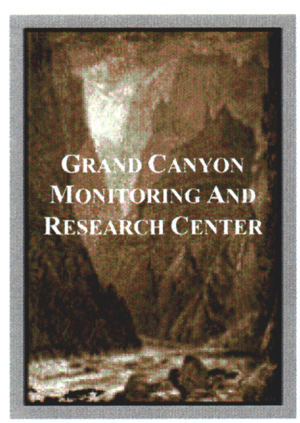
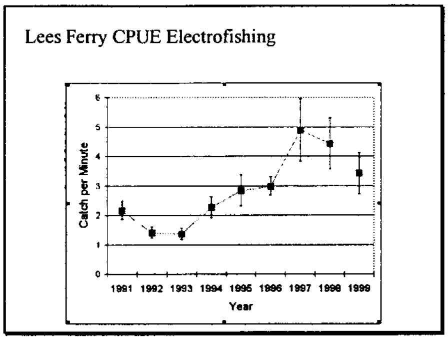
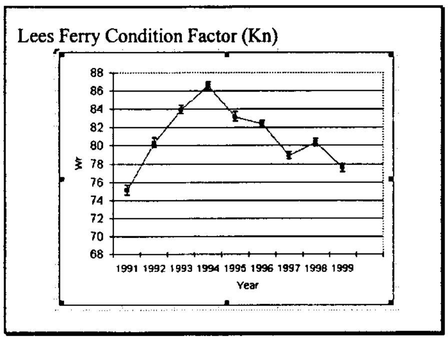


LEES FERRY TROUT FISHERY STATUS AND TRENDS
TECHNICAL WORK GROUP MARCH 23, 2001



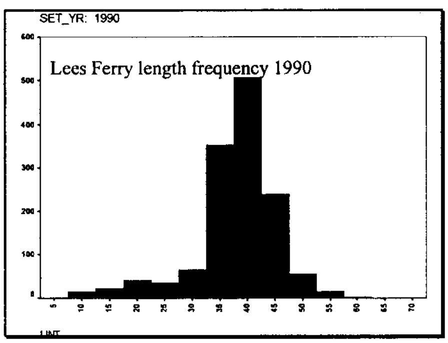
Catch per minute electrofishing at standard sites declined somewhat during 1999, from 4.4 fish per minute to 3.4 fish per minute. Difference was not statistically significant (error bars are 95% Confidence Intervals).

December 2000 Update: Mean CPE = 3.5 fish/ minute

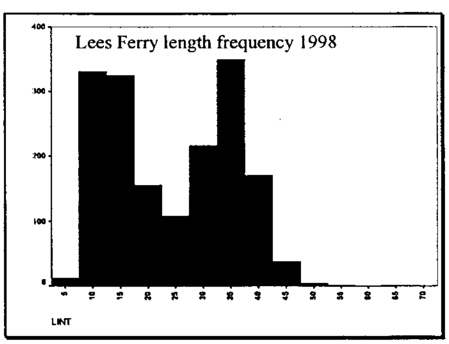


Kn (Wr) during 1999 was 77.5, down from 80.3 during 1998

December 2000 Update: Mean Kn = 73.9



Size composition of fish collected by electrofishing during 1990 shows an absence of small fish (< 150 mm) in the catch.



Size composition of fish collected by electrofishing during 1998 shows an abundance of small fish (< 150 mm) in the catch indicating successful natural reproduction.

Angler Use

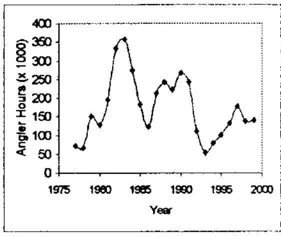


Figure 7. Annual use (angler hours), Lees Ferry 1977-1999.

Angler use remained fairly stable from 1998 to 1999 at 140,000 angler hours.

Angler catch per hour

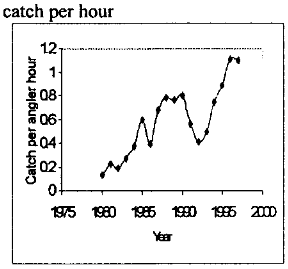


Figure 6. Mean catch of rainbow trout per angler hour, Lees Ferry 1980-1998.

Catch per angler hour remained stable from 1998 – 1999 at approximately 1.1 fish per angler hour. Stable angler use and catch rates suggest stability in the trout population.

Downstream emigration?

- > 400,000 hatchery stocked fish marked with coded wire tags 1991-1997
- 2021 trout examined in downstream reaches (1992-1999)
- 3 tested positive for cwt (or hook).
  - .14%

Downstream emigration of hatchery stocked fish from Lees Ferry to downstream reaches appeared to be negligible during 1991-1999.

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Fisheries Monitoring: Native & Non-native Fish in Grand Canyon

Grand Canyon Monitoring and Research Center: Biological Program

At present, very few reliable trend data (Meretsky, 2000) are available for native and non-native fish in the Colorado River. Most studies were primarily focused toward characterizing the life history characteristics; as well as directed toward understanding effects relative to Glen Canyon Dam operations. Although this information is very valuable it has not allowed us to reconstruct fish population dynamics. For this reason, in the last year we have restructured and changed the emphasis of the overall monitoring approach. Currently FWS, AGF and SWCA are conducting a joint sampling effort in monitoring and analyzing native and non-native fish population dynamics in the downstream sections of the Colorado River. This integrated effort is scaled back from previous years so that an alternate analytical method or model can be developed that incorporates disparate data sets in combination with ongoing data collection efforts. This year's monitoring program is directing its efforts toward:

1. Determining densities and distributional patterns of non-native fish by sampling with electrofishing gear. Sampling efforts include a combination of depletion and mark-recapture methods to develop catchability coefficients for population estimates of rainbow and brown trouts.

2. Development of stock assessment program for the LCR to provide seasonal estimates of abundance, over-wintering and post-monsoon survival/retention, age-size class structure, spawning abundance, and an index of recruitment strength.

3. Efforts will be coordinated with stock assessment activities in the Colorado River mainstem based on subsequent recapture and mark rates to estimate the relative proportion of mainstem to LCR populations. Secondly, this will be used to make inferences on various size class movement patterns and their survival in the river.

4. Data from this year's joint data collection effort combined with historical data will support the observational data for developing the stock synthesis model and evaluating catch-rate to indexed fish abundance data. This approach integrates a population model with an observational model to estimate key parameters of a population with respect to recruitment, abundance, and survival, so that we are capable of inferring how the population has responded through time.

Recognize that presently we have reduced the overall spatial scale and focus of this sampling and synthesis effort, directing it specifically to humpback chub and flannel-mouth suckers in the LCR tributary and inflow area (RM 58 to 65). This approach will provide a means to reconstruct observational data in order to infer historical population dynamics. Depending on our success, we intend on adapting this same approach and expanding it spatially to include other peripheral aggregations. For this reason, it is critical that we have access to the entire historical data in order to construct and develop the stock synthesis model. Data compilation and quality control efforts are ongoing for GCMRC, FWS and AGF. We expect to have received the source and synthesized historical data from these collaborators by early summer to populate the age-structured model being developed.

CPUE

Catch-per-unit-effort (CPUE) is an index used as a measure of relative fish abundance. Theoretically, the use of different gear types should be directly proportional to the abundance of fish locally caught. Yet, numerous environmental variables as well as fish behavior influence capture efficiency. Depending on the species, it has become apparent that this type of index does not provide an accurate estimate of abundance. However, it does seem to work quite effectively for monitoring non-natives, specifically trout. For the purpose of contrasting gear effectiveness (Gorman and Coggins 2000) we have been included a number of graphs to provide an example of CPUE variability for specific gear types and fish species. It is notable that CPUE variability for humpback chub is prevalent for all previous fish sampling efforts, which is the reason we are moving away from this conventional monitoring index.

Population Estimates

Population estimates for humpback chub (HBC) caught in the Little Colorado River are graphically represented by month (lower and upper 95% confidence intervals) (Douglas and Marsh 1996; Coggins 2001). The monthly estimates are not continuous for the period of record, and the break point reflects a nine-year gap from the most recent estimate (Oct-2000). To provide some semblance of trend, we have highlighted population estimates (red) that are similar in sampling date. However, recognized that population estimates are problematic since the LCR is not a closed population. Therefore, monthly population estimates will vary through time due to effects from immigration and emigration of spawning adults and juveniles moving locally or at great distances within the LCR and Colorado River ecosystem. Also, the accompanying histogram represents the distribution of abundance estimates by size class at intervals of 10 mm total length that were calculated for the LCR population during the 2000-fall sampling trip. Future monitoring efforts scheduled for this spring and fall will utilize this same stock assessment approach to provide seasonal population estimates (spring and fall) for HBC. Alternately, the stock syntheses model scheduled for development will provide us with a method to reconstruct demographic trends by size class for the period of observation.

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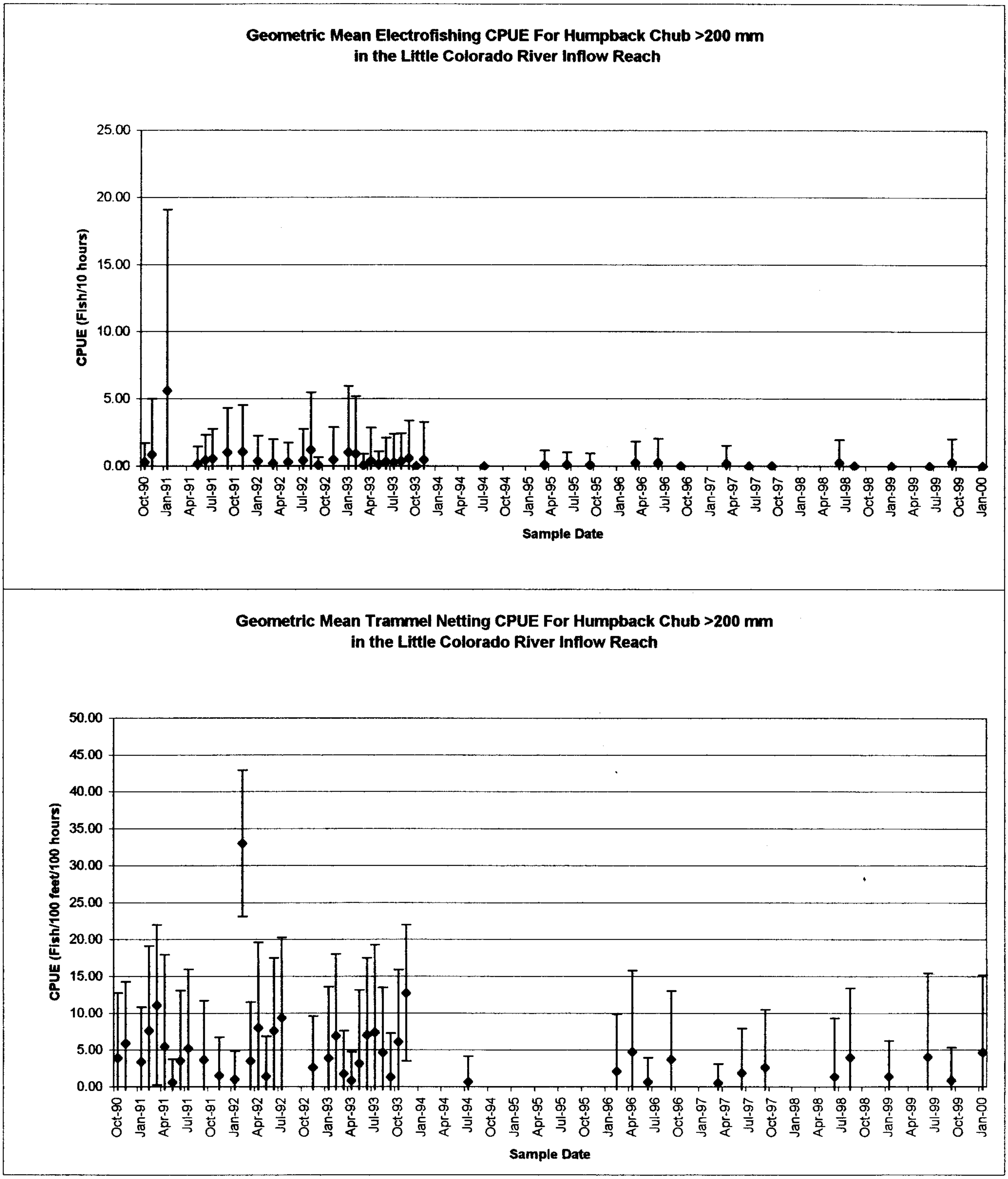
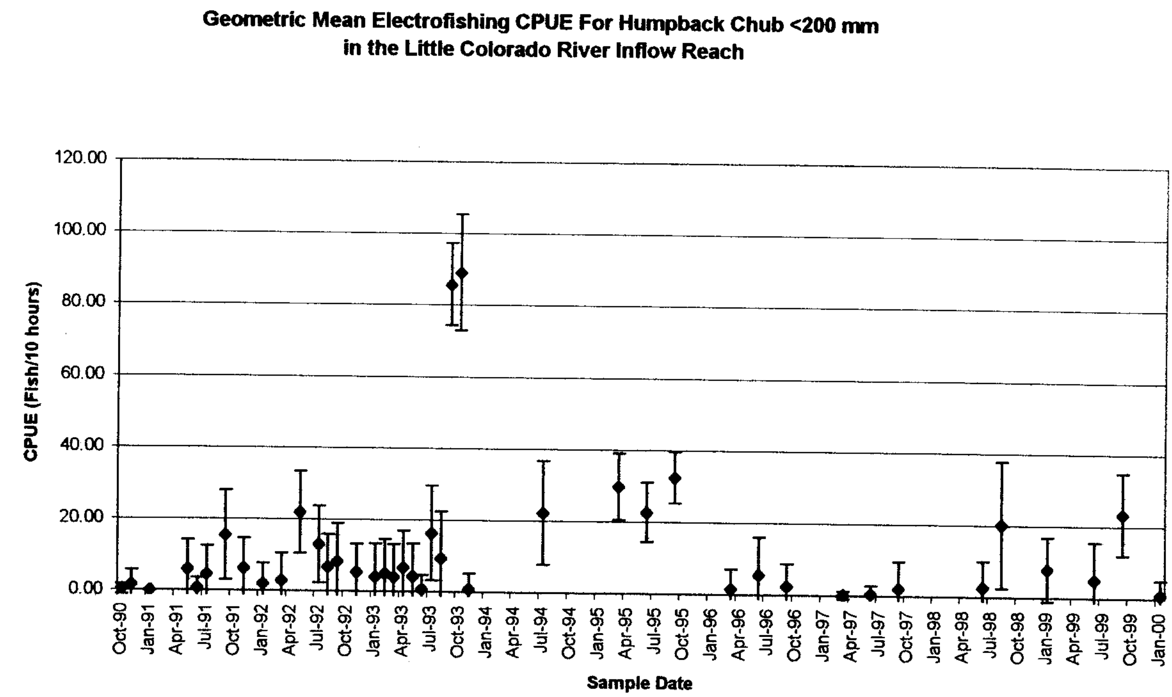


Figure 6. Electrofishing and trammel netting CPUE for humpback chub > 200 mm within the Little Colorado River Inflow Reach. Error bars are one standard error.



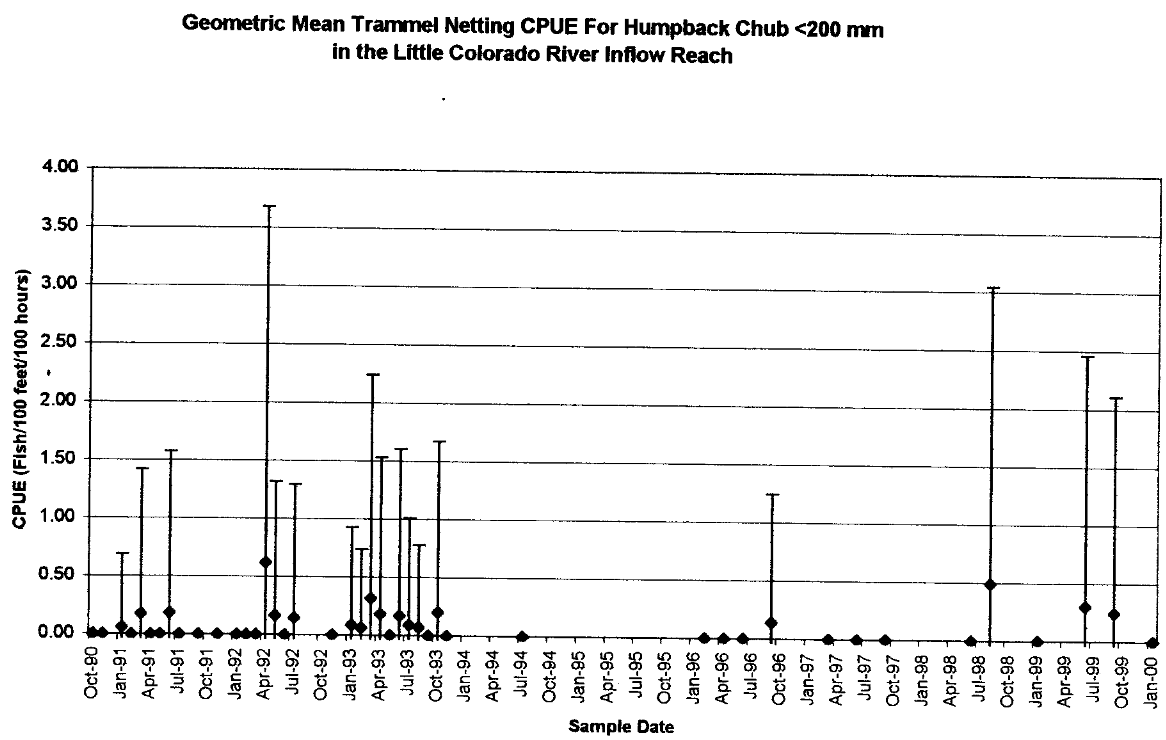
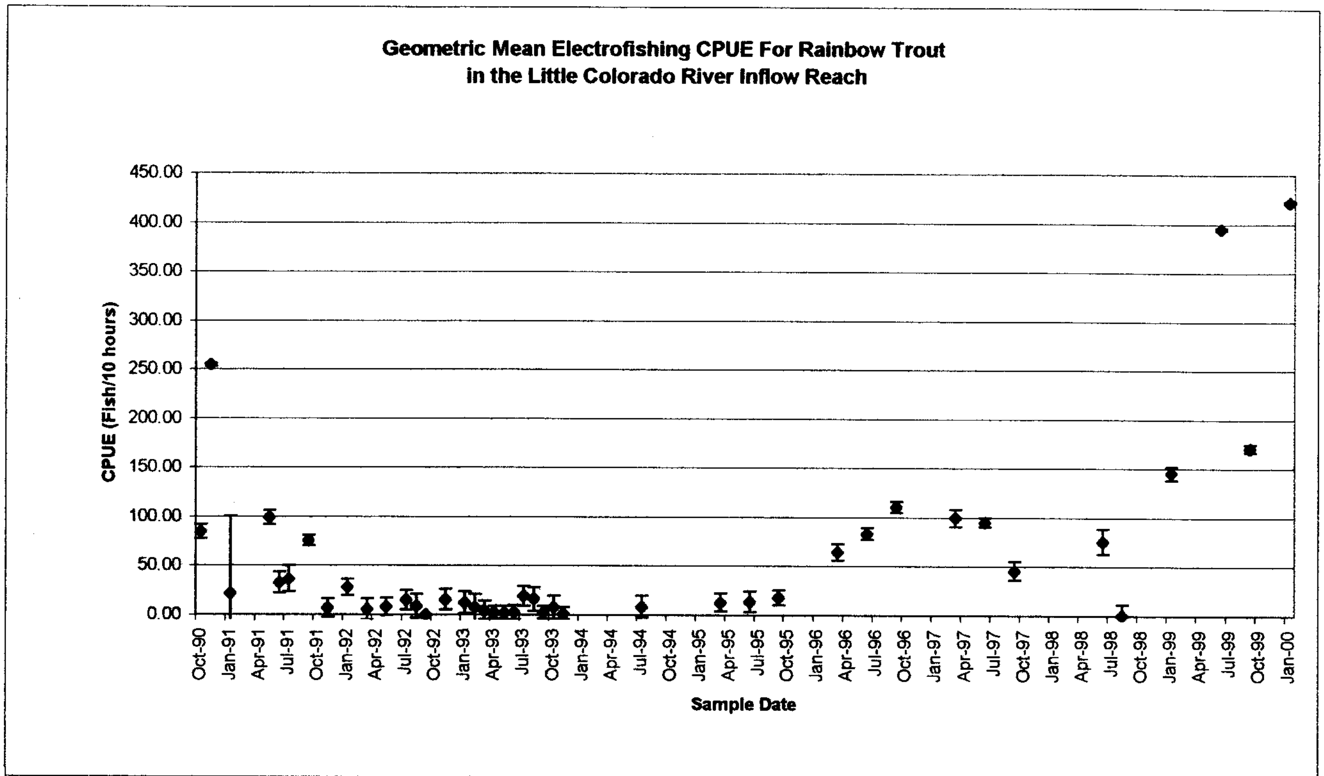


Figure 1. Electrofishing and trammel netting CPUE for humpback chub < 200 mm within the Little Colorado River Inflow Reach. Error bars are one standard error.



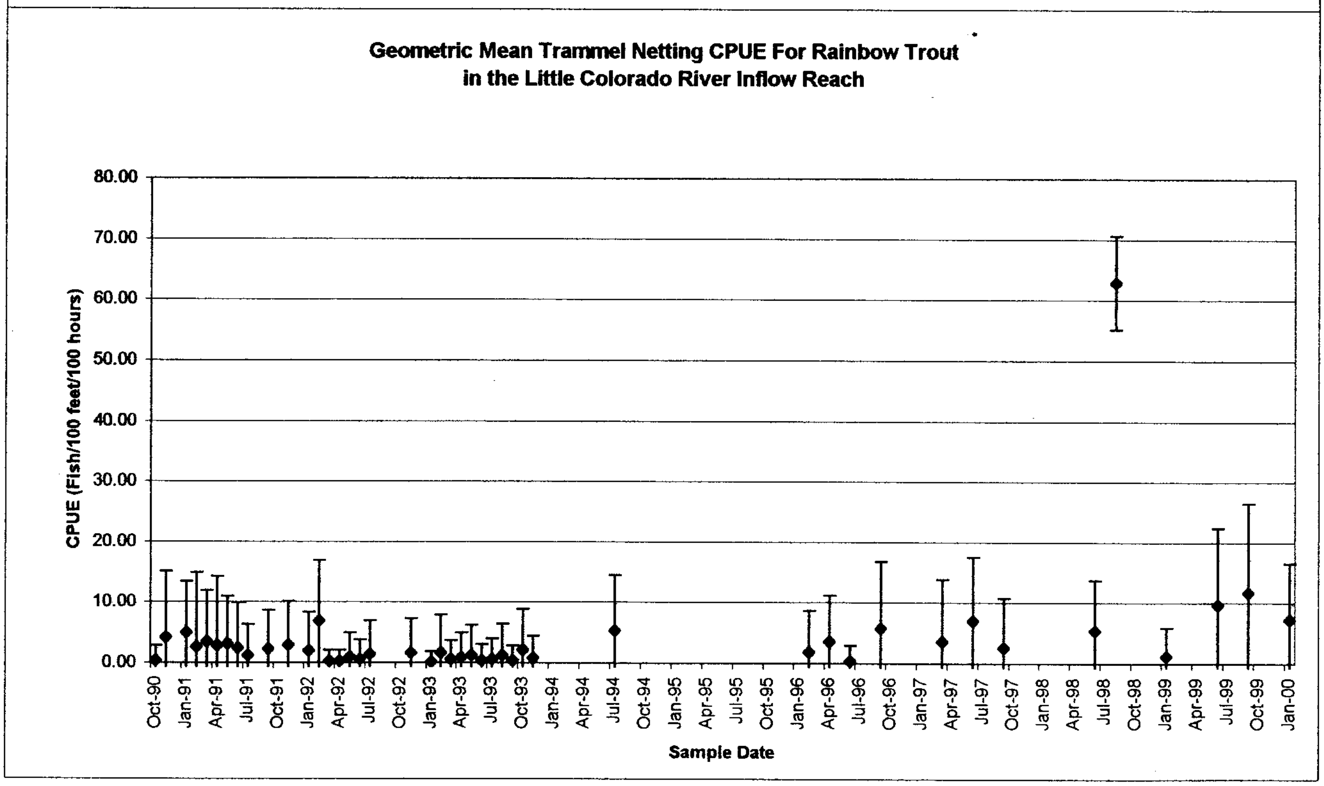
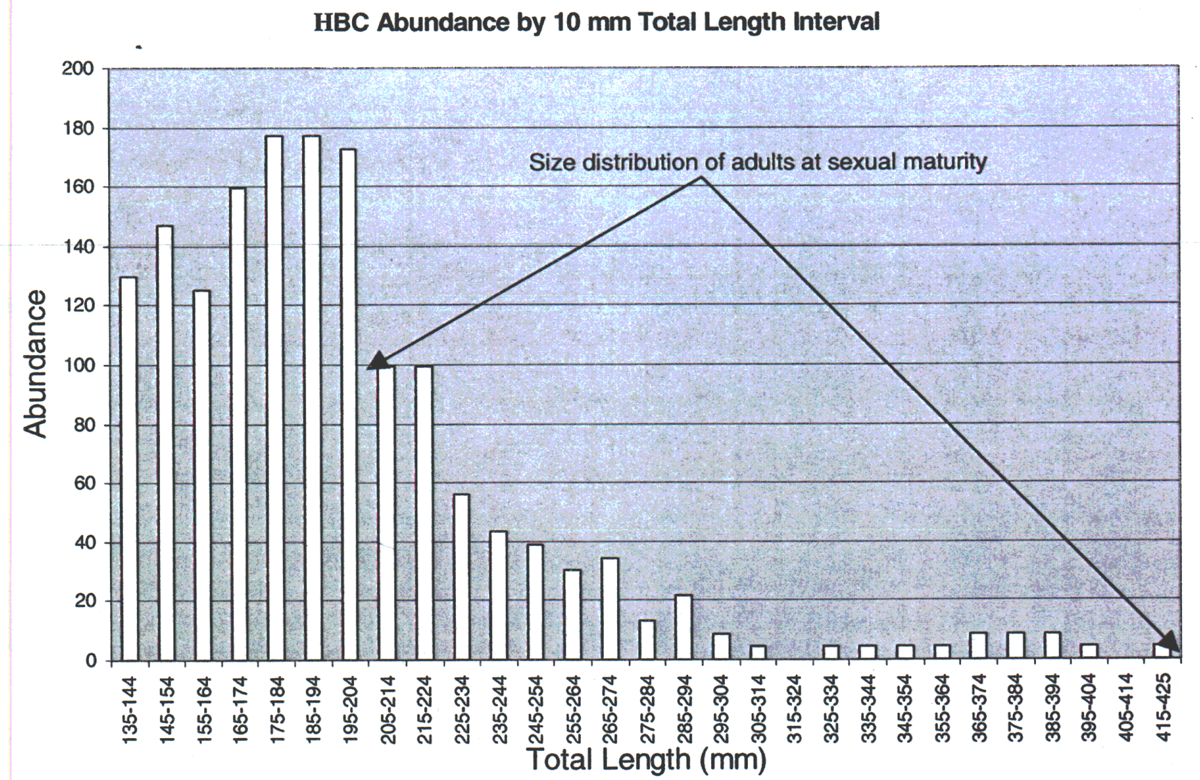
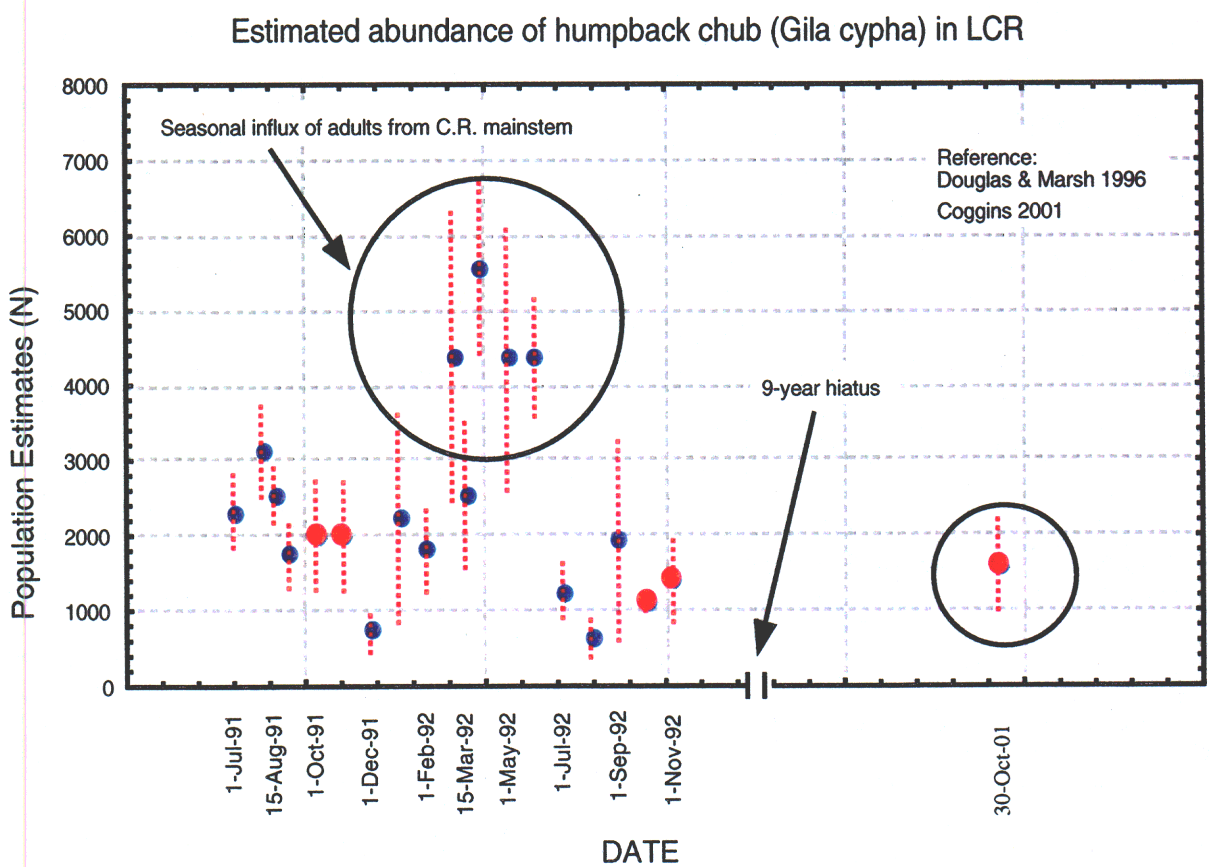


Figure 12. Electrofishing and trammel netting CPUE for rainbow trout within the Little Colorado River Inflow Reach. Error bars are one standard error.



HBC Abundance by 10 mm Total Length Interval
Size distribution of adults at sexual maturity
Abundance
0
20
40
60
80
100
120
140
160
180
200
135-144
145-154
155-164
165-174
175-184
185-194
195-204
205-214
215-224
225-234
235-244
245-254
255-264
265-274
275-284
285-294
295-304
305-314
315-324
325-334
335-344
345-354
355-364
365-374
375-384
385-394
395-404
405-414
415-425
Total Length (mm)



Estimated abundance of humpback chub (Gila cypha) in LCR
Seasonal influx of adults from C.R. mainstem
Reference:
Douglas & Marsh 1996
Coggins 2001
9-year hiatus
Population Estimates (N)
0
1000
2000
3000
4000
5000
6000
7000
8000
1-Jul-91
15-Aug-91
1-Oct-91
1-Dec-91
1-Feb-92
15-Mar-92
1-May-92
1-Jul-92
1-Sep-92
1-Nov-92
30-Oct-01
DATE

VARIABILITY OF HUMPBACK CHUB CONDITION

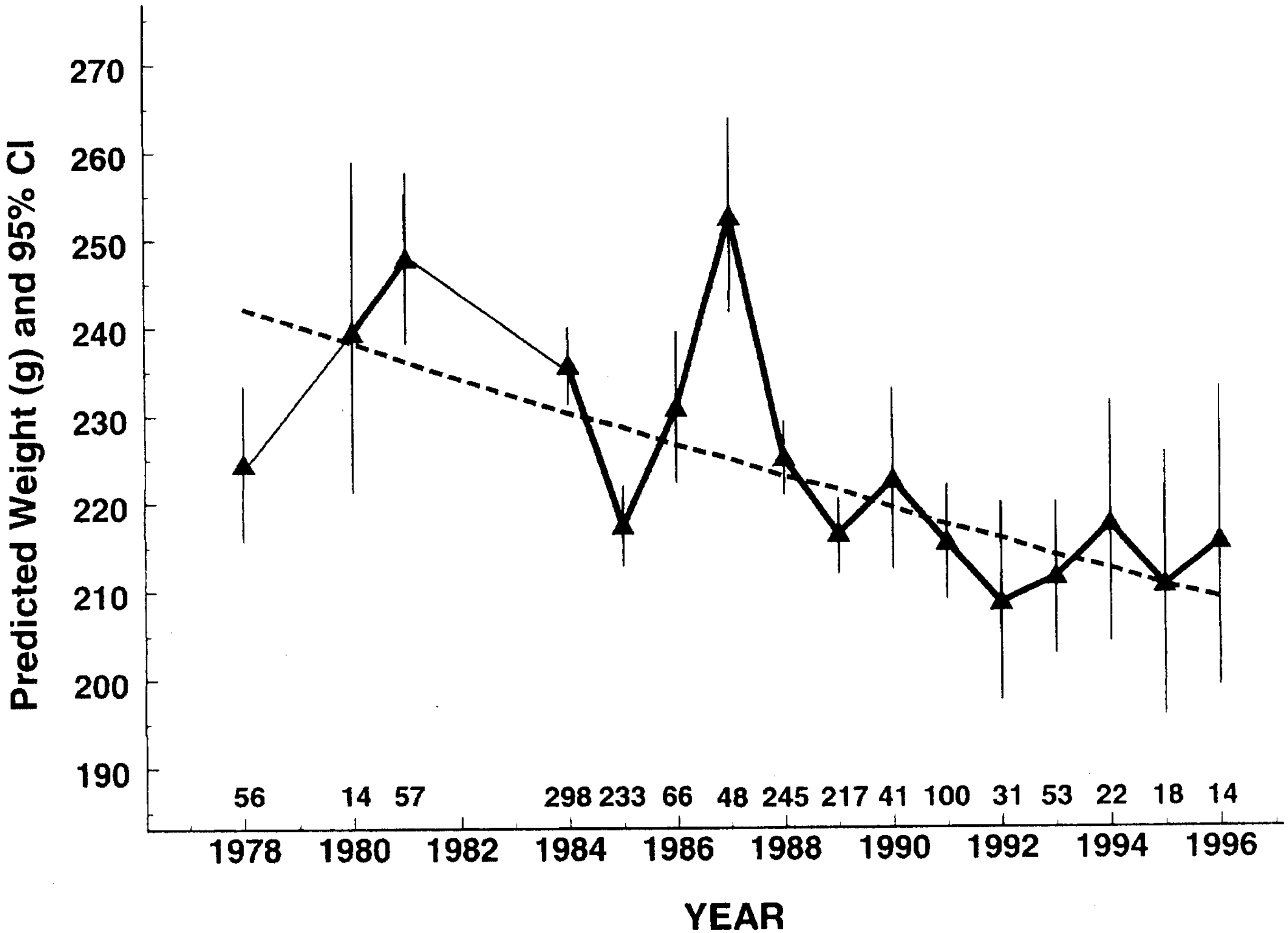


Figure 3. – Predicted weights and 95% confidence intervals (CI) of 300-mm TL adult male humpback chub from data collected at the Little Colorado River—Colorado River confluence, 1978-1996. The broken line shows the linear trend from a log-log analysis, back-transformed into the original units. Predictions are back-transformed output from a log-log analysis. Sample sizes are shown above the abscissa.

Figure 1. A specimen of the endangered Humpback Chub (Gila cypha)

Figure 2. Razorback Sucker (Xyrauchen texanus)

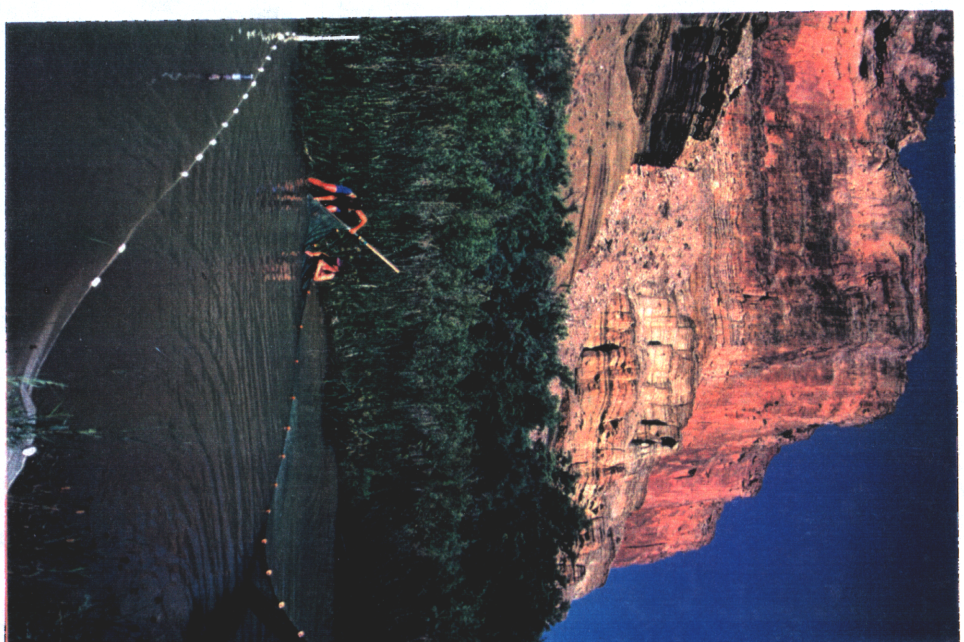


Figure 3. Seining for native fish, Kwagunt backwater, RM55. Warmer backwaters may provide breeding habitat

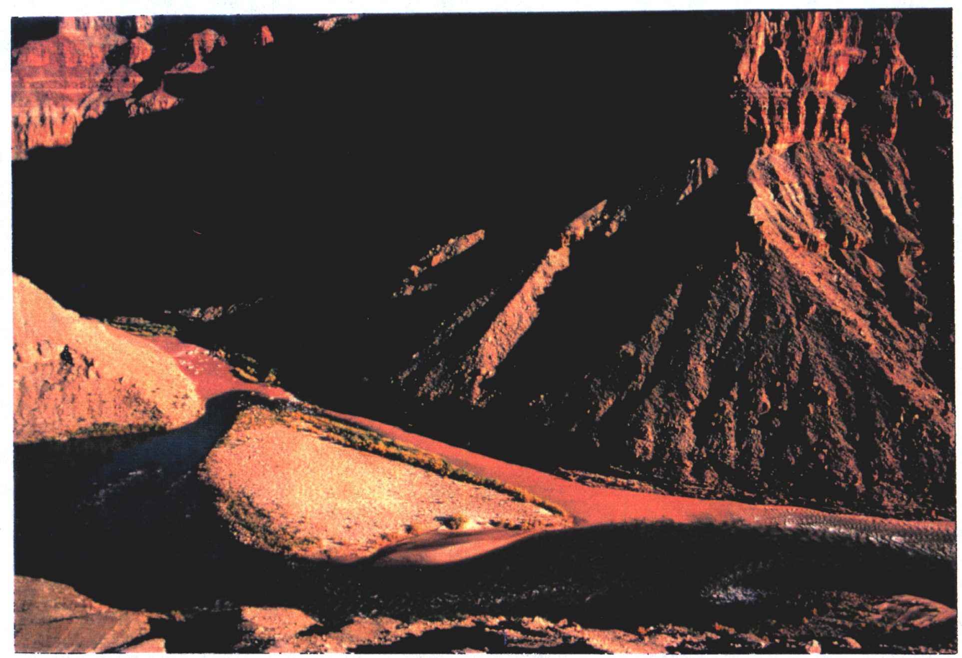


Figure 4. View up LCR. Higher mainstem flows push cold water into chub Fingerling habitat below LCR island

Integrated Terrestrial and Aquatic Ecosystem Activities

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GCMR-700

September 18, 2000

MEMORANDUM

To: Kathleen Wheeler

From: Barry D. Gold

Subject: Summary of Recent Sediment related Research Findings

A few months ago I sent you five published scientific papers that presented the results of recent sediment-related research sponsored or conducted by GCMRC. At that time you asked that we prepare a summary of those papers for your information. I asked Ted Melis, the GCMRC Program Manager for Physical Resources and the sediment researchers whose work we were citing to develop a summary memo. While the attached memo was reviewed by myself and Randy Peterson it represents the researcher's own perspectives on their recent findings.

Their conclusions could have important implications for the Glen Canyon Dam Adaptive Management Program. They challenge the two hypotheses on which the EIS and ROD were based. First they challenge the notion that sand can be stored in the channel bed over a number of years and then once sufficient accumulation has occurred it can be redistributed through a Beach/Habitat-Building Flow. Rather, they argue that the sand which enters the system from tributary events is transported downstream relatively rapidly. Second, they postulate that the fraction of sand that is remaining will not be sufficient to build bars and provide a positive sand balance.

The implications for their findings for sediment resources only are: (1) that releases above peak-power-plant discharge may need to be conducted immediately after substantial inputs of sand from tributaries; and (2) flows following sand inputs from tributary events should be maintained at 8,000 to 10,000 cfs to maximize sediment storage until peak power-plant discharges can be implemented.

Their findings also suggest two hypotheses that will need to be evaluated based on the data collected from the GCMRC long-term monitoring program. One is that the system will exist in the post-dam era in some sort of degraded equilibrium as compared to the pre-dam sediment balance. The other is that the system will continue to experience a long-term loss of sediment.

United States Department of the Interior

U.S. GEOLOGICAL SURVEY
Pacific Science Center
University of California at Santa Cruz
1156 High Street
Santa Cruz, CA 95064

MEMORANDUM

August 29. 2000

To: Barry D. Gold, Chief, Grand Canyon Monitoring and Research Center

From: David M. Rubin DMR and David J. Topping, U.S. Geological Survey
John C. Schmidt, Utah State University
Joe Hazel, Northern Arizona University

Re: Summary and Discussion of Recent Research Findings Related to Dam Operations and Sand Bar Resources of the Colorado River Ecosystem

<u>Background</u>

Sand bars are an essential component of the Colorado River ecosystem downstream from Glen Canyon Dam. They create habitat utilized by endangered fish; they contain and protect an array of Native American cultural resources; they provide campsites used by recreational boaters; and they are a distinctive attribute of the pre- and post-dam river landscape. Improving and maintaining sand bars below the dam is a fundamental long-term management objective of the Grand Canyon Protection Act, the Operation of Glen Canyon Dam Final Environmental Impact Statement, and the Glen Canyon Dam Adaptive Management Program (See Attachment 1).

Sand bars and sandy banks of the Colorado River in Grand Canyon are maintained by the sand that is transported through the canyon. The high-elevation parts of these sand bars (those parts at elevations above peak power-plant discharge) can be constructed only by flows that exceed peak power-plant discharge (i.e. flows greater than 31,000 cfs); in the absence of such high flows, these high-elevation areas are eroded by lower flows or canyon winds or are rapidly colonized by both native and exotic vegetation. Flows above peak power-plant discharge are necessary to maintain these high-elevation sand bars, but are effective only when the river contains sufficient sand resources.

Evaluating restoration and sustainability of sand resources is a complicated problem that involves sand storage on the Colorado River's bed, tributary resupply of sand, sand deposition induced by flows above peak power-plant discharge, erosion and transport of sand during normal power-plant operations, and recolonization by vegetation. Improving or sustaining sand resources is a difficult challenge because Glen Canyon Dam traps all of the sediment from the upper Colorado River, resulting in an approximate 94% reduction (relative to pre-dam inputs) in the amount of sand supplied to the Colorado River at the upstream boundary of Grand Canyon National Park.

With respect to restoration and sustainability of sand bars, the Secretary of the Interior's 1996 Record-of-Decision (ROD) for operations of Glen Canyon Dam is based primarily on two hypotheses:

(1) that much of the sand introduced to the Colorado River by tributaries downstream from Glen Canyon Dam can accumulate in the channel over multiple years if dam releases do not exceed average volume, and

(2) that flows above peak power-plant release (such as the 45,000 cfs flow in 1996) can effectively move that accumulated sand from the channel bed to bars, thereby rebuilding sand bars that are eroded by typical dam releases.

Recent Findings

Work conducted since the 45,000 cfs release in 1996 has shown that the first hypothesis on which the 1996 ROD was based is false and that the second hypothesis is only partially true. The 45,000 cfs release in1996 increased the amount of sand at high elevations (Figure 1), but the sand that was deposited at high elevations came largely from the lower portions of the sand bars (Schmidt, 1999) and not from the channel bed as originally hypothesized.

Under the dam operations imposed by the 1996 ROD, most newly input sand is not stored on the channel bed for long periods of time (Topping et al., 2000a; Topping et al., 2000b). Flows above peak power-plant release cannot take advantage of multiple years of sand accumulation, because substantial multi-year accumulation of sand does not occur. Instead, this sand is transported downstream relatively rapidly. The time required to export (transport downstream past the Grand Canyon gage) one-half of a 500,000 metric ton input of tributary sand (the contribution of a typical, moderate, Paria flood) varies from less than one week (for dam discharges of 25,000-30,000 cfs) to roughly one year (for discharges of 10,000 cfs), as illustrated in Figure 2.

The time required to export the second half of a tributary input is greater than for the first half (for a constant water discharge), because the second half is coarser, as a result of winnowing of the bed (Topping et al., 2000b; Rubin and Topping, in press). The remaining half, however, is not necessarily sufficient to enable both bar-building and a positive sand balance. For example, the 45,000 cfs release in 1996 exported 700,000 metric tons of sand from Marble Canyon in one week. Thus, a release above peak power-plant discharge is a double-edged sword: high discharges are indispensable for rebuilding high-elevation parts of bars, but high discharges deplete sand resources rapidly (Figure 2). Conducting a release above peak power-plant discharge when recent tributary sand inputs are greatest will tend to minimize the negative impact on the sand resources.

Since the 45,000 cfs release in 1996, six kinds of sediment and topographic data have been examined: sediment input and output, changes in grain size of sand on the river bed, changes in sand-bar size, geomorphic mapping, and changes in channel cross-sections. Some of these studies document rapid export of tributary sand (transport past the Grand Canyon gage), whereas others demonstrate a lack of substantial multi-year accumulation of sand, especially in upper Marble Canyon:

• Both measurements and calculations of sediment input and output have shown that most fine sediment (sand, silt, and clay) introduced by tributaries is exported within a few months (Topping et al., 2000a; Topping et al., 2000b). For example, field measurements show that most sediment introduced by floods on the Paria River in September, 1999, was exported within 6 weeks. On a longer time scale (August 11, 1999 to May 14, 2000), the Paria supplied approximately 0.8 million metric tons of sand to the Colorado River, while roughly twice this amount of sand (1.5-2 million metric tons) was exported past the Lower Marble Canyon gage.

• Changes in grain size of sand on the river bed also demonstrate rapid export of tributary sand. The bed was measurably enriched in finer sand as a result of Paria floods in September, 1998 (median grain size of Paria River sand is 0.11 – 0.13 mm). When sampled next (May, 1999), most of the new fine-grained sand on the bed had been winnowed (Topping et al., 2000b). The remaining sand in the channel was generally too coarse to be transported onto the high-elevation areas of sand bars.

• Topographic surveys of 11 sand bars in the first 76 miles downstream from the dam document a continuing depletion of sand-bar area from 1991 to 1999 (Figure 1A). High flows in 1996 and 1997 temporarily reversed this trend but did not halt the continuing decrease in sand-bar area. The sand bars (above 20,000 cfs) were 22% smaller in surface area in 1999 (Figure 1A), although they contained 2-3% more sand than in 1991 (Figure 1B).

• Topographic surveys of 35 sand-bar sites documented scour of sand during the 45,000 cfs release in 1996, followed by net accumulation (J. Hazel, personal communication). Comparison with tributary-input data for the same time, however, indicates that most of the observed accumulation occurred when there was no substantial tributary sand input.

• Repeated surveys of channel cross-sections from 1991 to 1999 have shown relatively large and rapid fluctuations in the amount of sediment present (M. Flynn and N. Hornewer, personal communications). These fluctuations are interpreted to represent temporary storage and subsequent down-river transport of sediment. These studies have not detected multi-year accumulation of sediment.

• Analysis of bed-elevation data at the historical Marble Canyon dam sites suggests considerable loss of sediment from the 1950's to the present. Not only does the post-dam river contain less sand than the pre-dam river, but the remaining sand is generally coarser (Rubin and Topping, in press).

• Geomorphic mapping indicates that deposition of the 45,000 cfs release in 1996 was least near Lees Ferry and was greatest downstream from the Little Colorado River (Schmidt et al., 1999; H. Sondossi, personal communication). The magnitude of "improvement" is greatest further downstream where more tributaries have delivered fine sediment to the channel. Thus, the "improvement" caused by any specific release above peak power-plant discharge differs both temporally and spatially, depending on how enriched or depleted a particular reach is at the time.

Implications for Current Management Actions

The features listed above characterize a system where increases in sand abundance result not from incremental multi-year accumulation but rather from temporary storage of individual tributary inputs. In such a system, where increases in sand abundance are temporary, the goal for building sand bars should be to exploit tributary inputs as soon as possible, because the volume of sand available for bar-building is greatest immediately after large tributary inflows. To be effective in rebuilding sand bars, releases above peak power-plant discharge should occur soon after these tributary inflows, before the new sand is lost downstream (Figure 2).

Large Paria tributary inflows typically occur during late summer and early fall. Under the rules of the 1996 ROD, however, releases above peak power-plant discharge cannot be implemented on a schedule that takes advantage of such inputs. If a release above peak power-plant discharge cannot be scheduled immediately following a tributary input, another option might be to maintain low flows until a release above peak power-plant discharge could be implemented; the low flows would reduce the amount of sand lost downstream. The magnitude of an acceptable low flow that limits the rate of sand export depends on the volume of sand introduced by tributary flooding, the length of time following the tributary input, and what loss of sand downstream is considered acceptable. At dam releases that are typical of recent years, half of the sand introduced by a tributary flood can be exported within days or weeks (Figure 2). Retention of sand for more than a few months requires sustained dam releases at the lower discharges currently permitted under the ROD (8,000 - 10,000 cfs).

Recommendations for Future Management Actions

Even if rules for releases above peak power-plant discharge are revised to allow scheduling during or shortly after periods of sand inputs, the objectives of improving or sustaining the desired abundance, form, and function of sand bars may still not be possible because the long-term sand supply from tributaries in critical reaches may be too small. The 76-mile reach downstream from Glen Canyon Dam has but one large sand source: the Paria River. The supply of sand from the Paria River is only about 6% of the sand that was supplied to this reach prior to the construction of Glen Canyon Dam. Natural floods from the Paria River may be too infrequent and too small to restore sand resources in this critical upstream reach, which includes the 60-mile length of Marble Canyon within Grand Canyon National Park.

Altering the timing of releases above peak power-plant discharge (or drastically reducing the dam's discharge until such flows can be released) may be insufficient to rebuild sand resources above existing levels or to achieve sustainability at present levels; additional monitoring will be required to see if these options are successful. If alternative timing of releases above peak power-plant discharge proves to be insufficient for sand-bar management goals, then other more effective alternatives should be evaluated.

One approach would be to selectively add sand downstream of the dam. This alternative ("sediment augmentation") was considered and eliminated during the Operations of Glen Canyon Dam EIS process. We are unaware of engineering feasibility studies of such a program, but sediment by-pass is an attribute of some recently built dams, as well as harbors and estuaries. A review of sediment pipeline technology is included on the EPA web site, http://www.epa.gov/glnpo/arcs/EPA-905-B94-003/B94-003.ch5.html. Addition of enough sediment (continuously, seasonally, or perhaps only during releases above peak power-plant discharge) would offer greater flexibility in dam operations, and it is conceivable that such an approach might cost less than imposing new constraints on dam operations. It is possible that sediment augmentation, substantial seasonal modification of flows released from Glen Canyon Dam, or both, might be able to restore the sand resources in the Colorado River ecosystem in Grand Canyon National Park without more extreme actions.

Conclusions

The post-dam Colorado River is depleted in sand resources relative to the pre-dam river. The existing management strategy permitted under the ROD is failing to restore sand resources in the ecosystem in Grand Canyon National Park. The bars are continuing to decrease in surface area, and no long-term retention of tributary sand has been detected.

Our opinion, based on the information presented in this summary, is that any of the following approaches will have a significantly greater likelihood of success in restoring or retaining sand resources in the Grand Canyon ecosystem:

(1) Implement releases above peak power-plant discharge immediately after substantial inputs of sand from tributaries.

(2) Maintain low flows following sand inputs until releases above peak power-plant discharge can be implemented.

(3) Add sediment downstream from the dam.

Dam operations of the last decade must have caused one of the following possible effects on sediment resources in the Colorado River ecosystem: sediment resources were enhanced or replenished relative to conditions in the early-to-mid 1990's, sediment resources were maintained in a degraded (post-dam) condition, or long-term export and loss of sediment resources is continuing. Distinguishing between such possibilities has been—and should continue to be—an important function of the GCMRC Adaptive Monitoring Program. The research reviewed above demonstrates that current operations are failing to increase sediment resources. At least one significant measure of sediment resources, surface area of sand bars above 20,000 cfs, documents continuing depletion of sand resources.

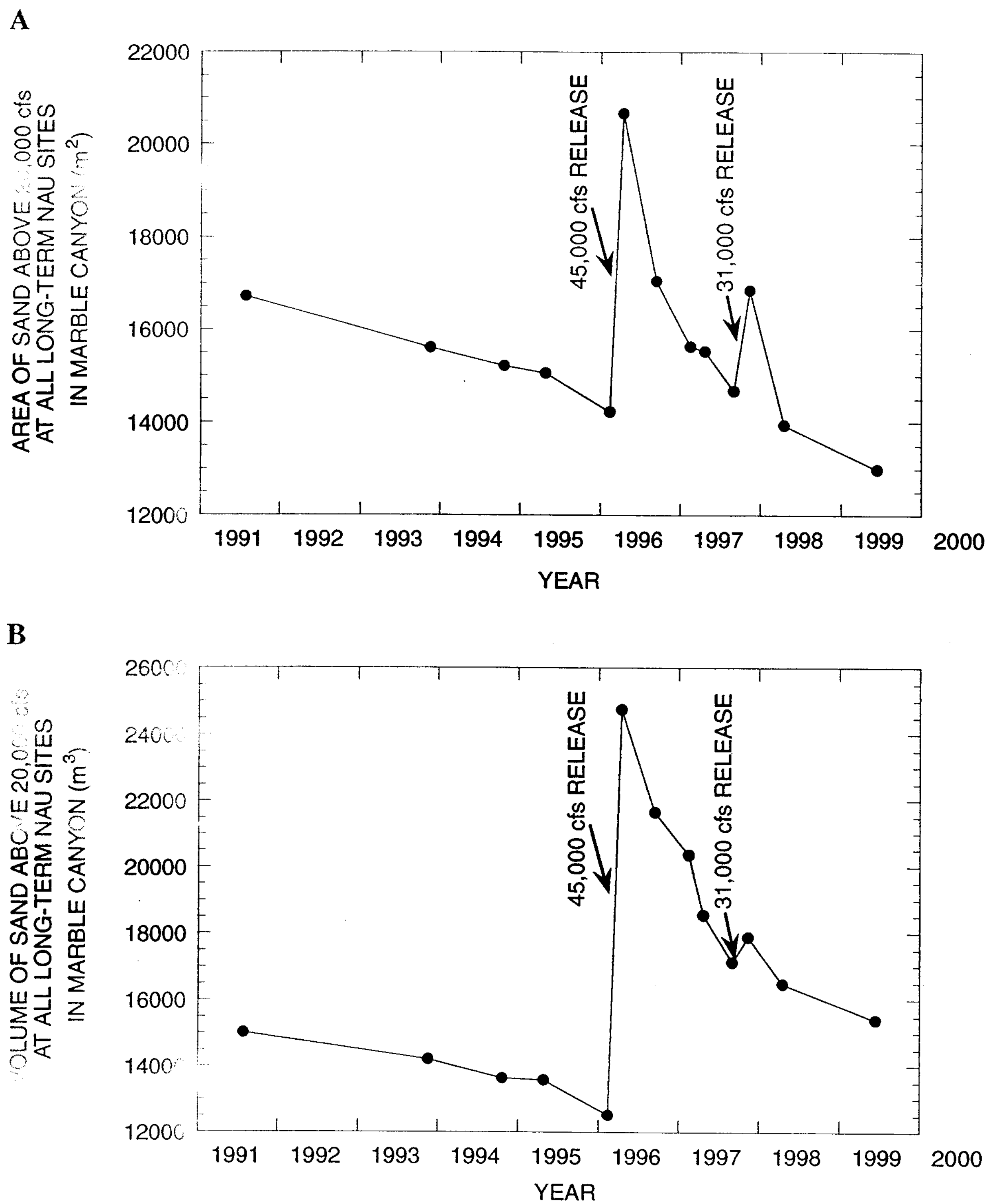

Figure 1. Changes in sand-bar surface area and volume at all 11 long-term Northern Arizona University study sites in Marble Canyon. **A.** Surface area of sand bars decreased by 22% from 1991 to 1999 despite temporary increases caused by high releases in1996 and 1997. **B.** Volume of sand bars in 1999 was 2-3% greater than in 1991.

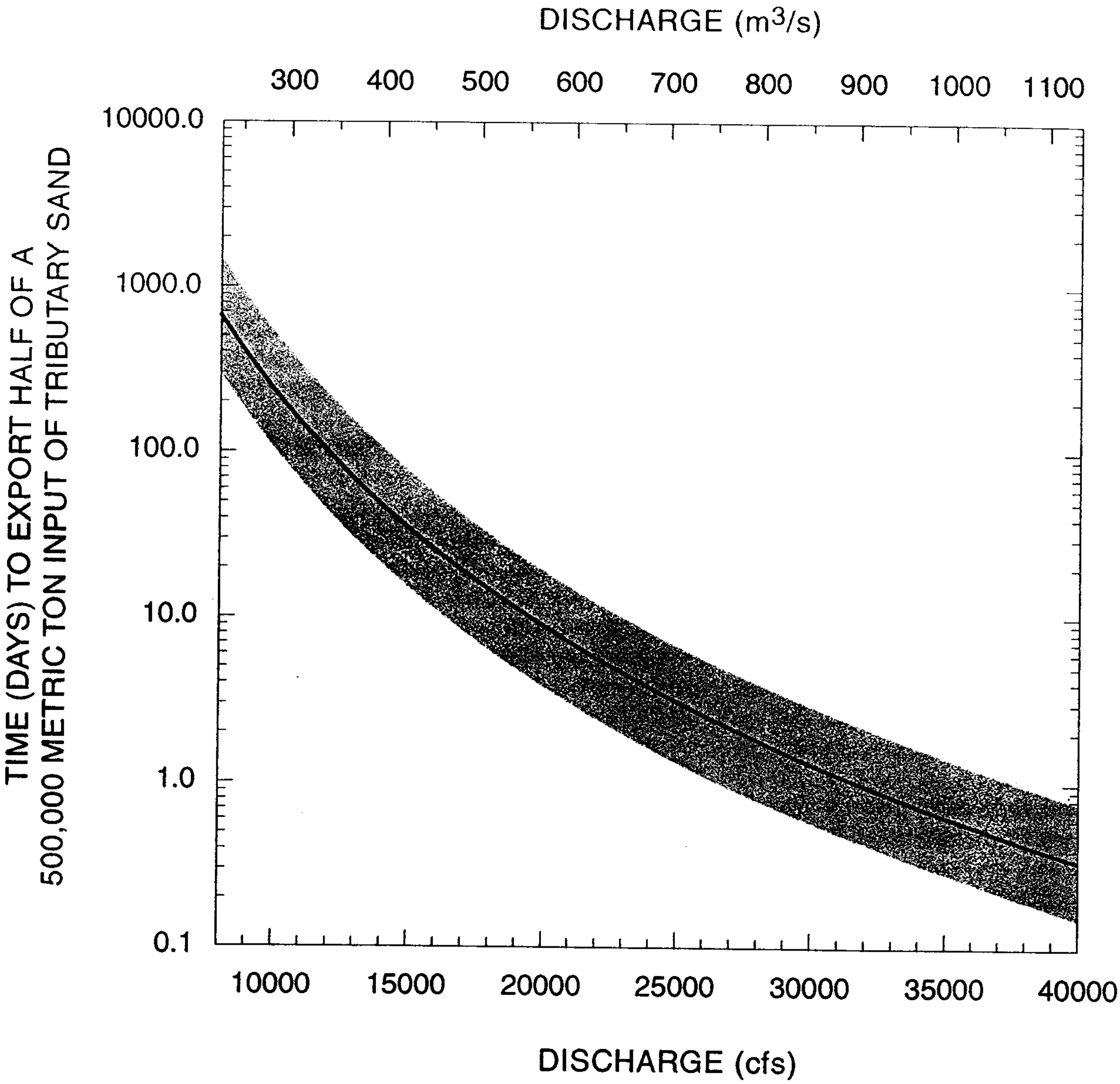

Figure 2. Calculated time to export one-half of a 500,000 metric ton input of tributary sand past the Grand Canyon gage. Calculations are based on sediment-transport data collected at the Grand Canyon and above LCR gages during the 1990's. The upper limit of the shaded area (slowest export) is calculated using the average suspended-sediment concentration for each specified discharge; the lower limit of the shaded area (most rapid export) is calculated for high concentrations of suspended sediment at each discharge; the solid line in the center of the shaded band is calculated using concentrations that decrease through time from high values (during and immediately following tributary inputs) to mean concentrations (after half of the tributary sand has been exported). At the upper range of dam operations, half of the sediment is exported within a few days; multi-year accumulation is only likely to occur if discharge is restricted to less than 8,000-10,000 cfs. To maximize the benefit of sand supplied by tributaries, releases above peak power-plant discharge should be implemented as soon as possible after tributary input events.

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Attachment 1. Management objectives for sediment resources within the Glen Canyon Dam Adaptive Management Program are stated as follows in the June 10, 1998 Management Objectives document adopted by the Adaptive Management Work Group.

SEDIMENT RESOURCES

Goal: to maintain a range of sediment deposits over the long-term, including an annually flooded bare-sediment (unvegetated) active zone, a less frequently flooded vegetated zone, terraces (within the 45,000 cfs river stage), and backwater channels. Managing sediment resources will be on a reach-scale basis. Should significant and localized adverse impacts occur, site-specific mitigation would be considered.

Definition: Sediment resources include a broad array of material, ranging from suspended fines to coarse gravels. Primary interest relates to both material in suspension, which affects benthic capability, as well as stored sediment in beaches and channel margins, which affects recreation.

MANAGEMENT OBJECTIVES

MO 1: Maintain a long-term balance of river-stored sand to support maintenance flow (in years of low reservoir storage), beach/habitat-building flow (in years of high reservoir storage), and unscheduled flood flows. Maintain system dynamics and disturbance by annually (in years which Lake Powell water storage is low) redistributing sand stored in the river channel and eddies to areas inundated by river flows between 20,000 cfs and maximum power plant capacity.

MO 2: As a minimum for each reach, maintain the number and average size (area and thickness) of sandbars and backwaters between the stages associated with flows of 8,000 and 45,000 cfs that existed during the 1990/91 research flows.

MO 3: Periodically increase the average size of sandbars above the 20,000 cfs river stage and number and average size of backwaters to the amounts measured during the high period of 1990/91 or the 1996 test of the beach/habitat-building flow in as many years as reservoir and downstream conditions allow.

M) 4: Maintain system dynamics and disturbance by redistributing sand stored in the river channel and eddies to areas inundated by river flows up to 45,000 cfs in as many years as possible when BHBF hydro logic and resource criteria are met.

RECREATION

MANAGEMENT OBJECTIVES

MO 2: Maintain flows (under approved operating criteria) and sediment processes that create an adequate quantity, distribution and variety of beaches for camping, as long as such flows are consistent with management of natural recreation and cultural resource values (other natural resource values).

DEVELOPMENT OF A DYNAMIC SEDIMENT BUDGET FOR THE COLORADO RIVER ECOSYSTEM

David J. Topping, USGS

This research is intended to develop predictive methods for determining the real-time inputs of sand, silt, and clay to Colorado River ecosystem and the spatial and temporal evolution of the sediment supply in the Colorado River. Because the grain size of sediment in the Colorado River evolves as functions of tributary activity and dam operations, mainstem sediment-transport rates evolve by over an order of magnitude. Thus, static sediment budgets using stable sediment-rating curves (as done in the 1995 Glen Canyon Dam Environmental Impact Statement) cannot be constructed. Our approach is to use a process-based methodology to develop a dynamic sediment budget for the Colorado River ecosystem. The methods that we are developing will allow managers to design dam releases to maximize the retention of fine sediment in the Colorado River ecosystem under very different sediment-supply conditions.

Analysis of sediment budgets suggests that both before and after completion of Glen Canyon Dam in 1963, the Colorado River in Grand Canyon was annually supply limited with respect to fine sediment (i.e., sand, silt, and clay). During each year, between 80 and 120% of the supply of fine sediment to the reach between the Lees Ferry and Grand Canyon gages was exported. In both the late pre- and early post-dam periods, storage of fine sediment in this reach was typically for 1-2 years. Completion of the dam decreased the supply of fine sediment to this reach by 83% , decreased the seasonal storage of sediment by about 50%, and radically altered the seasonal patterns of sediment storage and erosion. In the pre-dam era, during lower flows, the san-transport capacity of the Colorado River at the Lees Ferry gage was lower than that at the Grand Canyon gage, with the opposite being true during higher flows. Because of these differences in transport capacity, in the pre-dam era, storage of sediment in Marble and upper Grand Canyons increased rapidly during mid-July through October, the season of dominant tributary sediment input. Following this rapid increase, the volume of sediment stored in Marble and upper Grand Canyons continued to increase at a slower rate as sediment was supplied from the Colorado River above Lees Ferry. Finally, during the snowmelt flood, sediment would be eroded from Marble and upper Grand Canyons. In the post-dam era, storage of sediment in Marble and upper Grand Canyons only increases during the time of large sediment inputs form the Paria and Little Colorado Rivers. During the rest of the year in the post-dam era, the tendency is for erosion of sediment from Marble and upper Grand Canyons. Thus, Glen Canyon Dam has converted a system in which sediment would generally accumulate over 8 months of a year to one in which sediment is generally eroded over 8 months of a year.

As a result of the mismatch in the timing of maximum sediment supply and transport, the grain-size distribution of sediment both on the bed and in suspension in the Colorado River evolves over time. This grain-size evolution occurs as a function of changes in the upstream supply of sediment caused by both tributary activity and dam operation. Systematic changes in bed elevation also occur as functions of the discharge of water and upstream sediment supply. Sediment input to the Colorado River during tributary floods travels down the mainstem as elongating "sediment waves," with the finest sizes (because their lower settling velocities) traveling the fastest. As the front of these sediment waves pass a given location, the concentration of suspended sediment first increases as the grain size in the system fines, then subsequently decreases as the grain size in system coarsens. In the post-dam era, changes in sand-transport rates as high as a factor of 15 have been observed in connection to sediment fining during large tributary floods. As the finest sizes of sediment are winnowed form the bed, the bed and suspended sediment coarsen, causing the formation of inversely graded deposits. Because the grain size of sediment changes over time, sediment rating curves are unstable. Therefore, sediment budgets in a supply-limited river like the Colorado River cannot be constructed through use of stable sediment rating curves. We are developing predictive methods to determine the spatial and temporal evolution of the sediment supply in the Colorado River. These methods can be used by managers to design dam releases (both within powerplant capacity and above) to maximize the retention of sediment in the Colorado River ecosystem.

STATUS OF FINE-SEDIMENT IN THE COLORADO RIVER ECOSYSTEM PRIOR TO THE MAY 2000 31,000 cfs RELEASE

David J. Topping, David M. Rubin, and Nancy J. Hornewer (USGS)

Summary

Analysis of the intensive August 1999-April 2000 suspended-sediment dataset collected by the USGS - Arizona District at the Lower Marble Canyon Gage (a.k.a. the "above LCR gage") and the Grand Canyon Gage indicates that **at least as much sand was exported past these 2 gages as was supplied by the upstream tributaries during this period**. Moreover, analysis of the data from the Lower Marble Canyon Gage suggests strongly that sand was eroded from the Colorado River in Marble Canyon during August 1999-April 2000. Analysis of the suspended-silt and clay data indicates that about as much silt and clay was exported past these 2 gages as was supplied by the upstream tributaries during this same period. Thus, the fine-sediment mass balance in the Marble Canyon and upper Grand Canyon portions of the Colorado River Ecosystem was slightly negative at the beginning of the 2000 LSSF Experiment. These results are shown in Figure 1.

Computations of β values (Rubin and Topping, 2001) from the August 1999-April 2000 suspended-sand data indicate that, at both gages, the upstream supply of sand coarsened as it became depleted prior to the May 2000 31,000 dam release (Figure 2). As defined in Rubin and Topping (2001), β is a nondimensionalized measure of the grain size of the bed sediment that is accessed by the flow, and is computed from the suspended-sediment data. Comparison of the 1999-2000 β values from the Grand Canyon gage with β values computed from pre-dam and pre-1999 post-dam suspended-sand data indicates that the sediment supply was coarser and more depleted in April 2000 than at any other time except during the fall of 1985 (a period following 3 years of sustained high dam releases).

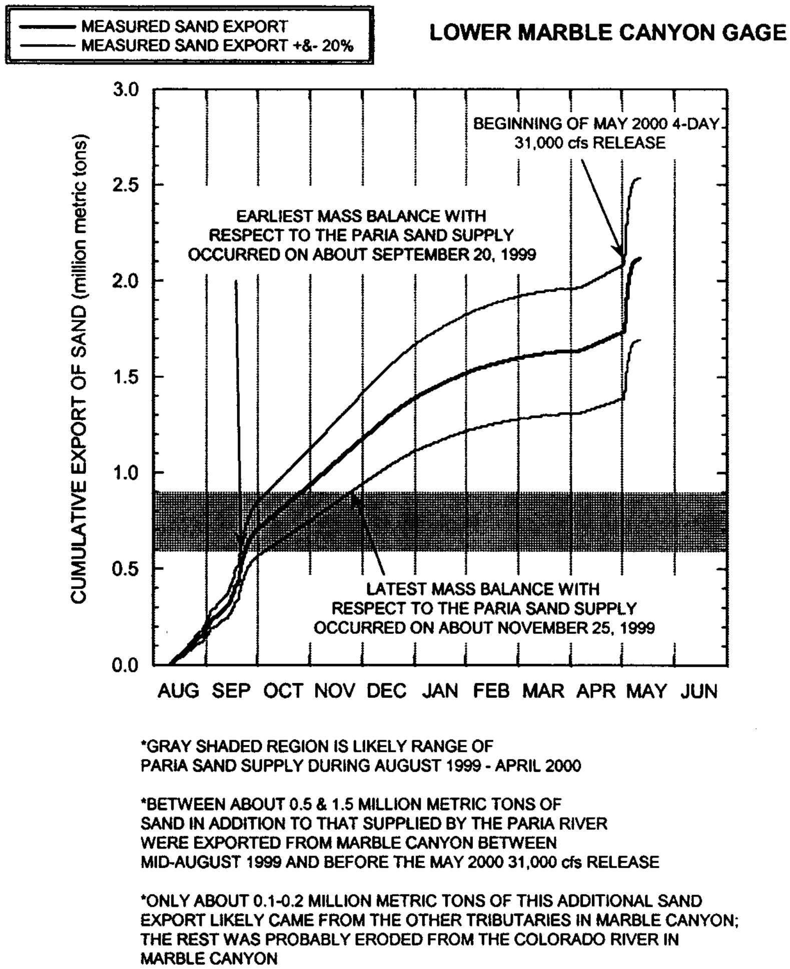
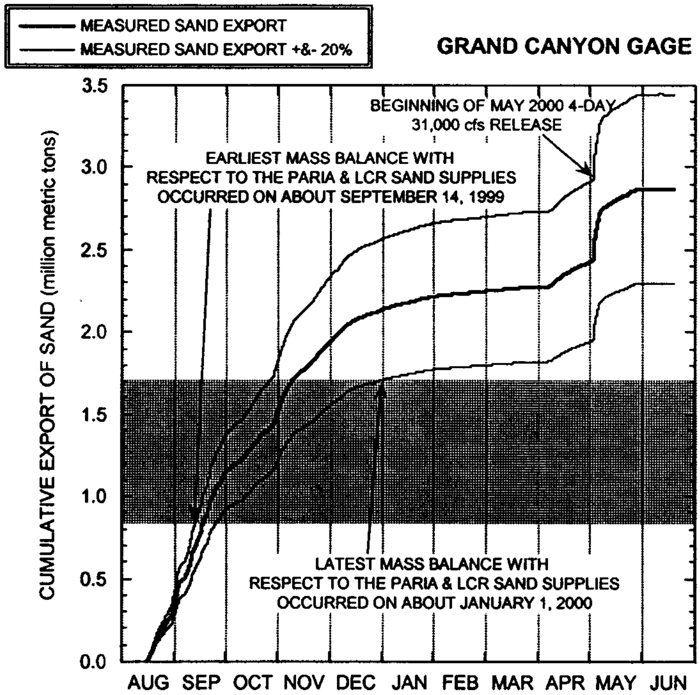


Figure 1a: Sand mass balance plot for the 98-km long reach from Lees Ferry to the Lower Marble Canyon gage for August 1999-early May 2000. The sand budget for this period becomes negative (indicating net erosion of sand from the canyon) when the export curves exceed the gray box by more than 0.1-0.2 million metric tons (the likely contribution of sand from the smaller tributaries). Estimates of the sand contribution from the smaller Marble Canyon tributaries based on Webb et al. (2000) and the results from the current monitoring program on these tributaries.



*GRAY SHADED REGION IS LIKELY RANGE OF THE COMBINED PARIA AND LCR SAND SUPPLIES DURING THIS PERIOD

*BETWEEN ABOUT 0.3 & 2.1 MILLION METRIC TONS OF SAND IN ADDITION TO THAT SUPPLIED BY THE PARIA RIVER AND LCR WERE EXPORTED FROM MARBLE AND UPPER GRAND CANYONS BETWEEN MID-AUGUST 1999 AND BEFORE THE MAY 2000 31,000 cfs RELEASE

*ONLY ABOUT 0.2 MILLION METRIC TONS OF THIS ADDITIONAL SAND EXPORT LIKELY CAME FROM THE OTHER TRIBUTARIES IN MARBLE AND UPPER GRAND CANYONS;
THE REST WAS PROBABLY ERODED FROM THE COLORADO RIVER IN MARBLE AND UPPER GRAND CANYONS

Figure 1b: Sand mass balance plot for the 141-km long reach from Lees Ferry to the Grand Canyon gage for August 1999-June 2000. The sand budget becomes for this period becomes negative (indicating net erosion of sand from the canyon) when the export curves exceed the gray box by more than about 0.2 million metric tons (the likely contribution of sand from the smaller tributaries).

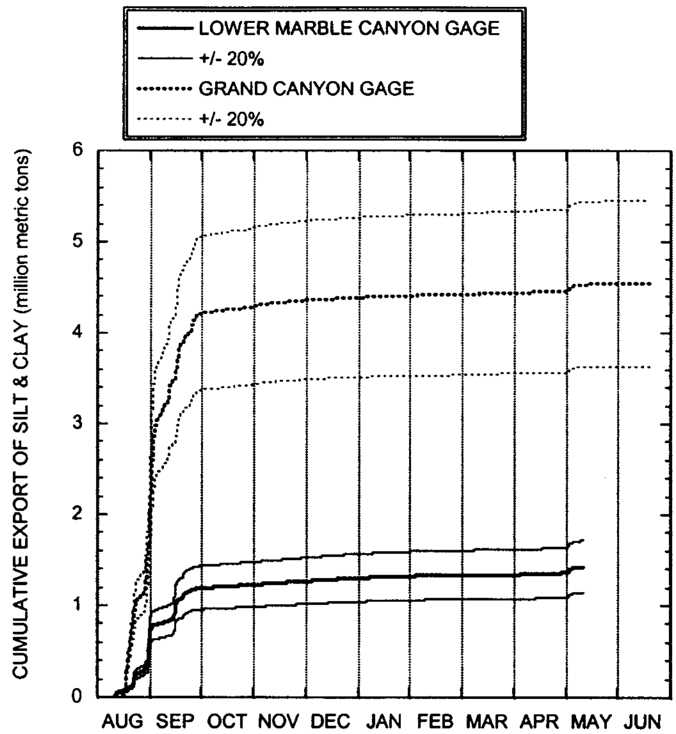


Figure 1c: Measured silt and clay exports past the Lower Marble Canyon and Grand Canyon Gages during August 1999-June 2000. During this period, the Paria River supplied about 0.8 million metric tons of silt and clay to the Colorado River, and the Little Colorado river supplied about 3 million metric tons of silt and clay to the Colorado River.

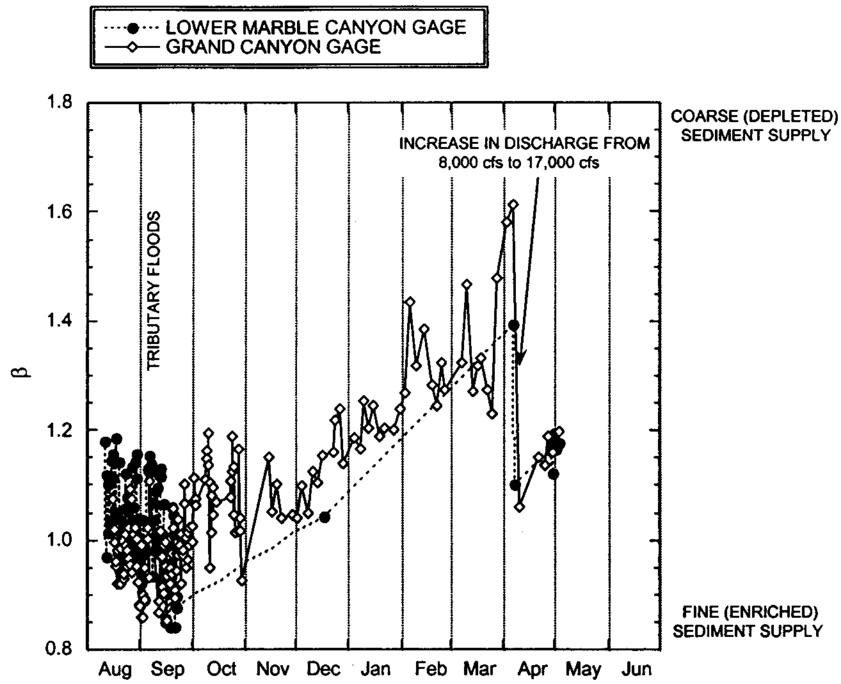


Figure 2a: Computed β values from the suspended-sand data collected at the Lower Marble Canyon and Grand Canyon Gages. At both gages, the upstream supply of sand: (1) first fined as it became enriched during the August-September 1999 period of tributary floods; (2) then coarsened as it gradually became depleted from October 1999 through March 2000; (3) then fined abruptly as the dam releases increased from 8,000 cfs to 17,000 cfs; and (4) finally coarsened again during the period of steady 17,000 cfs before the May 2000 31,000 release (values during the May high release not shown). The abrupt fining during the increase in discharge from 8,000 to 17,000 cfs occurred in response to finer sources of sand at higher elevations being accessed/eroded by the higher flow.

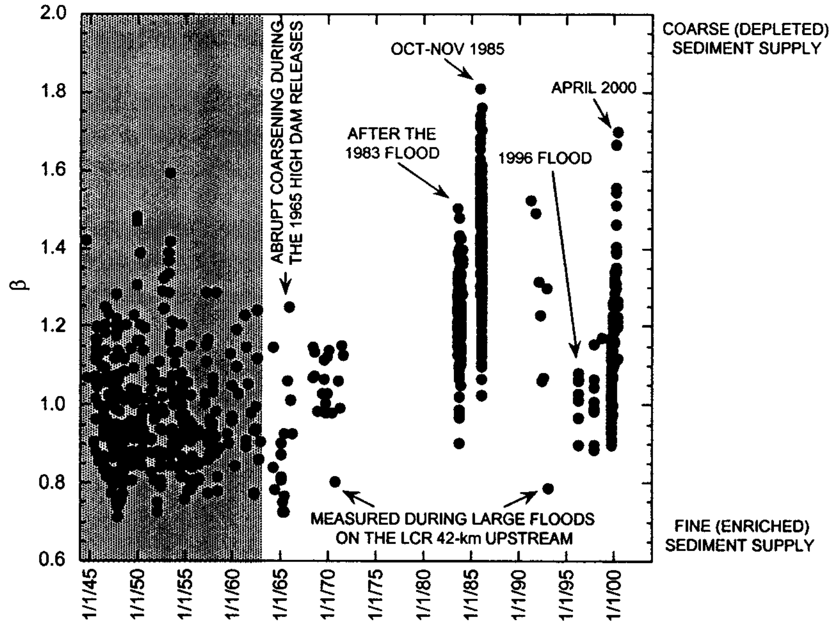


Figure 2b: Computed β values from all 1944-2000 suspended-sand data collected in flows of 8,000 cfs or higher at the Grand Canyon Gage. The shaded region indicates the pre-dam era. During April-June 1965, the first period of high flows following closure of Glen Canyon Dam in March 1963, the sand supply at the Grand Canyon Gage coarsened as 16 million metric tons of fine sediment (mostly sand) were eroded from the reach between Lees Ferry and the Grand Canyon Gage (Rubin and Topping, 2001). The sand supply at the Grand Canyon Gage never fully recovered from the 1965 event. After 1965, the sediment supply became as enriched as it was seasonally in the pre-dam era only during large tributary floods upstream. [During the pre-dam era, up to 13 million metric tons of sand would accumulate in the reach between Lees Ferry and the Grand Canyon Gage between July and March. This stored sand would then be depleted during the higher snowmelt flows during April-June (Topping et al., 2000).] The sediment supply at the Grand Canyon Gage was the coarsest and most depleted during the fall of 1985, following 3 years of sustained high dam releases. The second most depleted period for the sediment supply occurred during April 2000, just prior to the May 2000 4-day 31,000 cfs release. As shown in Figure 1, the fine-sediment mass balance between Lees Ferry and the Grand Canyon Gage was slightly negative during August 1999-April 2000. Interestingly, the sand supply was coarser and more depleted during April 2000 than it was immediately following the 97,000 cfs 1983 flood.

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Monitoring Fine-Sediment Storage of the Colorado River Ecosystem below Glen Canyon Dam, Arizona

Sand Bar Studies Fact Sheet
Department of Geology
Northern Arizona University

December 1999

The distribution of fluvial sediment downstream of Glen Canyon Dam is of fundamental importance to the Colorado River ecosystem in Glen, Marble, and Grand Canyons. Sand deposited along the channel margins creates the foundation of the ecosystem by providing substrate and habitat for aquatic and terrestrial species. Sand bars deposited within eddies are also the primary campsites for rafting and hiking groups. Glen Canyon Dam has transformed the once sediment-laden Colorado River into a sediment-limited system. The only remaining sources of fine-sediment (sand and finer) input are tributaries, primarily the Paria and Little Colorado Rivers.

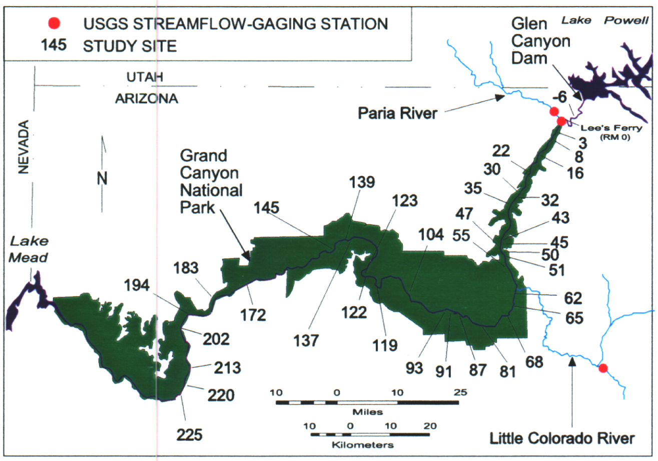


Figure 1. Location of NAU study sites and streamflow gaging stations. River miles after Stevens (1983).

In cooperation with the Glen Canyon Environmental Studies and the Grand Canyon Monitoring and Research Center, we have monitored the movement and accumulation of fine-sediment throughout the Colorado River ecosystem since 1990. Our approach is to conduct repeated topographic and hydrographic surveys at 35 long-term study sites and to use these data to estimate reach and system-wide responses of sediment to changing dam operations (Figure 1; see Kaplinski et al., 1995; 1998; or Hazel et al., 1999, for an extensive description of our methodology and study sites). In our analysis, we divide the river corridor into the Glen, Marble, and Grand Canyon reaches to describe sediment storage changes above and below the Little Colorado River. For each site, the volume of sediment stored within main channel, eddy, and sand bar environments are measured (Figure 2). These values are compared to previous surveys to determine site-specific changes, then averaged or summed over the entire reach to assess reach-scale effects. While these 35 sites are not wholly representative of the entire fluvial system, they provide the most accurate and complete time-series available to date for medium-term, volumetric and area changes in sediment storage. Furthermore, volumetric data from these monitoring sites, in conjunction with reach-scale aerial photogrammetric mapping (Schmidt et al., 1999a), flow modeling (Wiele et al., 1999), and suspended sediment sampling (Topping et al., 1999), is critical to the development of a Colorado River ecosystem sand budget (Schmidt, 1999; Hazel et al., in prep.). In this fact sheet, we briefly summarize our monitoring and stress the importance of tributary floods and controlled flood flows in conserving sediment and rebuilding eroded sand bars.

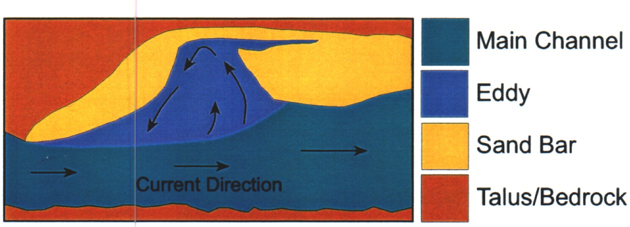


Figure 2. Cartoon map view of typical Colorado River sand bar showing areas where volumes are calculated.

Discharge data shown in Figure 3a summarizes the pattern for Glen Canyon Dam operations from 1991-1999. Interim flows, released during completion of the Glen Canyon Dam EIS (DOI, 1995), occurred from 1991 through 1996, and were intended to minimize sand bar erosion and export of sand, as well as to maximize potential fine-sediment storage in the river channel. Despite the reduced peak daily flows,

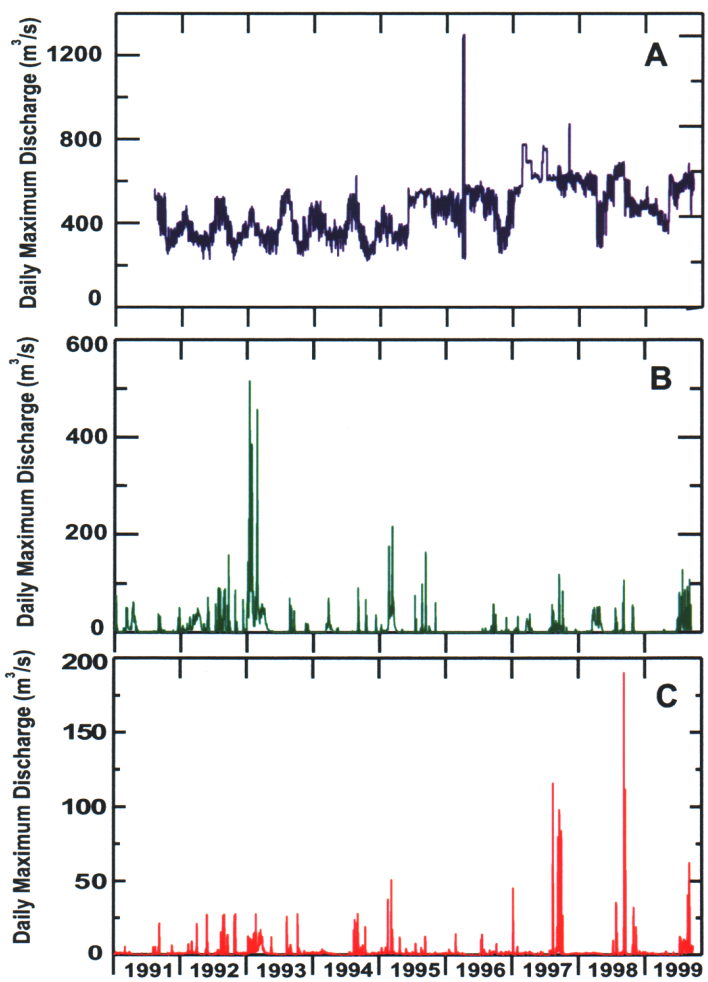


Figure 3. Daily maximum discharge hydrographs from U.S.G.S. gaging stations. A) Colorado River near Lee's Ferry (09380000), B) Little Colorado River near Cameron (094020000), C) Paria River near Lee's Ferry (9382000).

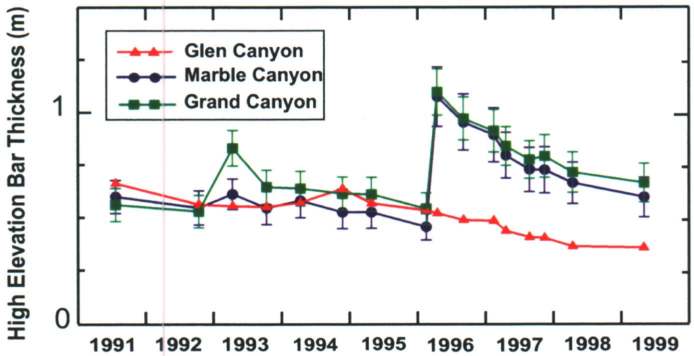


Figure 4. Average sand thickness of high-elevation sand bars in Glen, Marble, and Grand Canyons.

limited hourly ramping rates, and fluctuation range characteristic of interim flows, high-elevation (above the 556 m³/s [20,000 ft³/s] stage elevation) sandbars were progressively eroded (Figure 4).

Sand bars aggraded during tributary flood events from the Paria and Little Colorado Rivers in 1993 and 1995. Floods from the Little Colorado River during the winter of 1993 raised mainstem flows to over 950 m³/s (33,000 ft³/s) (Figure 3b). Following these floods, we measured a substantial increase in high-elevation sand bar thickness downstream of the Little Colorado River confluence. The observed bar building demonstrated that flows in excess of power plant capacity were a viable mechanism to aggrade high elevation sand bars.

In the final EIS, it was hypothesized that controlled flooding could transfer sediment from the channel bed to the channel banks and re-build eroded sand bars (Schmidt et al. 1999b). Aggraded sandbars would potentially provide more area for riparian habitat development, camping, and prolong the residence time of sediment within the system by removing it from direct downstream transport. A controlled flood would also re-introduce a "disturbance" to the ecosystem; much like controlled burns are used in forest ecosystems. Short-duration dam-released floods, in excess of powerplant capacity, were included as an integral part of the preferred alternative in the final EIS on operations of Glen Canyon Dam (DOI, 1995) and the Record-of-Decision (DOI, 1996).

The 1996 controlled flood, released on March 26, 1996, was designed to test these hypotheses (Figure 3a). The hydrograph consisted of a seven day, sustained high discharge of 1,274 m³/s (45,000 ft³/s), preceded and followed by three days of a constant low discharge of 227 m³/s (8,000 ft³/s). The data summarized by Webb et al. (1999) indicate that the 1996 controlled flood achieved many of the intended goals. The high-elevation parts of sand bars accumulated a significant volume of sand (Figures 4 & 5). Even the site in Glen Canyon was aggraded, where sand supply is thought to be most limited. Hazel et al. (1999) correlated the magnitude of deposition to space available for deposition and stressed the importance of antecedent conditions in the prediction of future floods intended to aggrade sand bars. In contrast to high-elevation deposition, sediment was scoured from low-elevation storage areas in the main channel and large eddies (Figure 5 & 6). Significant scouring of sand from the low-elevation parts of large eddies suggests that eddy systems can store as much, or more sand than the adjacent main channel pool. The 1996 experiment demonstrated that controlled flooding could transfer fine-sediment from the bed to the channel margin.

Perhaps more important than the deposition during the 1996 controlled flood was the longevity of the newly aggraded bars. Subsequent monitoring from 1996 to 1999, showed that sand bars eroded rapidly during the first six months of "normal" dam operations following

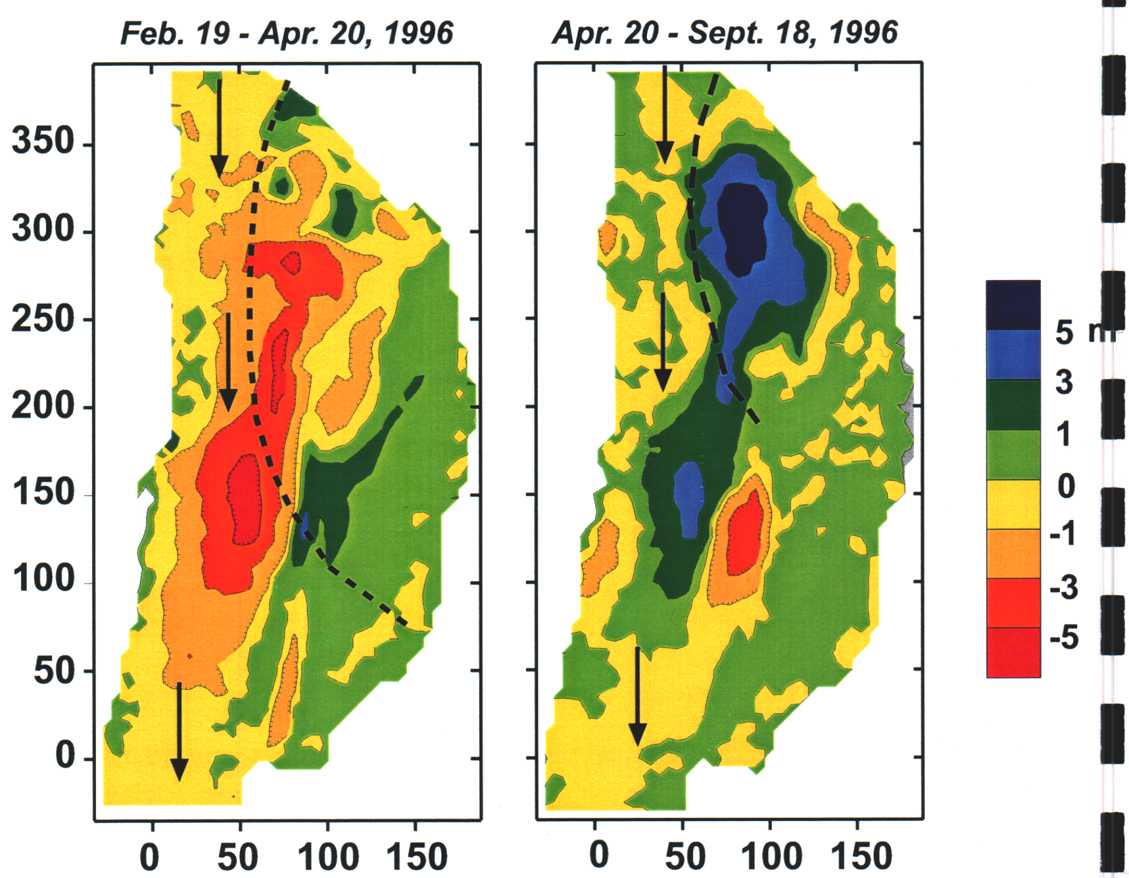


Figure 5. Topographic changes at the 51 mile study site. Areas of deposition are shown in greens and blues, and areas of erosion are shown in yellows and reds. Arrows indicate the direction of the main current. A) Changes from before and after the 1996 controlled flood. Approximate location of the eddy fence at a discharge of 1,274 m³/s is shown by the dashed line. Note the low-elevation scour within the eddy and main channel, and high-elevation deposition along the sand bar. B) Changes six months after the 1996 controlled flood. Approximate location of the eddy fence at 556 m³/s eddy fence is shown by the dashed line. Note the low-elevation deposition within the eddy and the main channel, and high-elevation erosion of the downstream end of the sand bar exposed to direct downstream current.

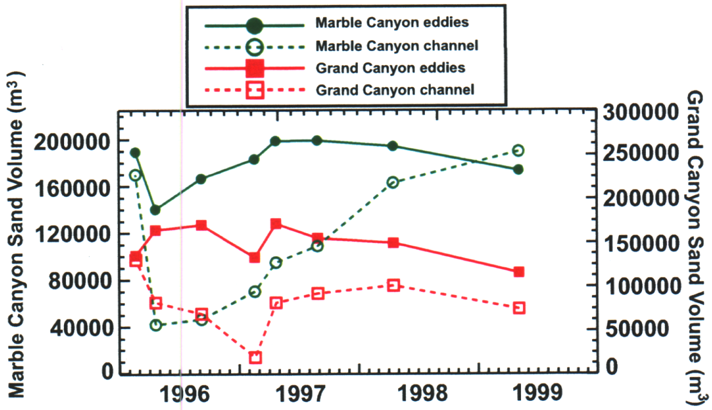


Figure 6. Total cumulative eddy and channel sand volume in Marble and Grand canyons.

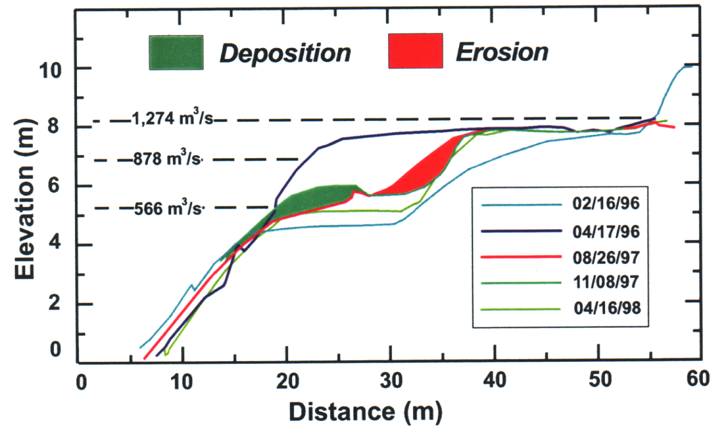


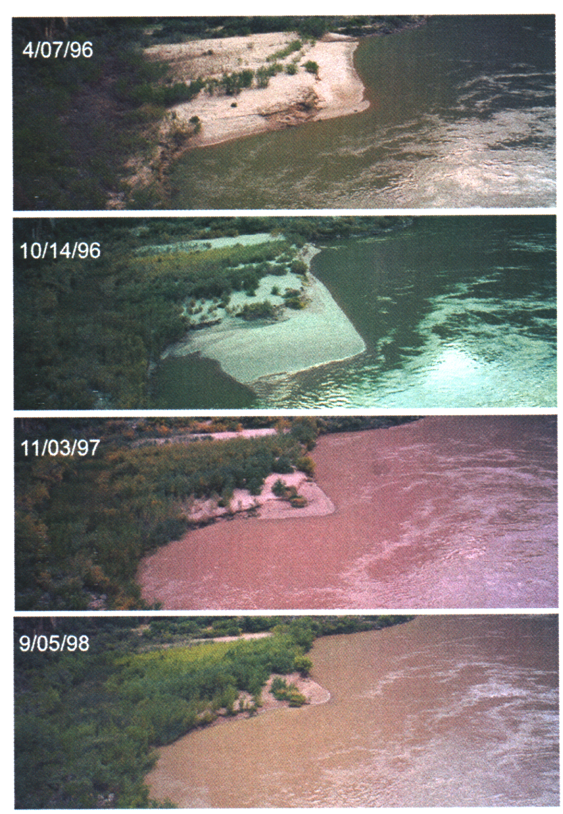
Figure 7. Topographic cross-sections of the 30 mile sand bar in upper Marble Canyon. Flow stage elevations for thehigh-elevation volume calculations (556 m³/s, 20,000 ft³/s), the 1996 controlled flood (1,274 m³/s, 45,000 ft³/s),and 1997 test flow (878 m³/s, 31,000 ft³/s) are shown.

the controlled flood, but erosion rates then decreased with time (Figure 4). In contrast, low elevation eddy and main channel environments aggraded (Figures 5 & 6). Sand eroded from high-elevation bars was gradually transferred back to low elevation storage environments in eddies and the main channel (Figures 4 & 6).

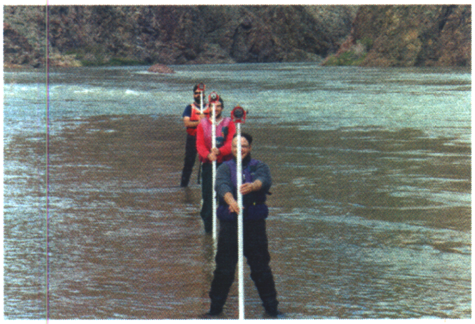
Beginning in 1995, and continuing into 1999, dam releases were generally high to prevent spills from Lake Powell (Figure 3a). In 1997, four closely-spaced floods from the Paria River in August and September 1997, delivered an estimated 770,000 m³of sand to the Colorado River (Figure 3c). Following these inputs, the Glen Canyon Dam adaptive management program recommended that a short-duration, powerplant capacity test flow be released in Fall 1997. The 1997 test consisted of a constant flow of 878 m³/s (31,000 ft³/s) for 48 hours. The 1997 test flow examined the hypothesis that a shorter-duration, lower magnitude dam release could mimic the results of the 1996 controlled flood and transfer Paria-supplied sediment from the channel bed onto channel margin sandbars before the sand was transported downstream from Marble Canyon.

Our monitoring shows that the 1997 test flow only temporarily and partially achieved this objective. The 1997 test flow did not reverse the trend of high elevation erosion following the 1996 controlled flood (Figure 4). Net high-elevation sand bar thickness did not increase because deposition of sand on the bar was offset by erosion of the deposit above the stage elevation reached by the 878 m³/s (31,000 ft³/s) flow (Figure 7). These results suggest that the stage elevations reached by the 1997 test flow were not high enough to result in deposits that could escape rapid erosion by the dam releases that followed.

Our latest monitoring data show that, as of April 1999, fine-sediment has accumulated within the channel and eddies and eroded from the sand bars to levels at, or near those measured before the 1996 flood (Figures 4 & 5). In 1998 and 1999, the Paria River continued to input a significant amount of sediment into the Colorado River (Figure 3c). Our monitoring does not indicate that these inputs increased storage at our sites, but the inputs may have been retained elsewhere in the ecosystem (Figure 5). This suggests that low-elevation storage areas scoured by the 1996 controlled flood had filled with sand eroded from the channel margin and from the 1997 tributary inputs. These results support the conclusion of Topping et al. (in press) that the amount of sand storage is limited in the Colorado River, and that when eddy and main channel environments are full, new sediment inputs are rapidly transported downstream because Record-of-Decision flows are relatively higher, on average, than pre-dam flows, and little space is available for deposition. Our latest measurements in April 1999, indicate that, at our monitoring sites, space is available for high elevation deposition and low elevation sediment is available for redistribution. In general, these data imply that a controlled flood, at the present time, will likely result in high-elevation deposition.



Selected Photographs from the 194 mile study site. Main channel flow is from bottom to top. Note the colonization of the 1996 controlled flood deposit by riparian plants.



Topographic surveys determine the amount of sediment stored on sand bars.

Hydrographic surveys determine the amount of sand stored in the channel.

Conclusions

As of April 1999, sand storage levels measured at our study sites are near those measured before the 1996 controlled flood. High- elevation sand bars have eroded to levels slightly higher than pre-flood measurements. Low elevation storage environments in eddies and in the main channel have recovered to approximately equal to pre-flood measurements.

The 1996 controlled flood resulted in widespread high-elevation sand bar deposition.

The 1997 test flow resulted in some high-elevation deposition of sand, however most of these sand deposits were rapidly eroded under high dam releases by April 1998.

In addition to sediment availability, the volume of sand occupying depositional sites prior to flooding is an important factor in determining the magnitude and persistence of flood related deposition.

The most efficient way to conserve fine sediment in the system is to release controlled floods that redistribute sand to higher elevations along the channel margins where it will remain in storage for relatively long periods.

- Matt Kaplinski, Joseph E. Hazel, Jr., Rod Parnell, and Mark Manone

Sand bars built by flood flows and used as campsites are continually being eroded by flows from Glen Canyon Dam.

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NORTHERN ARIZONA UNIVERSITY
Department of Geology
Sand Bar Studies Fact Sheet

Monitoring the Effects of the 1997 Glen Canyon Dam Test Flow on Colorado River Ecosystem Sand Bars

July 2000

Controlled floods of appropriate stage and duration have important potential for resource management of the Colorado River ecosystem in Grand Canyon National Park. High releases from Glen Canyon Dam can be used to scour sand-sized sediment on the channel bottom and redistribute it to the banks and bars along the channel margin. New and existing deposits are valued components of the riverine ecosystem. They provide habitat for native and non-native fish, the substrate for riparian vegetation, erosion-protection for archeological sites, and are used for camping by river runners. The first opportunity to study physical processes during controlled flooding occurred in spring 1996, with a seven day release of 1,274 m^3/s (45,000 ft^3/s) (Webb et al., 1999). The 1996 flood was considered a short-term success but several studies demonstrated the importance of decreasing river sand concentrations on transport and deposition (Schmidt, 1999). The possibility that a shorter duration and lower magnitude release than the 1996 flood (i.e., a non-spill release) could achieve some level of sediment conservation was of interest to the Glen Canyon Dam adaptive management program. Following significant sand inputs from the Paria River in late summer 1997, and before the sand was lost downstream to Lake Mead, a test flow was released to transfer some of this sediment to the channel margin. Termed the 1997 Test Flow, the release started on November 3, and consisted of a constant flow of 878 m^3/s (31,000 ft^3/s) for 48 hours.

Sand Delivery by the 1997 Paria River Floods

Most of the sand supplied to the Colorado River ecosystem comes from the Paria River, about 25 km below Glen Canyon Dam, and the Little Colorado River, about 125 km below the dam (Fig. 1). In August-September 1997, the Paria River produced four large floods that delivered approximately 2.0 million Mg of sand to the Colorado River (Fig. 2a) (Topping et al., 2000). This sand input was nearly twice the mean-annual input from this tributary and ranked among the top 20% during the 75 years of gage record on the Paria River (Topping et al., 2000). The Little Colorado River was also active during this period.

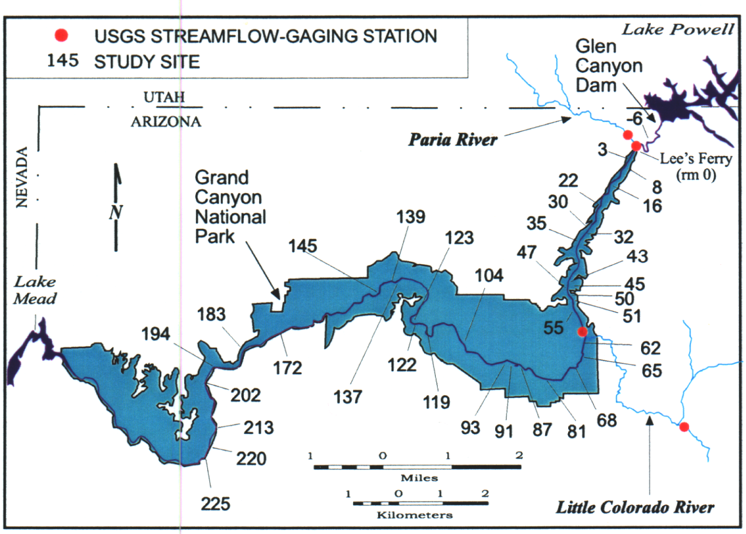

Figure 1. Location of study area, major sand supplying tributaries, USGS streamflow-gaging stations, and sand bar monitoring sites.

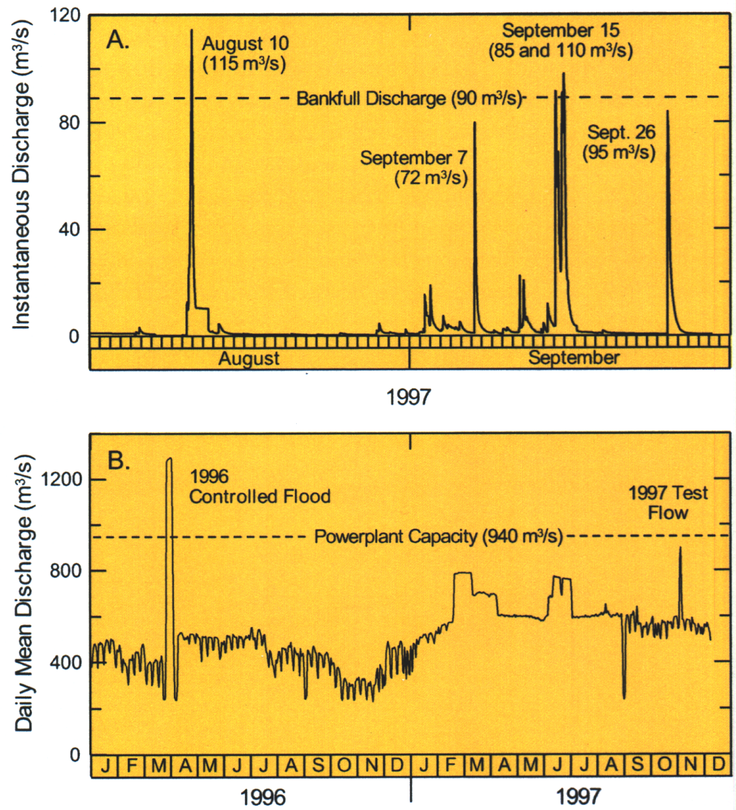

Figure 2. Discharge hydrographs. A, Instantaneous discharge at USGS streamflow gaging station Paria River at Lee's Ferry, Arizona, August and September 1997. B, Daily mean discharge at the USGS streamflow-gaging station, Colorado River above Little Colorado River near Desert View, Arizona, January 1996 to December 1997.

High-Elevation Sand Bars Were Monitored at 35 Long-Term Study Sites Before and After the 1997 Test Flow

Thirty-five long-term study sites are located throughout the Colorado River ecosystem (Fig. 1). Each site contains one or more sand bars. Ground points were collected with electronic total stations and topographic surface models created using the triangulated irregular network method of contouring with surface modeling software [study site locations, descriptions, and methods are provided by Kaplinski et al. (1995) and Hazel et al. (1999)]. At each site, the volume and thickness of sand stored at high elevation within the bar was calculated and then compared to previous surveys to determine site-specific changes. These values are then averaged or summed to assess reach-scale effects. We define the high-elevation sand bar as bedforms deposited in eddies occurring above the 566 m^3/s (20,000 ft^3/s) stage elevation. Above this topographic level sand bars are considered campsites because the campable area is greatest and more substrate is available for riparian vegetation, marsh and wetlands. Areas below this level are regularly inundated and reworked by dam releases and typically are not available for camping or colonization by plants.

The 1997 Test Flow Did Little to Offset Erosion of the 1996 Flood Deposits

We examined the net high-elevation change in sand thickness at the sites by producing a time series from data collected since 1996 (Fig. 3). The sample population is divided into sites in Marble Canyon, upstream from the Little Colorado River; and those in Grand Canyon, downstream from the Little Colorado River (Fig. 1). The time series demonstrate that sand was successfully redistributed to high-elevation by the 1996 Controlled Flood. Following the 1996 Flood, adjustment of the newly aggraded bars to lower, sustained high flows led to rapid but declining rates of erosion (Fig. 2b). The 1997 Test Flow did not result in aggradation great enough to compensate for the erosion that had occurred between April 1996 and November 1997. Net high-elevation bar thickness did not increase at the sites because deposition of sand on the inundated part of the bar was offset by erosion of high-elevation parts of the pre-existing deposits (Hazel et al., 2000; Kaplinski et al., 1999). In general, erosion resulted from cutbanks that retreated horizontally as much as 5 m. The base of the cutbanks developed at the stage elevation reached by the 878 m^3/s flow.

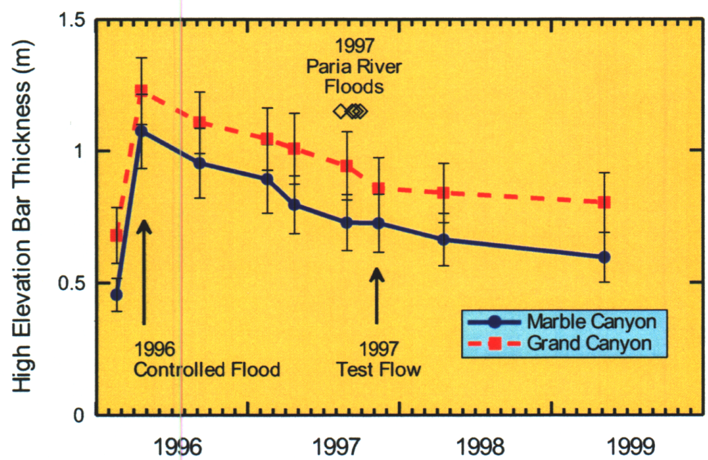

Figure 3. Average high-elevation sand thickness changes in Marble and Grand Canyons versus time. Diamond symbols indicate dates of the 1997 Paria River floods. Error bars are standard error about the mean.

The Stage Change of Controlled Floods is Important for Net Bar Deposition

The 1997 Test Flow did not completely inundate the sand bars in this study. As a result, the stage change was not high enough to redistribute sand to areas where depositional sites were open. The erosional trend following the 1996 Flood, however, suggests that potential depositional area was open in late 1997 (Fig. 3). Hazel et al. (1999) showed that the magnitude of stage change caused by the 1996 Flood was an important factor in net deposition. The stage change during the 1997 Test Flow was roughly half that of the 1996 Flood at the study sites. There was no significant correlation between bar thickness change and stage change during the 1997 Test Flow (Fig. 4). In contrast, a positive correlation was observed as a result of the 1996 Flood (r^2=0.59, significant at the 95% confidence level). It is possible that the 2-day duration of the 1997 Test Flow was too short and a longer test may have resulted in net deposition. However, suspended- and bed-sediment measurements at USGS streamflow-gaging stations indicate that the 1997 Test Flow depleted a major portion of the supply of finer sand throughout the Colorado River ecosystem (Topping et al., 2000). The sand export rate from Marble Canyon was twice that observed during the 1996 Flood. These observations suggest that 1997 Test Flow was high enough to transport large amounts of sand supplied to the Colorado River channel but the new sand was not effectively redistributed to the channel margin.

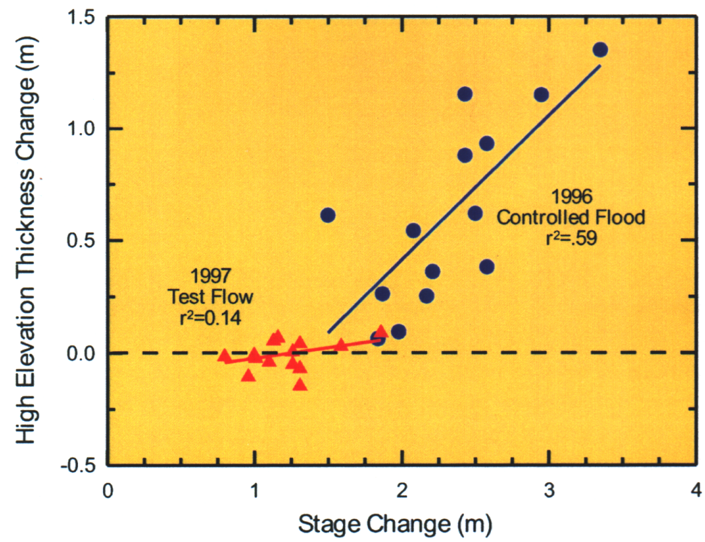

Figure 4. The relation between stage change and high-elevation thickness change in Marble Canyon. The stage change is based on the elevation difference from 566 to 878 m^3/s (1997 Test Flow) and from 566 to 1,274 m^3/s (1996 Controlled Flood) at each study site.

The results of this study suggest that in order to prolong the residence time of tributary-supplied sand in the Colorado River ecosystem, a greater stage increase is required to access high elevation areas available for deposition. Even the largest floods on the Paria River do not raise mainstem discharge high enough and for sufficient duration to result in deposition above stage levels reached by normal dam releases. Timing controlled high releases to coincide with or shortly follow the summer and fall sediment input season may improve the likelihood that inputs are conserved, especially within upstream reaches closest to the dam.

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NORTHERN ARIZONA UNIVERSITY

Monitoring the Effects of the Spring 2000 Habitat Maintenance Flow on Colorado River Ecosystem Sand Bars

Department of Geology
Sand Bar Studies Fact Sheet

January 2001

The magnitude and timing of controlled floods required to distribute large amounts of sand into eddies and rebuild eroded sand bars is a critical objective of research and monitoring in the Colorado River ecosystem, downstream from Glen Canyon Dam. Aggradation of sand bars at higher elevations is dependent on the size and abundance of sand temporarily stored on the channel bottom and the duration and stage of the high release. New and existing deposits are valued components of the riverine ecosystem. They provide habitat for native and non-native fish, the substrate for riparian vegetation, erosion-protection for archeological sites, and are used for camping by river runners. The 1995 Glen Canyon Dam Environmental Impact Statement recommends scheduled high releases of short duration be implemented for environmental purposes (U.S. Department of Interior, 1995). Habitat maintenance flows (HMF) are within powerplant capacity (~940 m^3/s), whereas those above this discharge are beach/habitat-building flows (BHBF). The former were intended to maintain existing camping beaches and wildlife habitat and the latter to more extensively modify and create sand bars, and thus restore some of the dynamics that result from flooding in the ecosystem.

Flood Experiments in the Colorado River Ecosystem

In this study we evaluate the effects of three intentional, controlled floods that were released in 1996, 1997, and 2000. We compare the results to a natural flood that occurred in 1993. The first test of a BHBF occurred in spring 1996, with a 7-day release of 1,274 m^3/s. A HMF test occurred in November 1997, following large sand inputs from the Paria River in late summer 1997. The objective of the 1997 HMF was to transfer some of the tributary supplied sand to the banks and bars before it was transported downstream. This release had a 2-day duration of 868 m^3/s. A second HMF experiment occurred as part of the Low Summer Steady Flows (LSSF) in 2000 (Fig. 1). The LSSF was designed to test the benefits of low flows on native fishes of the Colorado River below Glen Canyon Dam. The LSSF was preceded in May by a 4-day spike of 858 m^3/s, partly intended to improve aquatic habitat by rebuilding and restructuring sand bars. In addition, an unregulated January 1993 flood on the Little Colorado River delivered large amounts of sand and increased the discharge of the Colorado River to a peak of approximately 950 m^3/s (Wiele et al., 1996). Together, these four floods of near powerplant capacity or greater provide an opportunity to measure sand bar response to flow magnitude and the timing relative to tributary sediment supply.

High-Elevation Sand Bars Were Measured Before and After the Spring 2000 HMF

In 1990, a project monitoring sand bars in the Colorado River ecosystem was initiated by Northern Arizona University. Since then, the study sites have been monitored annually and before and after flood events. Site locations, methods, and results can be found in Hazel et al. (1999). The sites are representative of the different types of eddy sand bars and are spatially distributed throughout the Colorado River ecosystem.

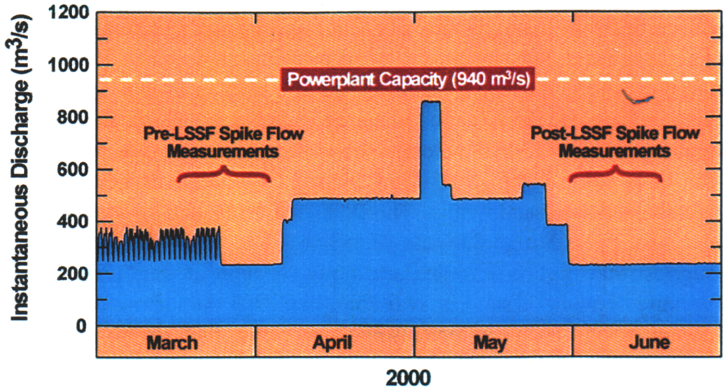

Figure 1. Instantaneous discharge at USGS streamflow gaging station Colorado River at Lees Ferry, Arizona, March-June, 2000. The timing of measurements made before and after the spring 2000 HMF are shown.

We calculate the area, volume and thickness of sand stored at high elevation at each bar. We define high-elevation as the area that is emergent at a flow of 566 m^3/s, a moderately high flow in the post dam era (Hazel et al., 1999). Areas below the stage elevation reached by this flow are regularly inundated and reworked by dam releases and typically are not available for camping or colonization by plants.

Long-Term Trends in High Elevation Sand Bar Storage

To identify long-term trends, our approach is to develop a time series of average high-elevation change (Fig. 2). The sample population is divided into sites in Marble Canyon (upstream from the Little Colorado River) and those in Grand Canyon (downstream from the Little Colorado River). One site is located in Glen Canyon, the reach closest to the dam. Figure 2 indicates that the 1993 Little Colorado River flood and the 1996 BHBF were the only high flows to significantly replenish sand in high elevation bars. Although rapid adjustment of newly-aggraded bars to normal dam releases led to high rates of erosion following these events, the rates decreased with time. After more than a year, on average, the sand bars were still larger than they had been before either the 1993 flood or the 1996 BHBF.

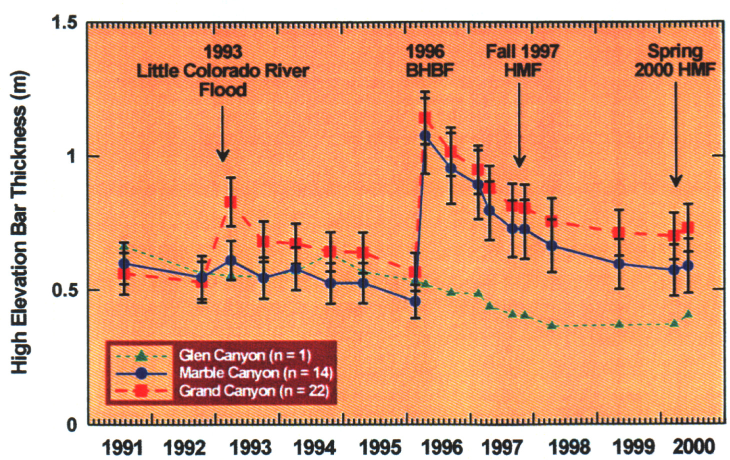

Figure 2. Average high-elevation sand thickness changes versus time. Error bars are standard error about the mean.

Controlled Flood Magnitude

One reason the 1997 HMF and the 2000 HMF did not replenish high-elevation bars is that the flow magnitude was not great enough. In Figure 3, photographs illustrate this pattern of change. Higher stages increase the accomodation space available for deposition (Hazel et al., 1999). Average area and volume changes for the three controlled floods, and for the 1993 Little Colorado River flood, are shown in Figure 4. At discharges below powerplant capacity the changes are not significantly different from 0, suggesting that HMF-type flows are stage-limited. The changes downstream of the Little Colorado River in 1993 show large positive values at a discharge of 950 m^3/s, a flow only slightly higher than a HMF. Note that the area increase in 1993 is greater than that of the 1996 BHBF, whereas the volume increase is about half of the 1996 value. The 1993 flood created large deposits because of a greatly increased sand supply. The 1996 BHBF resulted in larger volume deposits, even though the sand supply was lower. While these results suggest that high discharges are more efficient at producing larger volume deposits if sand is available, the 1993 data show that lower discharges are capable of replenishing sand bars during tributary flooding.

Controlled Flood Timing

Timing deliberate floods to coincide with or closely follow tributary sand inputs, typically in late summer for Marble Canyon tributaries, may provide more effective results than when following periods of prolonged high discharge (U.S. Department of Interior, 1995). The 1993 flood and 1997 HMF were associated with large tributary inputs of sand. The 1996 BHBF and the 2000 HMF occurred in the spring, when suspended sand measurements suggest that tributary sand inputs have been mostly exported from the system (Topping et al., 2000). As a result, during the 1993 flood, sand concentrations in Grand Canyon ranged from 3 to 6 times higher than those during the 1996 BHBF (Rote et al., 1997). During the HMF tests in 1997 and 2000, sand concentrations in Marble Canyon were about the same (D. Topping, USGS, pers com., 2001), and only slightly lower than those of the 1996 BHBF (Topping et al., 2000). Unfortunately, the 1997 HMF occurred more than a month after cessation of Paria River flooding, otherwise the sand supply would have been considerably greater (Hazel et al., 2000). There was little difference in bar response between the HMF tests in 1997 and 2000 (Fig. 4). In contrast, the 1993 flood built large bars, showing that if sand concentrations are high enough, net deposition will result from HMF-type flows.

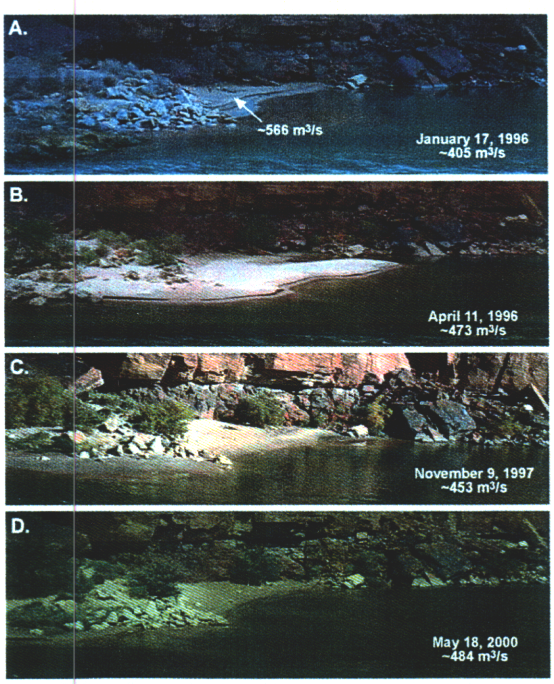

Figure 3. Selected photographs from the study site located at river mile 16.4 in Marble Canyon. A. Pre-1996 BHBF. B. Post-1996 BHBF. C. Post-1997 HMF. D. Post-2000 MHF. Flow in main channel is from left to right.

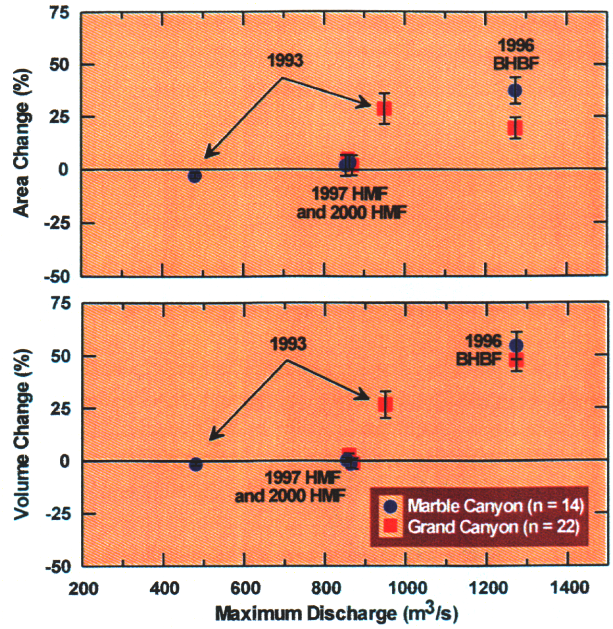

Figure 4. Average high-elevation area and volume changes plotted as a function of the maximum daily mean discharge. The change between two successive surveys was scaled by the maximum area or volume observed at each site. Error bars are standard error about the mean.

Our data demonstrate that sedimentation in eddies is at least as sensitive to flow magnitude as sand supply, because of the major role of accomodation space in determining depositional volume and rate. The effect of lower sand supply can be offset by higher stages. The duration of high flows is considered less important because suspended-sand concentration decreased rapidly during each of the controlled releases (Topping et al., 2000), and deposition rates were highest during the first day or two (Wiele et al., 1999). Flows greater than powerplant capacity may be the only means by which eroded bars can be maintained or rebuilt, especially if HMF releases cannot be scheduled closely with newly input, tributary-supplied sand.

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SAND TRANSPORT AND BED EVOLUTION MODELING APPLICATIONS IN THE COLORADO RIVER, GRAND CANYON

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INTRODUCTION

The closure of Glen Canyon Dam in 1963 shut off the mainstem sand supply and altered the natural flows in the Colorado River through the Grand Canyon. The effect of these alterations to the natural river has been the subject of ongoing research, including studies of the changes in sand supplies and sedimentary processes, with an emphasis on the erosion and restoration of sand bars. One component of these studies has been the development and application of unsteady flow models (Wiele and Smith, 1996; Wiele and Griffin, 1997), 1-dimensional sand transport models (Randle and Pemberton, 1987; Bennett, 1993), and multi-dimensional models of flow, sand transport, local erosion and deposition (Wiele and others, 1996; Wiele, 1997; Wiele and others, 1999; Wiele and Franseen, 1999). This paper is a brief overview of the multi-dimensional model and outlines modeling applications to date.

BACKGROUND

Prior to the closure of Glen Canyon Dam (Fig. 1), approximately 57 million metric tons of sediment, 40% sand, was delivered to the Grand Canyon in the mainstem annually (Topping and others, 2000a). Two main tributaries continue to supply sand. The Paria River, located about 24 km downstream from the dam, delivers about 3 million metric tons of sediment annually, 50% sand (Topping and others, 2000a), and the Little Colorado River, located about 120 km below the dam, supplies about 8.6 million metric tones of sediment annually, 30 to 40% sand (Topping and others, 2000a). Ungaged tributaries deliver about 0.70 million metric tons of sediment, 75% sand, between the dam and the Little Colorado River confluence (Webb and others, 2000). Peak discharges, which typically exceeded 2800 m^3/s during spring flows prior to the dam, currently rarely exceed the 900 m^3/s maximum that can used for power generation at the dam.

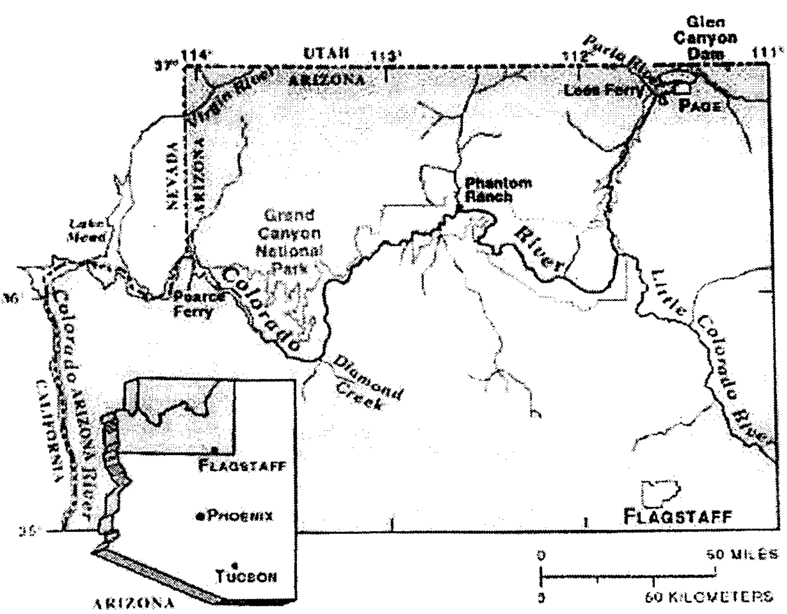

Figure 1. Map of the Colorado River below Glen Canyon Dam.

Maintenance and restoration of sand deposits has focused on distributing the sediment supplied by tributaries to near-shore sites by releasing high discharges in excess of power-plant capacity (Bureau of Reclamation, 1994). Optimum use of tributary-supplied sediment would require high flows to coincide with or shortly follow tributary activity (BOR, 1994). Timing releases with Little Colorado River flows was recommended by Lucchita and Leopold (1999). Careful analysis of suspended sediment measurements and the implications for sand transport processes by Topping and others (2000b) led to their recommendation that high releases instead be triggered by Paria River flows. They concluded that this would produce maximum deposition in the critical Marble Canyon reach, which is upstream from the confluence with the Little Colorado River and has a relatively small sand supply.

A controlled release from the dam in 1996 of 1270 m^3/s for 6 days, although not closely following major tributary activity, rejuvenated many of the near-bank sand bars, especially below the confluence with the Little Colorado River (see Schmidt, 1999, for a summary of monitoring and research results). This release demonstrated that judicious high releases from Glen Canyon Dam can be effective in mitigating some of the deleterious effects of the dam on the downstream river corridor. The model described below is designed to provide a predictive capability of the effects of sand supply and dam operation on sand deposits.

OVERVIEW OF THE MODEL

The multi-dimensional model is an extension of a model initially developed to study bank erosion and bar formation and stability in gravel-bed rivers (Wiele, 1992). For Grand Canyon applications, suspended-sand transport was added. The flow field is calculated with the vertically averaged momentum and continuity equations for open channel flow. A 3-dimensional advection-diffusion equation that governs the suspended sand field is solved using a parabolic eddy viscosity related to the local shear velocity to quantify the turbulent mixing. A sand concentration near the bed (Smith and McLean, 1977; Wiberg and Rubin, 1985) is used for the lower boundary condition. The sand fall velocity is calculated using the method of Dietrich (1982). The vertical variation in velocity is estimated using a logarithmic velocity profile consistent with the parabolic eddy viscosity. The product of the velocity and suspended sand concentration is integrated vertically to calculate the local suspended sand discharge. The sand transported as bedload is calculated using a bedload function (Meyer-Peter and Mueller, 1948) including the effect of local bed slope on transport rates (Nelson and Smith, 1989). In areas with sufficient sand thickness, local roughness and skin friction are calculated using the method of Bennett (1995) that relates bedform dimensions to flow conditions and sand size. In areas with little or no sand, local channel roughness is calculated as a function of the spatial variability in the bathymetric measurements that form the basis for the gridded channel topography. Local change in bed elevation is then calculated for a small time step with a sediment continuity equation. More detailed descriptions of the model can be found in Wiele and others (1996, 1999).

The bathymetry used to generate the gridded topography in the model was measured by the U.S. Geological Survey (USGS) and the Grand Canyon Monitoring and Research Center. Sand flux into the reaches was taken from measurements (Konieczki and others, 1997) or rating curves for specific events (G.G. Fisk, USGS, personal communication, 1994), or from a model that predicts sand flux as a function of discharge for specified sand supplies (Topping, 1997).

MODEL APPLICATIONS

The model has been used to examine processes during a tributary flood, compare the effects of natural and dam-generated high flows on sand deposits, predict the effects of variations in water discharge and sand supply on deposition rates and magnitude, and examine the effect of channel shape on locations of deposition and scour and changes in deposit volume. Applications to other disciplines include predictions of sand bar response in reaches containing archeological artifacts (Wiele and Franseen, 1999) in which preservation has been linked to the size and persistence of sand bar deposits (Hereford and others, 1993; Thompson and Potochnik, 2000). The flow component has been used to examine the effect of discharge on endangered fish habitat.

A comparison of natural and artificial events and the effect of sand concentration on sand deposition was examined by Wiele and others (1999) by comparing the results of a flood on the Little Colorado River (LCR) in 1993 and the 1996 controlled release from Glen Canyon Dam. The LCR flood transported about 4 million metric tons of sand into the main channel and increased the mainstem water discharge to a peak of about 950 m^3/s. Massive sand deposits were observed after the LCR flood receded, especially in the 20 km below the confluence. The USGS measured 3 to 5 channel cross sections in 4 reaches ranging from 1/4 to about 1 km in length before and after the LCR flows. The reaches are typically bounded upstream and downstream by riffles or rapids that are formed by debris flows that partially constrict the channel. Recirculation zones form in the lee of the debris fans and can act as effective sand traps. Sand input into the mainstem estimated from gage records (G.G. Fisk, USGS, personal communication, 1993) was used to set the upstream sand boundary-condition for the reaches.

In the reach known colloquially as the Salt reach (Fig. 2a), about 129 km below the dam, model predictions agree well with the measured cross sections (Wiele and others, 1996). Both the model and the measured cross sections show deposition in the main channel, filling a deep hole scoured into the bedrock downstream from the reach inlet, as well as extensive deposition within the recirculation zone during the LCR flood (Fig. 2b). This result contrasts sharply with the deposition pattern during the 1996 controlled release (Fig. 2c) during which sand concentrations were much lower than during the LCR flood and the water discharge was higher. During the 1996 controlled release, which had a discharge of 1270 m^3/s, the main channel was scoured. Deposition in the recirculation zone was focused at the reattachment point. Sand was carried in suspension into the recirculation zone and initially deposited rapidly. Once the initial accommodation space (defined by Hazel and others, 1999, as the underwater volume of potential deposition sites) was filled, the model shows that further deposition could proceed only at the rate at which sand was redistributed within the recirculation zone as bedload. Model predictions are compared to bathymetric measurements during the 1996 controlled release (Andrews and others, 1999). The model accurately predicts the general deposition and scour patterns recorded by the bathymetric measurements (Wiele and others, 1999). A disparity exists, however, downstream from the main channel scour zone where deposition was documented by the bathymetric measurements in a high-stress zone. This discrepancy is likely a result of the transport and deposition of coarser material than is represented in the model.

In reaches in which deposition is dominated by recirculation zones, model predictions of sand deposition as a function of water discharge and sand supply follow a consistent pattern. A reach designated the Palisades reach (Fig. 3) by Hereford and others (1991, 1993), at 134 km below the dam, was modeled with 2 discharges, 1270 and 2800 m^3/s, and with 3 different sand supplies (Topping, 1997). The sand conditions represent sand supplies during historically high measurements (high); during the 1996 controlled release, which is representative of the post-dam conditions (intermediate); and a relatively depleted state resulting from prolonged high discharges approaching 2800 m^3/s after the closure of the dam (low). At the highest flows modeled, 2800 m^3/s, with the lowest sand supply, modeled deposit volume exceeds the volume deposited predicted at lower discharges even with the highest sand supply (Fig. 4). This result demonstrates the importance of the magnitude of the accommodation space in determining deposit volume and the effect of the hydraulic isolation from the main channel on the accumulation of sand in the recirculation zones.

Recirculation zones have tended to be the focus of sediment research due to the effectiveness with which they retain sand. While reaches dominated by recirculation zone show a consistent pattern, other reaches can show considerable variability in response to discharge and sand supply. The reach designated the Above Lava-Chuar (ALC) reach (Fig. 5a), about 133 km below the dam, contains a relatively constrained recirculation zone, but also has a gradual expansion with a sand deposit just downstream from the reach inlet. At 1270 m^3/s and the intermediate sand supply, this bar is partially eroded (Fig. 5b), but at 2800 m^3/s with the intermediate sand supply, the bar is scoured out (Fig. 5c). This modeling result is consistent with the conclusions of Melis (1997) that the slope of the channel side at constrictions plays an important role in determining whether scour or deposition occur in the lee of the constrictions. Increased scour at the higher discharge for a given sand supply is opposite to the response in recirculation zones. Overall, the response of sand deposits in reaches such as the ALC reach is likely to be far outweighed by deposition in recirculation zones, but the response is of particular interest in some reaches, such as those containing archeological artifacts.

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Prepared in cooperation with the Grand Canyon Monitoring and Research Center

Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon

Introduction

Sediment supply and transport in Grand Canyon is an important management issue because of the presence and operation of Glen Canyon Dam on the Colorado River (U.S. Department of the Interior, 1995). Most of the fine-grained sediment that formerly entered the canyon from upstream is trapped in Lake Powell; this sediment once replenished beaches and provided substrate for the riverine ecosystem in Grand Canyon. With the closure of the dam in 1963, sources of fine-grained sediment have been limited to major tributaries, such as the Paria and Little Colorado Rivers and Kanab and Havasu Creeks, and numerous small tributaries. Small tributaries are also the source of coarse-grained sediment (cobbles and boulders), which forms debris fans and rapids, defines pools and eddies that trap and store fine sediment, and provides substrate for aquatic and terrestrial habitats throughout the river channel. Between Glen Canyon Dam and the Grand Wash Cliffs (fig. 1) 768 small tributaries were designated, most of which range from 1 through 5 km^2 in area. All of these tributaries produce streamflow, but only the 736 tributaries between Lee's Ferry and the Grand Wash Cliffs produce debris flows (fig. 2). With the exception of Bright Angel Creek and the major tributaries, these small tributaries between Glen Canyon Dam and the Grand Wash Cliffs were ungaged before 1999.

A combination of fluvial and hillslope processes occurs in small tributaries in Grand Canyon, making estimates of sediment yield complicated. Sediment-yield estimates must consider the contributions of both streamflow, which occurs annually in all tributaries, and debris flow, which occurs rarely. Debris flows are slurries of clay- to boulder-sized sediment with sediment concentrations of 70 to 90 percent by volume. In contrast, streamflow typically has a sediment concentration by weight of less than 40 percent. A total of 12,072 km^2 in 736 tributaries produces debris flow, and 12,900 km^2 produce streamflow. The tributaries were organized into seven sediment-yield reaches that correspond to river segments between major tributaries with gaging records or other estimates of sediment input (fig. 1).

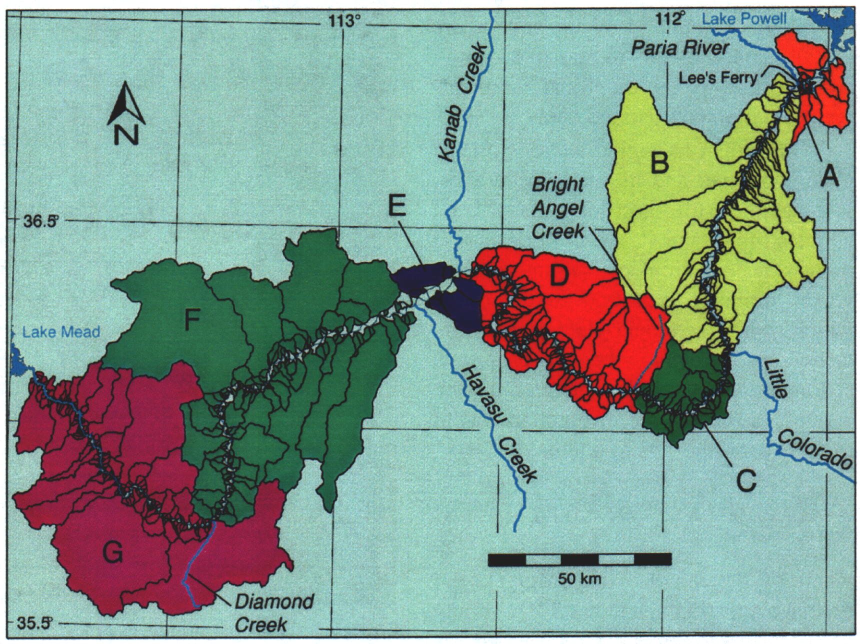

Figure 1. 768 ungaged tributaries of the Colorado River between Glen Canyon Dam and Lake Mead. Sediment-yield reaches are indicated by letter.

Development of a sediment budget for the Colorado River through Grand Canyon requires an estimate of the long-term sediment yields for both coarse and fine particles from all 768 tributaries but particularly from tributaries in Reaches A and B (fig. 1), where sand bar resources are most threatened. Because the size of particles transported by the river vary with discharge, data on the particle-size distribution of sediment delivered by both debris flow and streamflow are also needed. Increased knowledge of debris flow and mainstem processes in Grand Canyon will contribute to efforts to operate Glen Canyon Dam in ways that minimize downstream impacts. This Fact Sheet summarizes a report (Webb and others, 2000) that presents the total sediment yield and sand delivery rates for the ungaged tributaries.

grained sediment into the river (Webb and others, 1999).

The results of this model indicate that debris flows deliver 0.14-0.30.106 Mg/yr of sediment to the main channel. Reach B (Marble Canyon) contributes the greatest amount of debris-flow sediment, which is consistent with both the empirical observations on where debris flows have occurred in the last century as well as the mapped distribution of probabilities in Grand Canyon (Griffiths and others, 1996). Depending upon the assumptions of the debris-flow sediment-yield model, sediment yield by debris flow ranges from 4 to 23 percent of total sediment yield.

Particle-Size Distributions

The size of the sand fraction is of particular interest for the management and restoration of sand bars in Grand Canyon. Measurements of particle-size distributions stored in stream terraces in various tributaries, as well as suspended sediment samples from Bright Angel Creek and other small tributaries, provide sand contents ranging from 1 - 99 percent with no discernible pattern. These data were collected from a large discharge range and thus highly variable sand contents would be expected. An average sand content of 50 percent of total streamflow sediment yield was used in this study, which compares favorably with average sand content weighted by discharge for the Little Colorado and Paria Rivers (30 and 50 percent, respectively). Sand contents of 15, 50, and 75 percent are reported. Sand delivery by streamflow from the Glen and Marble Canyon reaches averages about $0.032 \cdot 10^6$ and $0.305 \cdot 10^6$ Mg/yr, respectively ($0.34 \cdot 10^6$ total), with a combined total of the two reaches ranging from $0.10\text{-}0.51 \cdot 10^6$ Mg/yr, depending on the assumed sand content. Sand contributed by tributaries in Glen Canyon is notably coarser (D_{50}=0.24 mm) than sand in other reaches (D_{50}=0.11-0.20 mm), including the Marble Canyon reach (D_{50}=0.20 mm) (fig. 4).

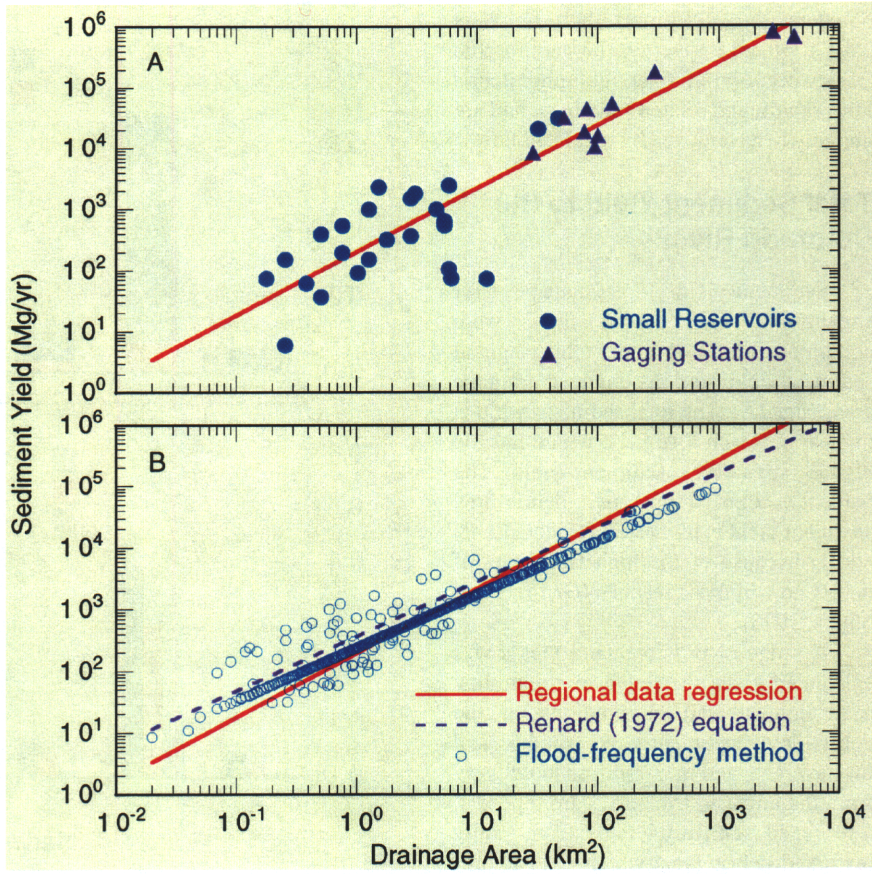

Figure 3. Comparison of methods for calculating streamflow sediment yield. A. Gaging station and reservoir data from the Colorado Plateau region (r^2 = 0.86). B. Comparison of regional data regression equation, Renard (1972) equation, and estimates for 768 ungaged tributaries by the flood-frequency rating-curve method.

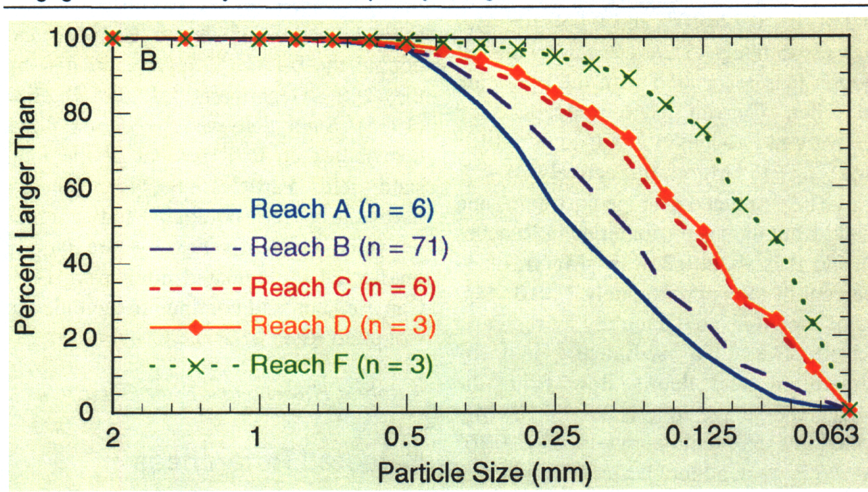

Figure 4. Particle-size distribution of sand delivered by streamflow from ungaged tributaries. Sand input by streamflow is increasingly finer downstream from the dam.

The particle-size distributions of 41 fresh, unaltered deposits of debris flows that occurred between 1965 and 1999 were determined. Pebbles are the most abundant particles at 41 percent by weight, and boulders typically account for about 14 percent. The sand content of debris flows averages about 18.2 percent and ranges from 2.4-47 percent. With debris-fan reworking limited by the operation of Glen Canyon Dam, debris flows transport from $0.006\text{ -}0.013 \cdot 10^6$ Mg/yr of sand to the regulated Colorado River, while $0.023\text{-}0.048 \cdot 10^6$ Mg/yr is stored in unreworked parts of debris fans. Depending on the volume model used and the amount of debris-fan reworking, the total sand yield of debris flows in all reaches ranges from $0.006\text{-}0.054 \cdot 10^6$ Mg/yr. Although debris

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Monitoring of Coarse Sediment Inputs to the Colorado River in Grand Canyon

Introduction

Coarse sediment (particles with an intermediate diameter > 64 mm) affects the primary components of the Colorado River ecosystem. The deposition of coarse sediment at tributary junctures builds large debris fans that constrict the river and form rapids (fig. 1). Debris fans, and the debris bars that develop below rapids, provide stable substrate for aquatic organisms, notably the alga *Cladophora glomerata*. The pool above and recirculating eddy below the debris fan effectively trap fine sediment for storage on the bed or in sand bars. Debris fans and debris bars form the fan-eddy complex that attracts humpback chub (*Gila cypha*), an endangered species. Monitoring the input of coarse sediment to the Colorado River ecosystem and its long-term redistribution by the river is critical to the understanding and management of these valued resources. This fact sheet presents an overview of methods for monitoring coarse sediment input and redistribution in Grand Canyon. These methods are discussed more thoroughly in Melis (1997), Melis and others (1994, 1997), and Webb and others (1999a, 1999b, 2000).

Debris Flows and the River

In small tributaries of the Colorado River between Powell and Mead reservoirs, coarse sediment is transported to the river almost exclusively by debris flow. While tributary streamflow deposits are well-sorted and typically have less than 3% coarse sediment by weight, debris-flow deposits are poorly sorted and contain 5 to 76% coarse sediment (Webb and others, 2000).

Debris flows can have an immediate and dramatic effect on the river corridor. Even a single small debris flow may significantly alter the topography and hydraulics of a debris fan and rapid in a matter of minutes. However, the Colorado River redistributes the coarse sediment introduced by debris flows almost immediately after deposition and during subsequent high flows. Before closure of Glen Canyon Dam, large floods on the river routinely removed all fine sediment and some coarse sediment from aggraded debris fans (a process called *reworking*), transporting coarse sediment through the pool below the rapid and depositing it as debris bars (fig. 1). In the regulated river, floods of reduced magnitude do not have sufficient stream power to rework aggraded debris fans as thoroughly (Webb and others, 1999a, 1999b). Coarse particles that are entrained by these lower discharges may be deposited in the pools below rapids, potentially altering the eddy pattern and increasing the length of the rapid. As a result, debris fans and rapids may be aggrading over the long term.

Monitoring Debris Fans

The effective monitoring of coarse sediment requires both the short-term documentation of inputs by debris flow and the long-term evaluation of the redistribution of that sediment by the Colorado River. Both efforts involve measuring the volume and particle-size distribution of sediment delivered, as well as the effects of its redistribution on the morphology and hydraulics of the river channel. Monitoring debris flows at regular intervals will not only alert managers and researchers to sudden, potentially important changes to channel resources but also will add to an existing database designed to enable modeling of the interaction of coarse sediment and the Colorado River. The effective and efficient monitoring of

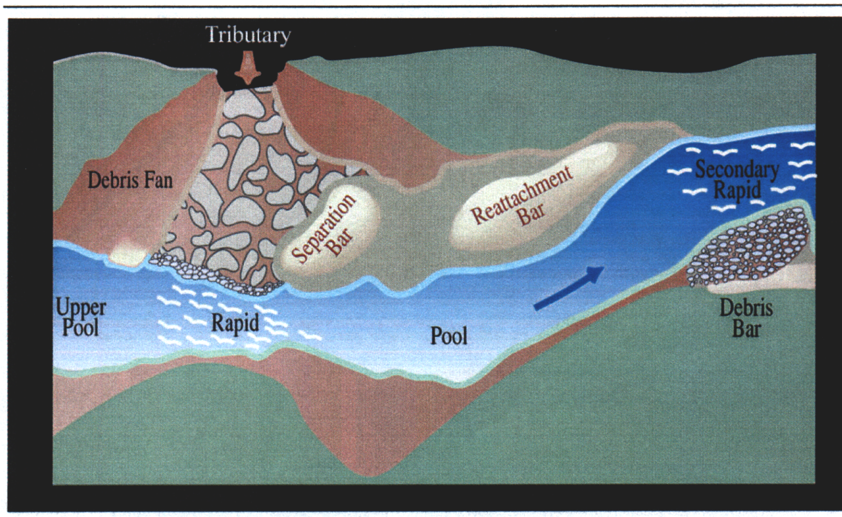

Figure 1. Schematic diagram of the fan-eddy complex on the Colorado River.