ENGINEERING AND ENVIRONMENTAL CONSIDERATIONS OF GRAND CANYON SEDIMENT MANAGEMENT

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Abstract

Glen Canyon Dam and Powerplant are located on the Colorado River in northern Arizona, 16 miles upstream from Grand Canyon National Park. The dam releases only clear water, since all of the inflowing sediment is trapped in Lake Powell. The dam also has reduced the river's capacity to transport sand-size sediment by significantly decreasing the river's annual peak discharge. The Paria and Little Colorado Rivers are now the principle sources of sediment in Grand Canyon and enter the Colorado River 16 and 78 miles downstream from Glen Canyon Dam.

Dam releases change throughout each day in response to changing demand for electrical power. Fluctuating discharges transport significantly more sand than steady discharges of the same volume.

Within the Grand Canyon, hundreds of sandbars intermittently form the banks of this otherwise talus- and bedrock-lined river. Sandbars are important for riparian habitat, fish and wildlife, and recreation.

The long-term mass balance of sand was analyzed using sand-discharge rating curves, historical records of tributary flow, and projected releases for a wide range of operational scenarios. Extreme daily discharge fluctuations would likely result in long-term erosion of sand and sand-dependent resources. Release patterns of either restricted fluctuations or steady discharge would likely result in net accumulation of sand on the bed and banks of the river. Assuming that long-term sand transport does not exceed tributary supply, greater daily or seasonal discharge fluctuations would result in sandbars that are more dynamic and exist at higher elevations than under steady releases.

Location and Setting

Glen Canyon Dam is located on the Colorado River in northern Arizona. The dam was built by the Bureau of Reclamation as part of the Colorado River Storage Project and began storing water in March 1963. Lake Powell is formed behind Glen Canyon Dam and has a gross capacity of 27 million acre-feet (maf)—over two times the average annual flow of the Colorado River.

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The primary purpose of the dam is to allow the Upper Basin States of Colorado, Utah, Wyoming, and New Mexico to utilize their apportioned share of Colorado River water while guaranteeing compact and treaty apportioned flows to the Lower Basin States (Arizona, Nevada, and California) and Mexico. According to the authorizing legislation, hydroelectric power is generated from releases "as an incident of the foregoing purposes."

The dam's powerplant has a release capacity of 33,200 cfs. Since 1963, hourly releases have fluctuated in response to power system load changes. Median daily fluctuations have ranged from about 12,000 cubic feet per second (cfs) in October to 16,000 cfs in January and August.

Downstream from the dam, the Colorado River flows southward through Glen and Marble Canyons and westward through Grand Canyon to Lake Mead (figure 1). The uppermost 15 miles of the river are in Glen Canyon, which is part of the Glen Canyon National Recreation Area; the remaining 278 miles of river flow through Grand Canyon National Park—a World Heritage Site.

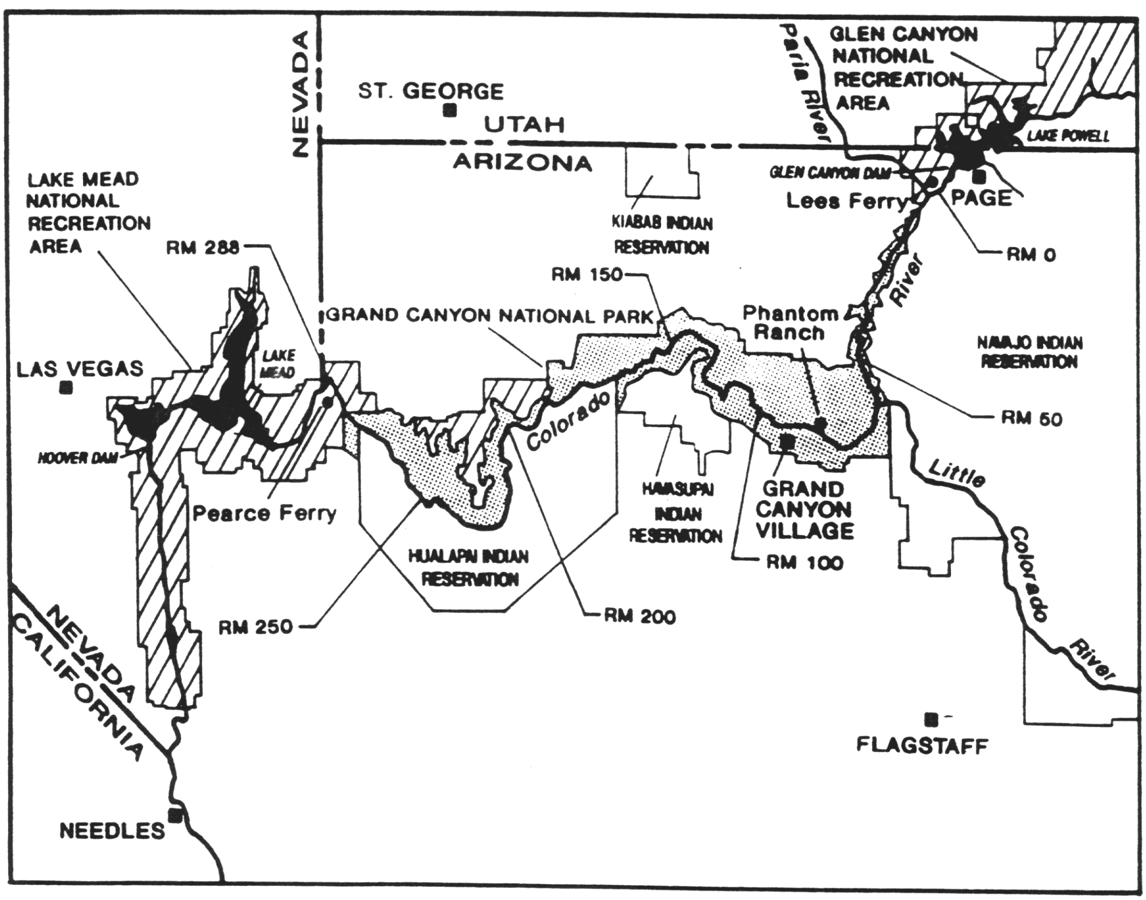

Figure 1.—Location Map.

Several Native American groups have cultural and spiritual ties to Grand Canyon and live in and adjacent to the canyon. These include the Havasupai, Hopi, Hualapai, Kaibab Paiute, and San Juan Southern Paiute Tribes, the Paiute Indian Tribe of Utah, the Shivwits Band of Paiute Indian Tribe, the Navajo Nation, and the Pueblo of Zuni.

Rapids and riffles of the Colorado River account for about 90 percent of the elevation drop through Marble and Grand Canyons but only about 10 percent of the distance (Leopold, 1969). These rapids and riffles have a very large capacity to transport sand; the pools and eddies created by rapids have a relatively low transport capacity and thus store sand.

Sandbars below Glen Canyon Dam are fine-grained alluvial deposits that intermittently form the banks of an otherwise talus- and bedrock-lined river. These bars are comprised mainly of sand; however, they may contain some silt, clay, or gravel. Sandbars are a dynamic resource upon which other resources and activities are dependent. Some examples include vegetation, wildlife habitat, archeological sites, fish, and recreation.

Environmental Challenges

The Grand Canyon Protection Act of 1992 requires the Secretary of the Interior to operate Glen Canyon Dam "...under existing law in such a manner as to protect, mitigate adverse impacts to, and improve values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established..."

Much has changed since the establishment of Grand Canyon National Park. Exotic species of plants and animals were introduced to Grand Canyon prior to the dam's construction. Lake Powell—formed behind the dam—now inundates all but 16 miles of river in Glen Canyon. Glen Canyon Dam has replaced seasonal flow fluctuations with daily fluctuations, sediment is only supplied by downstream tributaries, and water temperatures are nearly constant year round—averaging a cool 50°F. A naturalized system now exists downstream and species and communities that were rare or nonexistent before the dam are now abundant: *Cladophora, Gammarus*, trout, bald eagles, peregrine falcons, and riparian vegetation and its wildlife. From 1960 to 1972, the number of boaters annually rafting the Colorado River in Grand Canyon grew from 205 to 16,432 persons. Today approximately 15,000 to 20,000 commercial and private boaters annually raft the river.

The challenge for the future is to manage the sometimes competing resources of the new naturalized system. Fluctuations in hourly dam releases have provided peaking power throughout the region with environmental consequences. Some environmental problems could be alleviated by having reduced flow fluctuations which would reduce sand transport and increase the abundance of the aquatic food base and reduce trout stranding. However, such changes in release patterns would still have release temperatures that are too cold to promote mainstem spawning of native fish. Now, native fish are only able to successfully spawn in Grand Canyon tributaries because of cold mainstem temperatures.

Postdam Sediment Change

Glen Canyon Dam has caused two major changes related to sediment resources in Glen, Marble, and Grand Canyons. The first is reduced sediment supply. Because the dam traps virtually all of the incoming sediment in Lake Powell, the Colorado River—which once flowed red from high concentrations of sediment—is now released as clear water from Glen Canyon Dam. The second major change caused by the dam is the reduced capacity of the Colorado River to transport sand and other sediment. Sand load is proportional to riverflow raised to about the third power. The natural peak flows that occurred annually prior to dam construction commonly exceeded 80,000 cfs and had a tremendous capacity to transport sediment. Maximum releases from Glen Canyon Dam are normally less than 31,500 cfs.

Measured sediment loads (sand silt and clay) at Phantom Ranch averaged 86 million tons per year during 1941-57. Since construction of Glen Canyon Dam, this average has been reduced to an estimated 11 million tons per year (Andrews, 1991).

The stability of sandbars depends on the rates of erosion and replenishment. Many tributaries supply sediment, including sand, to the Colorado River downstream from Glen Canyon Dam. The Paria and Little Colorado Rivers are estimated to supply over 70 percent of the average annual sand load to Marble and Grand Canyons (Randle and Pemberton, 1987). Other tributaries typically deliver sediment during flash floods or debris flows. There are no tributaries that deliver substantial quantities of sediment to Glen Canyon—the 16-mile reach between the dam and the Paria River—although sediment occasionally is delivered to the river by side canyon flash floods.

Operational Alternatives

Several operational alternatives for Glen Canyon Dam were evaluated in support of the Bureau of Reclamation's Glen Canyon Dam Environmental Impact Statement. The alternatives cover the range of daily operations from maximum flow fluctuations to steady flow and from steady flow throughout the year to seasonal variations (table 1).

Methods

Most of the sediment delivered to and transported by the Colorado River is silt and clay. Since they can be transported at most discharges in Grand Canyon, the quantity of silt and clay transport depends principally on tributary supply rather than on dam release patterns.

Although sandbars along the banks of the Colorado River contain some silt and clay, their existence primarily depends on the availability and transport of sand. Sandbar deposition and erosion depends on riverbed sand availability and the seasonal and daily fluctuations in river discharge. Long-term losses in the number and size of sandbars are assumed to result from a long-term loss of riverbed sand. Such a loss would occur if the sand-transport capacity of the river exceeds the long-term supply from tributaries.

Table 1.—Glen Canyon Dam Operational Alternatives.

	Minimum releases (cfs)	Maximum releases (cfs)	Allowable daily change in flow (cfs/24 hrs)
No Action	1,000 winter 3,000 summer	31,500	30,500 winter 28,500 summer
Maximum Powerplant Capacity	1,000 winter 3,000 summer	33,200	32,200 winter 28,500 summer
Restricted Fluctuating Flows			
High	3,000	31,500	15,000 to 22,000
Moderate	5,000	31,500	± 45% of mean flow for the month, not to exceed ± 6,000
Low	8,000 day 5,000 night	20,000	5,000 to 8,000
Steady Flows			
Existing Monthly Volume	8,000	NA	± 1,000
Seasonally Adjusted	8,000 to 18,000	NA	± 1,000
Year-Round	11,000	NA	± 1,000

Future changes in the quantity of riverbed sand storage depend on tributary sand supply and the daily and seasonal operation of Glen Canyon Dam. The release that transports the most sand over time was determined by combining sand-load discharge rating curves developed by Pemberton (1987) with projected flow duration curves for each alternative. High releases have a relatively large sand transport capacity but occur infrequently. Low releases occur frequently, but have relatively low sand transport capacity.

A sand mass-balance model was developed to estimate the impacts to riverbed sand from various operating criteria at Glen Canyon Dam. This model uses the following basic equation:

Riverbed sand change = Tributary sand supply + Upstream reach sand supply - Downstream sand load

This equation was used to compute net changes in riverbed sand storage for two reaches of the Colorado River between the USGS gauging stations at Lees Ferry (river mile (RM) 0), above Little Colorado River (RM 61), and near Phantom Ranch (RM 87). Changes in sand mass may occur locally at sandbars, eddies, or main channel pools, and changes would not necessarily be uniform throughout the reach. Historic changes were computed for the period 1965-89 for both reaches. Future changes over a 50-year period were computed for the Marble Canyon reach—Lees Ferry to the Little Colorado River (RM 0-61)—for each operational alternative.

The Paria and Little Colorado Rivers were assumed to be the only sources of sand. The future patterns of tributary sand supply were assumed to be the same as historical estimates for the period 1941-90 (figure 2). These sand loads were computed from the mean daily flows and the sand-load discharge rating curves developed by Randle and Pemberton (1987).

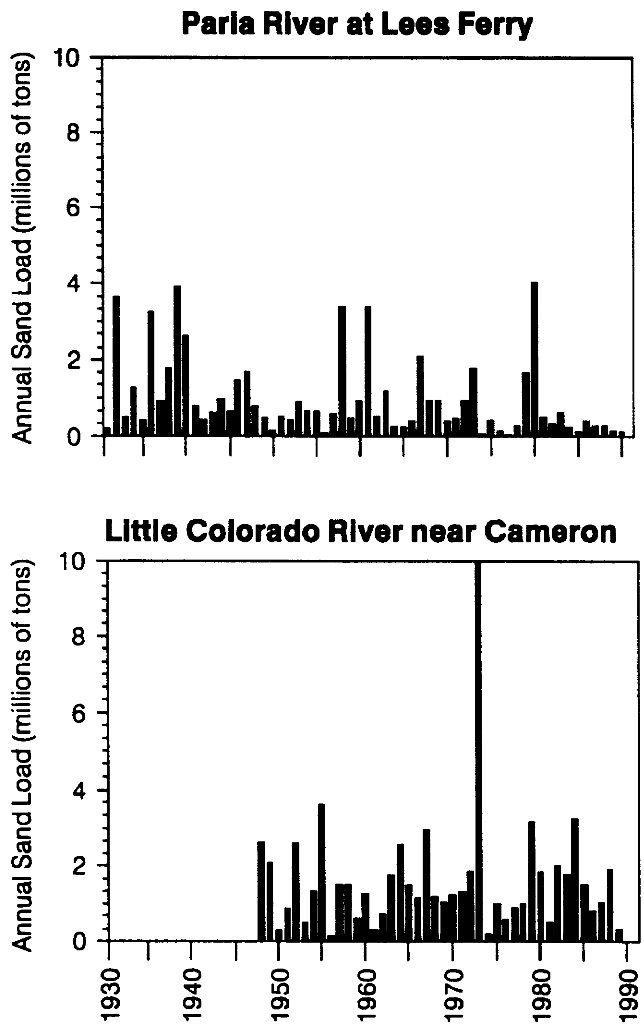

Figure 2.—Annual sand load contributions from the Paria and Little Colorado Rivers. Annual sand loads are highly variable from year to year and from tributary to tributary.

Contributions of sand to the Colorado River from the upstream Glen Canyon reach were assumed to be zero since this reach has no substantial source of sediment. Ungauged tributaries throughout Marble and Grand Canyons can supply large amounts of sediment during flash floods and debris flows; however, these are relatively infrequent events, and no general models exist to predict their occurrence. Therefore, sand contributions from ungauged tributaries also were assumed to be zero.

Colorado River sand loads were computed using the sand-discharge equations developed by Pemberton (1987) and future estimates of monthly release volumes. The original equations developed by Pemberton were adjusted for each fluctuating flow alternative to account for the variations in hourly releases. Future hourly release patterns were projected by S. Rosekrans (Environmental Defense Fund, written communication, 1992) using the Environmental Defense Fund's peak-shaving model. For each alternative, a relationship between monthly release volume and sand transport was developed by computing sand transport for each hour of the month and then performing a regression analysis between monthly release volumes and the computed monthly sand transport.

Future water-release scenarios (50 years of monthly release volumes) were computed by C. Phillips (Bureau of Reclamation, 1992) using Reclamation's Colorado River Simulation Model. For each operational alternative, 85 water release scenarios were developed based on a natural flow data base from 1906 to 1990. Existing levels of the Upper Colorado Basin reservoirs served as the initial conditions for all future release scenarios. These 85 scenarios included both wet and dry cycles.

Colorado River sand loads, computed from each water-release scenario, were matched with the historical sand loads from the Paria and Little Colorado Rivers (1941-90) to estimate changes in riverbed sand over the next 50 years for a given alternative. As an example, cumulative changes in riverbed sand are shown for three scenarios of the Moderate Fluctuating Flow Alternative (figure 3).

The probability of having a net gain in riverbed sand at the end of various time periods was determined from the 85 scenarios. Cumulative probability curves are shown in figure 4 for conditions at the end of 10, 20, and 50 years of the moderate fluctuating flow alternative.

The relationship between discharge and sand load over time was assumed to be constant. This would tend to over estimate either long-term deposition or erosion. Downstream transformation of discharge waves from fluctuating releases were not accounted for because calibrated models to reliably predict this were not available. Therefore, computed sand loads are somewhat overestimated, and riverbed sand storage is somewhat underestimated under strong fluctuating flow alternatives such as no action, maximum powerplant capacity, and high fluctuating flows.

The sand mass balance model could be improved by developing more accurate methods to predict sand transport and also by using synthetic hydrographs to estimate future flow conditions.

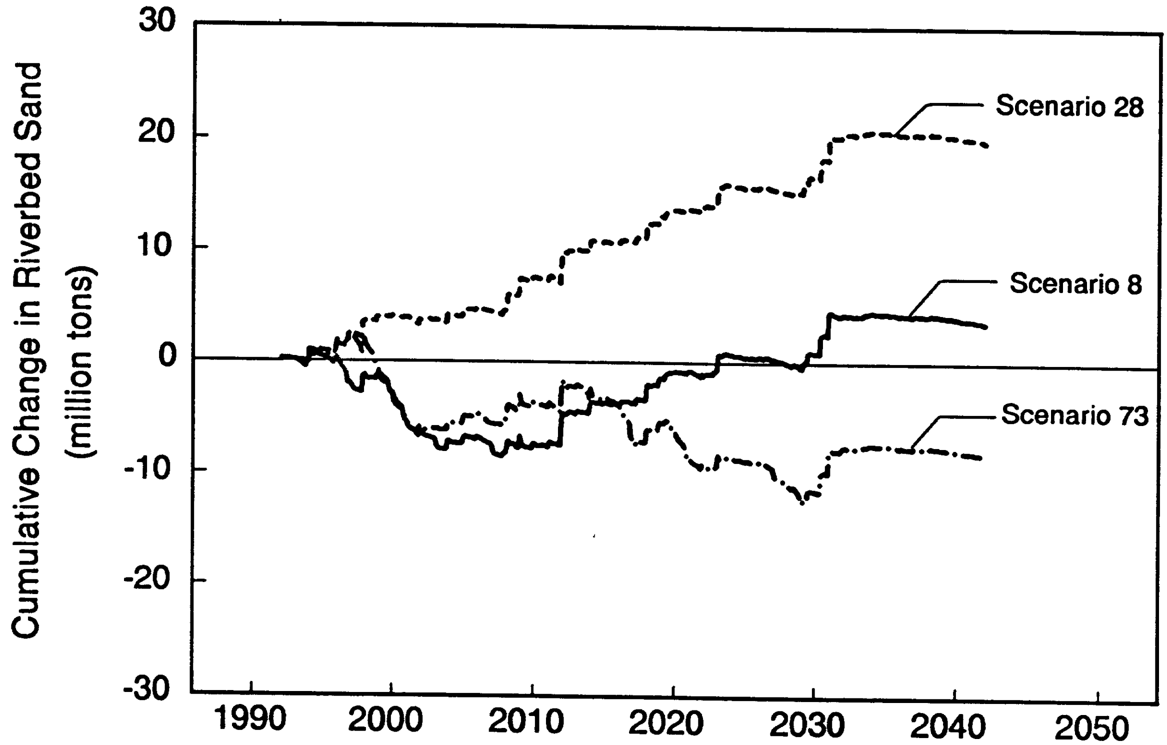

Figure 3.—Cumulative changes in riverbed sand for three water-release scenarios of the Moderate Fluctuating Flow Alternative in Marble Canyon.

Impacts to sandbars were determined using the principles of slope stability as presented by M. Budhu (University of Arizona, written communication, 1992). An illustration of these principles is shown in figure 5. Sandbars aggrade during high river stage and at slopes of about 26 degrees. As the river stage recedes, this slope may be unstable due to seepage, high velocities, or wave action. Under any of these conditions, erosion would likely occur until a stable slope of about 11 degrees was achieved. Assuming sufficient quantities of riverbed sand, an eroded sandbar would likely rebuild during subsequent periods of high river stage.

The active width of a sandbar is that part of the bar subjected to cycles of deposition and erosion—the hydrologically active zone. Estimates of active widths are determined by reach from computed differences in river stage corresponding to changes in discharge. The modeling effort by Randle and Pemberton (1987) was extended to compute daily and annual differences in river stage for each alternative.

Results and Discussion

Analysis of flow duration and sand-load discharge rating curves for all operational alternatives indicates that only 4 to 8 percent of the sand would be transported during periods when releases exceed powerplant capacity (2 maf per month or 33,200 cfs). The most sand would be transported during release of 1.17 maf per month to 1.23 maf per month (equivalent to mean release of 19,300 cfs to 20,400 cfs).

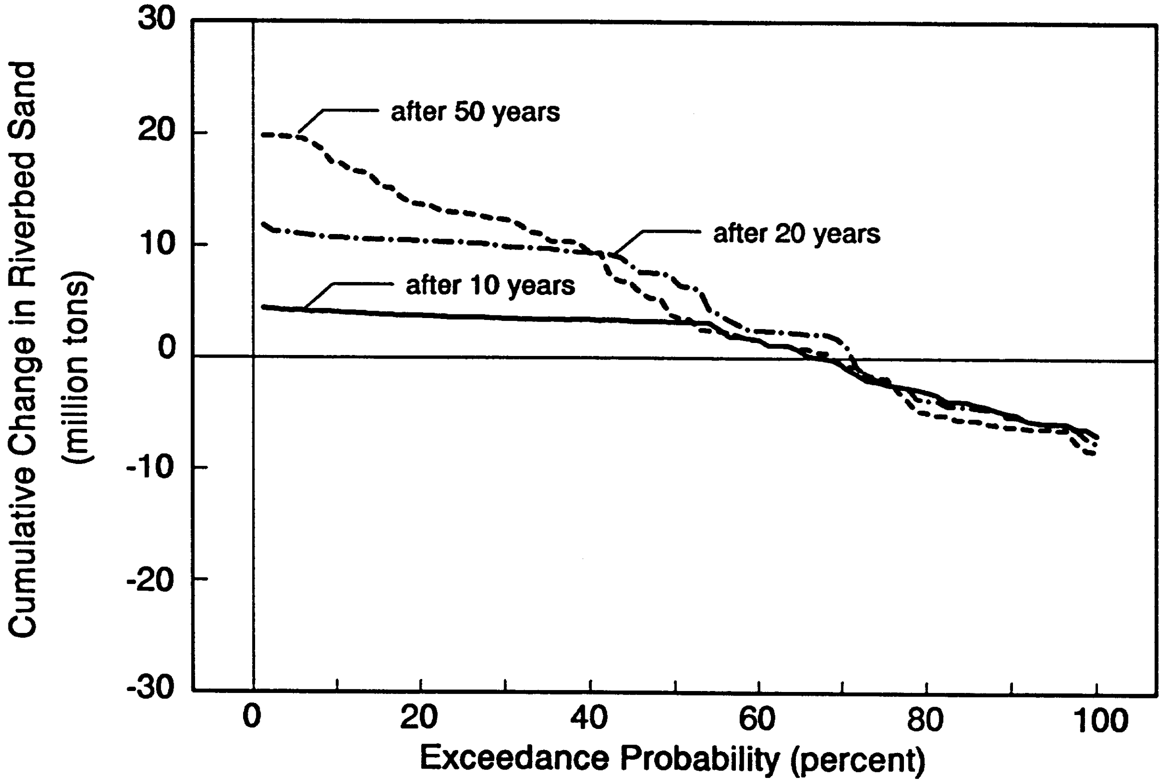

Figure 4.—Cumulative probability curves for conditions at the end of 10, 20, and 50 years in Marble Canyon for the Moderate Fluctuating Flow Alternative.

Historic changes in riverbed sand are shown in figure 6 for the period 1965-89. The probabilities of a future net gain in riverbed sand at the end of 50 years and potential sandbar height are shown in figure 7 for each alternative. Potential sandbar heights were determined from differences in river stage between 5,000 cfs and the peak annual flow during a minimum release year.

For all alternatives, the Marble Canyon reach is the reach most vulnerable to net sand loss because of the limited sources of supply—mainly the Paria River. The sand load-discharge equations from Pemberton (1987) are the same for the Colorado River above the Little Colorado River (RM 61), near Phantom Ranch (RM 87), and above Diamond Creek (RM 225). Therefore, Colorado River downstream from the Little Colorado River would be expected to remain in equilibrium, and long-term changes in riverbed sand would be negligible under any alternative. While some changes would occur from year to year, net changes would be expected to balance out.

The riverbed and banks will adjust over time so that sand loads will match tributary supply. Over the long term (20 years or more), the total amount of sand transported past Phantom Ranch (river mile 88) would approximately equal the average annual tributary supply regardless of the alternative.

The amount of riverbed sand and the normal peak river stage vary with operational alternative. Alternatives with strong daily flow fluctuations may have the potential to temporarily build sandbars but would have relatively little riverbed sand for deposition. Steady flow alternatives would have relatively large amounts of riverbed sand but little potential to rebuild sandbars. A large increase in riverbed sand will cause isolated backwater channels used by fish to become more vulnerable to sedimentation. Lower normal peak river stage would result in colonization of sandbars by woody riparian vegetation.

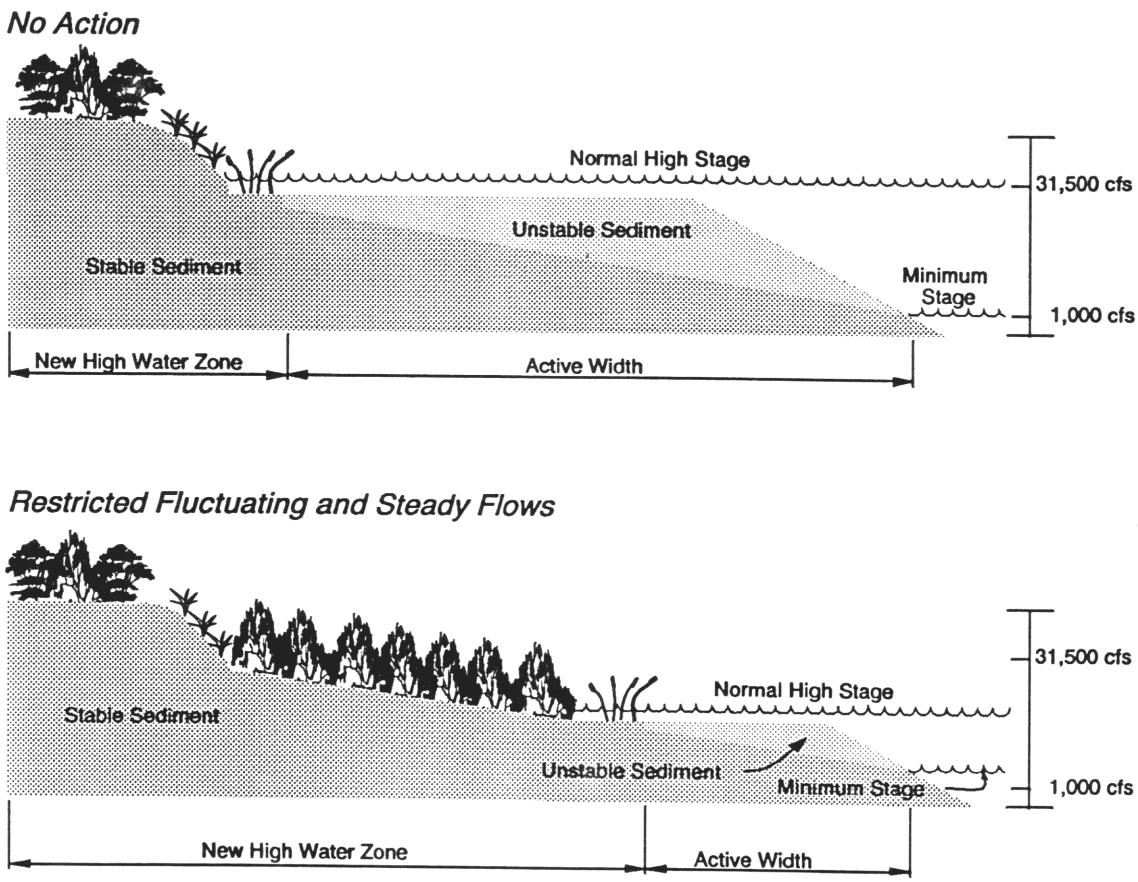

Figure 5.—Changes in sandbar height and active width in response to changes in dam operations. Reduced flow fluctuations or steady flow will produce sandbars that exist at lower elevations, are more stable, and are more vegetated than under strong fluctuating flow conditions.

Conclusions

A net increase in riverbed sand is likely for all operational alternatives except for the No Action, Maximum Powerplant Capacity, and High Fluctuating Flow Alternatives.

Flood frequency reduction measures would increase the probability of a net accumulation of riverbed sand. However, since relatively little sand is projected to be transported by releases in excess of powerplant capacity over the long term, a net gain in riverbed sand is more sensitive to changes in daily or hourly release patterns.

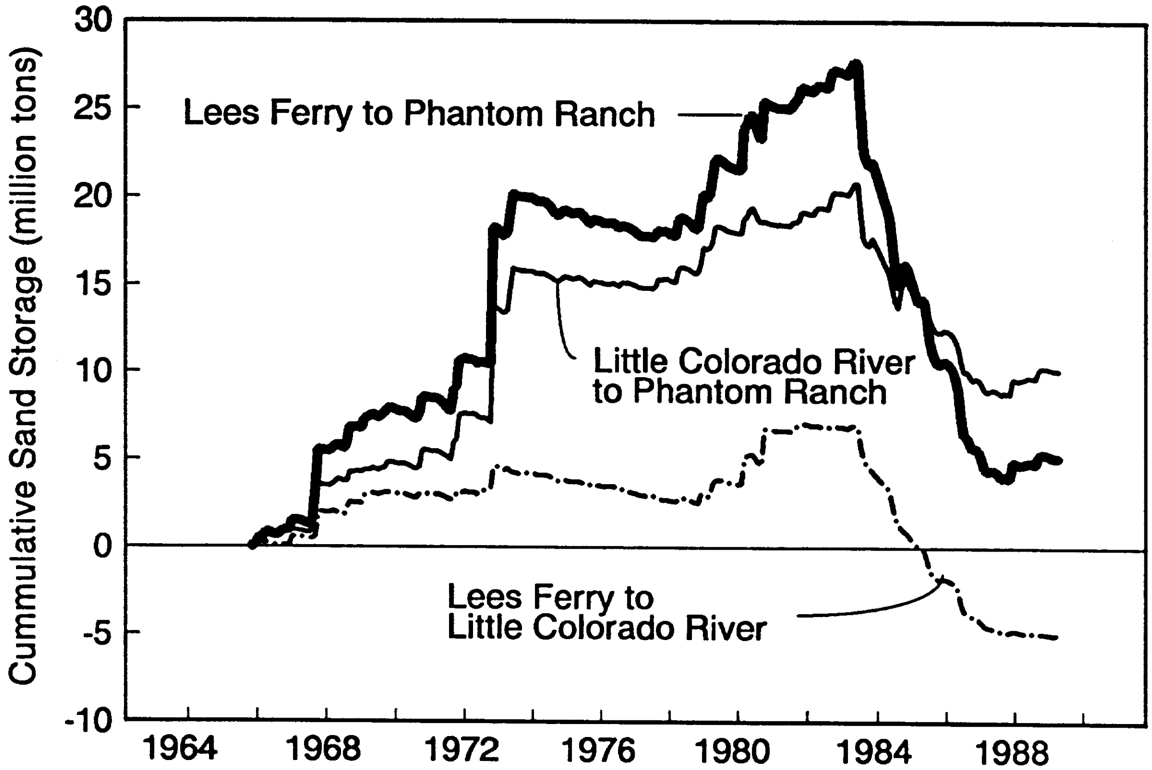

Figure 6.—Cumulative sand storage between Lees Ferry and Phantom Ranch. Sand accumulated in the reach when releases were relatively low while Lake Powell was filling, coupled with large sand contributions from the Paria and Little Colorado Rivers. Sand was eroded from the reach during the high water years of 1983-86.

Dam operations could be changed that would avoid progressive, long-term erosion and still provide some of the dynamics of a natural system. Release patterns of either restricted fluctuations or steady discharge would likely result in net accumulation of sand on the bed and banks of the river. Assuming that long-term sand transport does not exceed tributary supply, greater daily or seasonal discharge fluctuations would result in sandbars that are more dynamic and exist at higher elevations than under steady releases.

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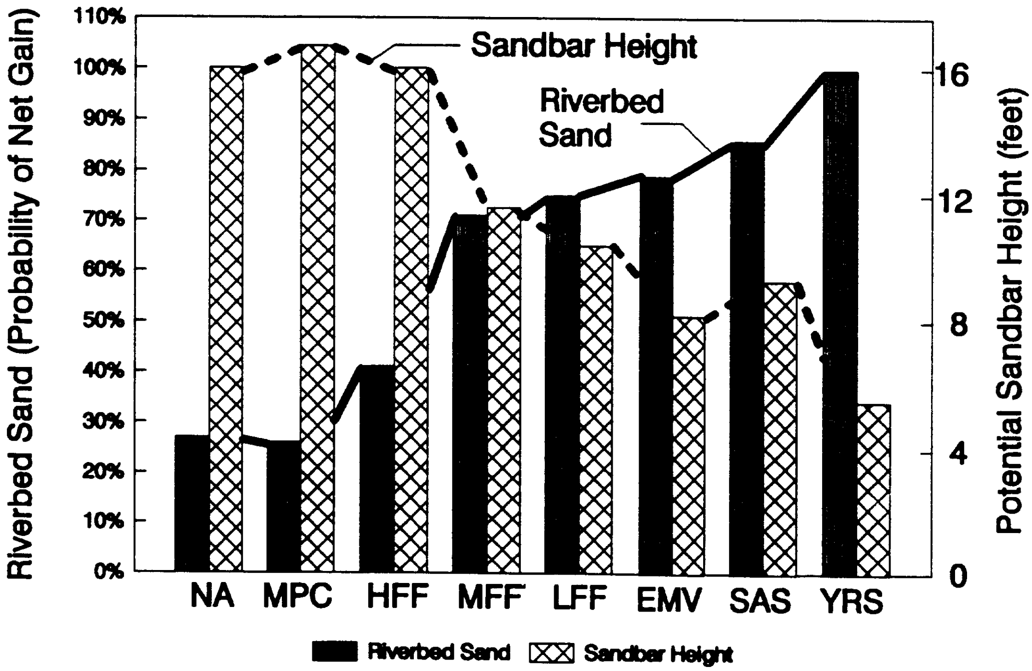

NA = No Action; MPC = Maximum Powerplant Capacity;
HFF = High Fluctuating Flows; MFF = Moderate Fluctuating Flows;
LFF = Low Fluctuating Flows; EMV = Existing Monthly Volumes Steady Flows;
SAS = Seasonally Adjusted Steady Flows; and YRS = Year-Round Steady Flows

Figure 7.—Probabilities of a future net gain in riverbed sand at the end of 50 years and potential sandbar height.

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