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COMPARISON OF THE MAGNITUDE OF EROSION ALONG TWO LARGE REGULATED RIVERS[1]

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ABSTRACT: Historical inventories of sand bar number and area are sufficient to detect large-scale differences in geomorphic adjustment among regulated rivers that flow through canyons with abundant debris fans. In these canyons, bedrock and large boulders create constrictions and expansions, and alluvial bars occur in associated eddies at predictable sites. Although these bars may fluctuate considerably in size, the locations of these bars rarely change, and their characteristics can be compared through time and among rivers. The area of sand bars exposed at low discharge in Hells Canyon has decreased 50 percent since dam closure, and most of the erosion occurred in the first nine years after dam closure. The number and size of sand bars in Grand Canyon downstream from Glen Canyon Dam have decreased much less; the number of sand bars decreased by 40 percent in some 8.3-km reaches, but by less than 20 percent elsewhere. These differences are in part related to the fact that flood regulation is much greater in Grand Canyon than in Hells Canyon, and that downstream tributaries resupply sediment to Grand Canyon but not to most of Hells Canyon.
(KEY TERMS: Colorado River; dams; erosion; geomorphology; Grand Canyon; Hells Canyon; Snake River.)

INTRODUCTION

Criteria for dam releases are being revised throughout the United States to better manage downstream river environments. Comparative assessment of the magnitude of environmental change on different regulated rivers would permit national prioritization of these management and restoration activities. Although such an assessment has been conducted for water quality (Smith *et al.*, 1987), no national assessment has been attempted for physical changes, such as those related to channel geomorphology.

Reconstruction of the history of fluvial geomorphic adjustment and comparison of measured changes on similar rivers can also assist reservoir-release rule revision at any one site. Such comparisons are rarely conducted, however. Numerous studies have been published about the geomorphology of alluvial deposits along the Colorado River in Grand Canyon and about the impacts of Glen Canyon Dam. These studies have been conducted since 1983, and about $10 million have been spent on the geomorphology parts of this federally-funded research program. However, no studies have compared the magnitude of observed changes in Grand Canyon with those of similar rivers. Thus, no data are available with which to evaluate the relative significance or magnitude of the measured changes in Grand Canyon.

Comparison of the style and magnitude of geomorphic change on different rivers is hampered because comparable data are not available for many rivers. Documentation of an historical sequence of geomorphic change of rivers typically focuses on repeated measurement of bed and bank elevations (many such studies are summarized by Williams and Wolman, 1984) and calculation of reach-scale sediment budgets (e.g., Andrews, 1986). These measurements and calculations depend on the availability of topographic and bathymetric surveys, stream-gaging and sediment-transport data, and aerial photography. However, these data are unavailable for many regulated rivers, yet the need remains to compare the history of channel change, the magnitude of downstream adjustment, and the relative significance of channel change. Historical aerial and oblique photographs may provide the only information that can be used to accomplish these tasks.

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Photographic data are necessarily limited to depiction of banks and alluvial bars exposed during photography. Analysis of change in these bars and banks yields ambiguous results on many alluvial rivers because site specific change may be related merely to the process of bar migration. However, historical changes are more systematic on rivers where bars do not migrate, such as rivers with abundant debris fans (Schmidt and Rubin, 1995).

The purpose of this paper is to illustrate the feasibility of conducting comparative assessments of fluvial geomorphic change by using photographic data. This paper illustrates feasibility by comparing geomorphic change on two rivers that flow through canyons that have abundant debris fans; these rivers are of comparable size but differ greatly in the magnitude of flow and sediment regulation. The Colorado River in Grand Canyon has a high degree of flow regulation and has substantial sediment resupply by downstream tributaries, but the Snake River in Hells Canyon has a low degree of regulation and no sediment resupply by downstream tributaries. Original data for Hells Canyon are analyzed, and geomorphic data for Grand Canyon are summarized from field work, air photos, and repeat ground-level photography. No previous measurements of geomorphic change have been made along the Snake River in Hells Canyon; these data provide context and comparison for managers of the Colorado River in Grand Canyon and may be useful to managers of the Columbia River system.

SEDIMENT TRANSPORT AND SEDIMENTATION IN CANYONS WITH ABUNDANT DEBRIS FANS

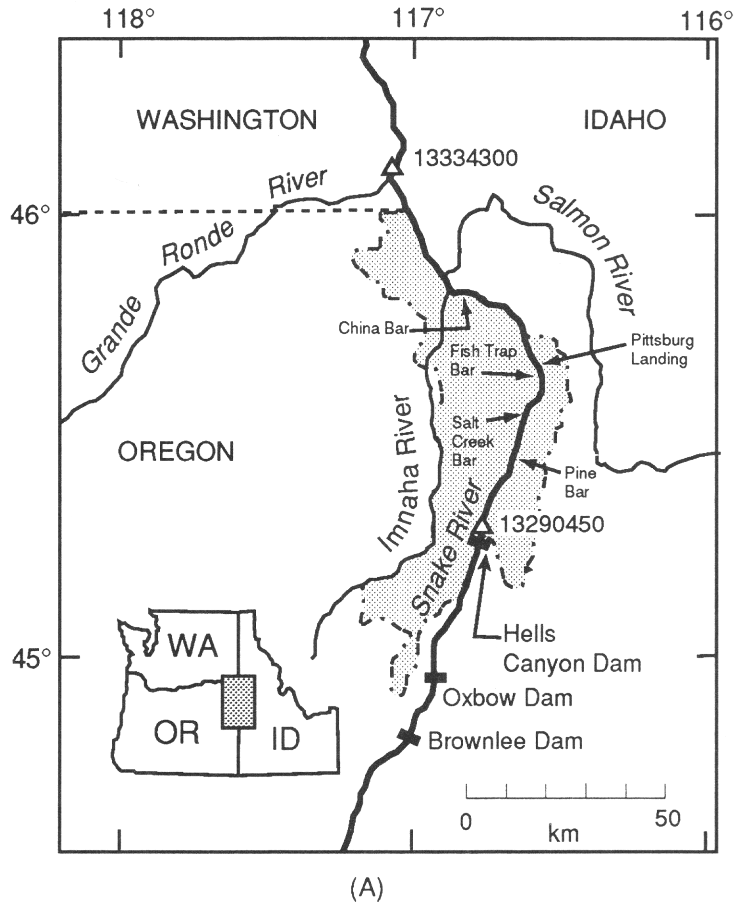
Recirculating currents develop in lateral zones of flow separation downstream from obstructions, such as debris fans, bedrock abutments, or talus cones. The detailed geometry of flow separation and associated recirculating currents are controlled by the morphology (e.g., elevation, size, roughness) of these flow-separation-inducing obstructions. In many narrow canyons, debris fans are common, and the sand bars that form in the associated eddies are the only significant storage sites for suspended load (Rubin *et al.*, 1994a).

Sand bars deposited within eddies have distinctive topography and location. Schmidt (1990) classified eddy bars: separation bars form near the flow-separation point and mantle the downstream parts of debris fans, and reattachment bars form under the primary recirculating eddy cell. Channel-margin deposits are a separate category of deposits that occur as narrow floodplain-like deposits, usually in the lee of large talus blocks or bedrock abutments. Schmidt and Graf (1990) suggested that reattachment bars erode more readily than do separation bars when sediment supply is reduced.

Interpretation of sedimentary structures and recovery of scour chains (Rubin *et al.*, 1990, 1994b) show that eddy bars are dynamic features, subject to deposition and erosion during floods and erosion after flood recession. However, eddy bars persist in specific zones of recirculation because the channel obstructions that give rise to flow separation rarely change. Although the shape of the bars varies with discharge, these bars remain within specific eddies and do not migrate elsewhere. Measurements and observations of the Colorado River in Grand Canyon show that the locations of eddy sand bars have persisted for at least the last 100 years (Howard and Dolan, 1981; Webb, in press).

COMPARISON OF THE STUDY REACHES: STREAMFLOW, FLOW REGULATION, SEDIMENT TRANSPORT, AND GEOMORPHOLOGY

Dams have regulated flow through Hells Canyon and Grand Canyon (Figure 1) for similar time periods. Construction of Glen Canyon Dam on the Colorado River began in 1956; official closure was in 1963. Of the three Snake River dams collectively known as the Hells Canyon Complex, the largest, Brownlee Dam, was completed in 1958; the farthest downstream, Hells Canyon Dam, was completed in 1968. The mean annual flow of the Snake River is about 20 percent greater than that of the Colorado River (Table 1), but the magnitude of flow regulation of the Colorado River basin is much greater (Table 2). The ratio of reservoir storage to mean annual discharge is 0.08 for the Hells Canyon Complex, and it is 2.56 for Lake Powell reservoir, formed by Glen Canyon Dam (Hirsch *et al.*, 1990). Consequently, Lake Powell has more than an order of magnitude greater flood-control capacity than does the Hells Canyon Complex. About 17 years were needed to fill Lake Powell, but less than two years were required to fill the three reservoirs of the Hells Canyon Complex. The longer filling time for Lake Powell resulted in a lengthy period during which annual peak discharge rarely exceeded powerplant capacity (Figure 2). In contrast, the much smaller storage volume and the short reservoir-filling time on the Snake River are such that the magnitude and frequency of peak discharges downstream from Hells Canyon Dam are essentially unaffected by regulation. During the period covered by this study, diurnal releases resulting from hydroelectric peak power



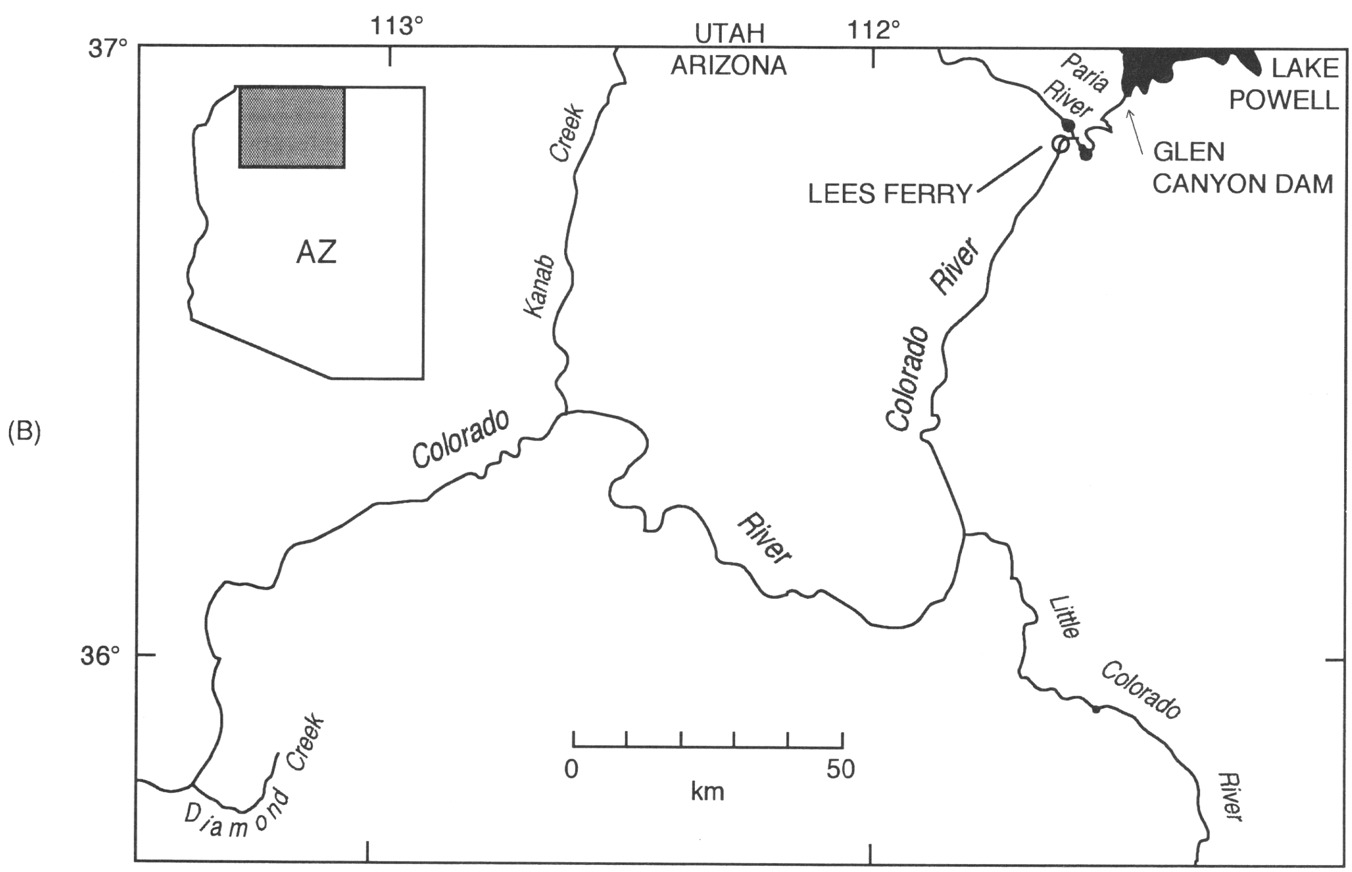


Figure 1. Maps Showing (A) Snake River in Hells Canyon, and (B) Colorado River in Grand Canyon. U.S. Geological Survey gaging stations are indicated by identification numbers. Shaded area in (A) is Hells Canyon National Recreation Area.

TABLE 1. Summary of Hydrologic Conditions for the Snake and Colorado Rivers, Pre- and Post-Regulation.

	Mean Annual Discharge (m^3/s)	Dimensionless Discharge* at Indicated Duration		
		5 Percent	50 Percent	95 Percent
		Snake River		
Unregulated	531	2.24	0.85	0.45
Regulated	538	2.37	0.85	0.39
		Colorado River		
Unregulated	470	3.79	0.48	0.24
Regulated	412	1.92	0.82	0.10

*Discharge divided by mean annual discharge for indicated period.

TABLE 2. Summary of Reservoir and Powerplant Characteristics Immediately Upstream from Study Reaches.

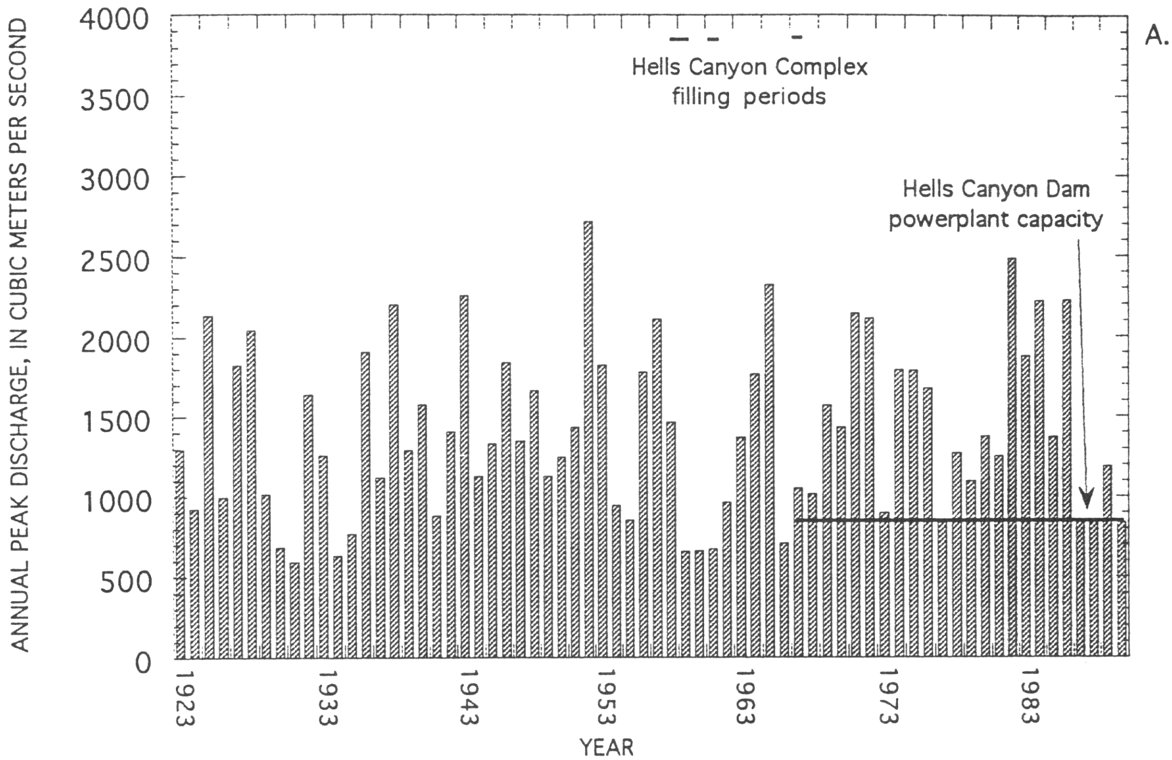
Dam	Filling Period	Active Storage (in million) cubic meters)	Minimum Hourly Discharge (in cubic meters per second)	Maximum Powerplant Discharge (in cubic meters per second)
		Snake River*		
Brownlee	May 1958-June 1959	1,209	–	991
Oxbow	February 1961-March 1961	6.7	–	750
Hells Canyon	October 1967-November 1967	121.9	142	849
		Colorado River**		
Glen Canyon	March 1963-June 1980	33,299	28-854***	892

*Total reservoir storage upstream from Brownlee Reservoir in 1980 was 11.8 million m^3 (Kjelstrom, 1986). Hydrologic data from U.S. Department of Energy (1985).
**Andrews (1991).
***Winter and summer minimum discharges, respectively, before August 1990.

production fluctuated more widely in Grand Canyon than in Hells Canyon.

Dams on both rivers are complete sediment traps, but the downstream distance between the dams and significant sediment-contributing tributaries differs greatly. The Paria River joins the Colorado River 26 km downstream from Glen Canyon Dam, and the Little Colorado River enters 123 km downstream from the dam (Figure 1); together these tributaries transport about 1.8 X 10^{10} kg of sediment annually (Andrews, 1991). In contrast, the unregulated Imnaha and Salmon Rivers join the Snake River about 100 km downstream from Hells Canyon Dam.

Grand Canyon and Hells Canyon both have abundant debris fans that constrict the channel and control the deposition of fine-grained sediment. The average channel slope and the width between bedrock walls of Hells Canyon are similar to narrow reaches of Grand Canyon (Table 3). Debris fans constrict the Colorado River to a greater degree than the Snake River in Hells Canyon, on the basis of a comparison of the frequency distribution of constriction ratios along the channel. The mean constriction ratio of large rapids in Grand Canyon is about 0.50 (Kieffer, 1985; Schmidt and Graf, 1990). The mean constriction ratio of all debris-fan constrictions that form rapids in Hells Canyon is 0.60, determined from air photographs taken in 1973. Melis *et al.* (1994) have shown that there are significant differences in the mean discharge required for overtopping debris fans in different reaches of Grand Canyon, but no analysis of debris fan shape has been completed in Hells Canyon.



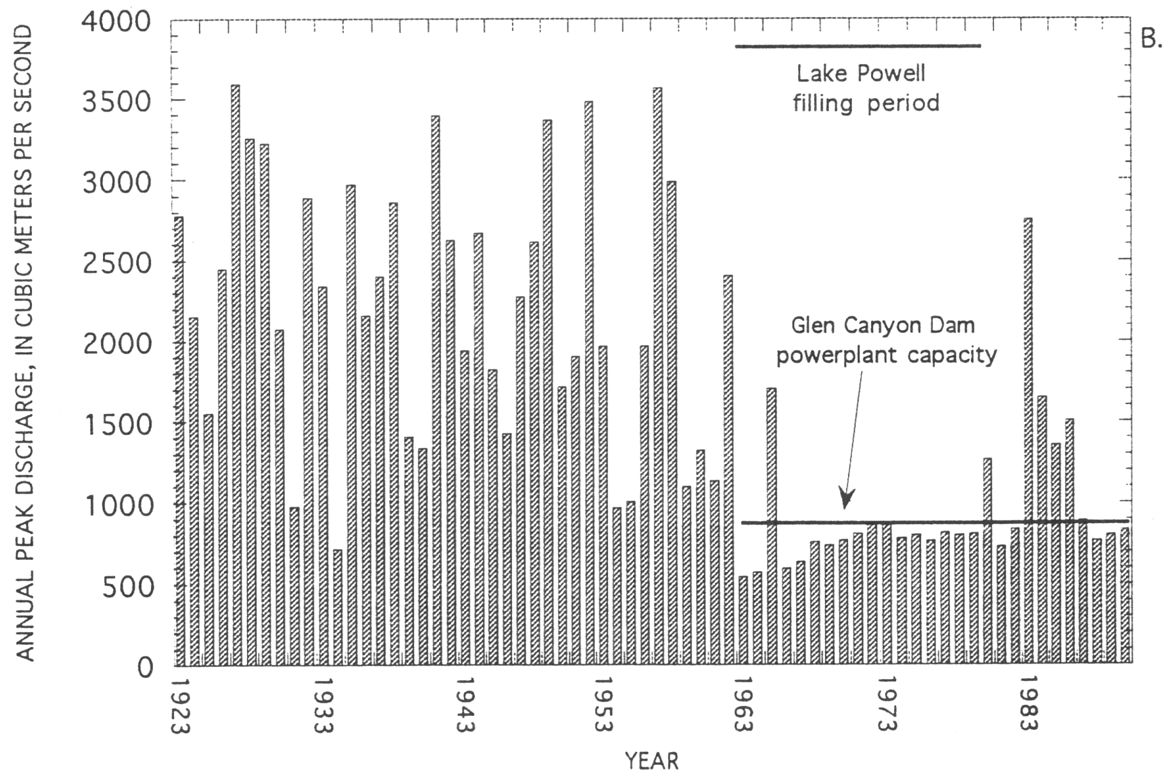


Figure 2. Graphs Showing Annual Peak Discharge for (A) Snake River at Hells Canyon Dam and (B) Colorado River at Lees Ferry.

TABLE 3. Summary of Geomorphic Characteristics of the Snake and Colorado Rivers.

Reach	Channel Slope (in meters per meter)	Mean Constriction Ratio*
Snake River		
Average for Study Area	0.0017	0.60**
Upstream from Salmon River	0.0018	–
Downstream from Salmon River	0.00092	–
Colorado River		
Average for Study Area	0.0015	0.49***
Narrow Reaches	0.00120-0.0023	–
Wide Reaches	0.00099-0.0021	–

*Channel width at constriction divided by upstream channel width.
**For all debris fan constrictions above the Salmon River confluence.
***For all debris fan constrictions in Grand Canyon.

METHODS

Hells Canyon

The methods used to inventory the number and size of sand bars in Hells Canyon are similar to those used in Grand Canyon (Schmidt and Graf, 1990; Kearsley *et al.*, 1994). The number of sand bars along the Snake River was counted on six air photo series taken between 1955 and 1982; these photos are at 1:20000 or larger scale (Table 4). The area of sand bars along the river was estimated for the four air photo series taken at 1:12000 scale. Discharge at the time of photography was determined from the unpublished hourly records of the U.S. Geological Survey's Snake River at Hells Canyon Dam stream gage (station number 13290450) and time-of-travel estimates (Koski, 1974). Discharge was very similar during the photography of 1955, 1964, and 1970, but it was much less during the 1973 and 1977 photography. Discharge at the time of photography in 1982 was higher than in any other year. The maximum difference in water stage among the different photograph series was approximately 1.3 m (Table 4). Measurements of changes in the number or area of sand bars are unbiased for the period 1955 to 1970 and for the period 1973 to 1977. Because lower stream discharge results in larger subaerial exposure, measurements of change in number and area of sand bars between 1970 and 1973 are biased to show aggradation. Conversely, changes between 1977 and 1982 are biased to show degradation.

All sand bars subaerially exposed in 1964 in the 100-km reach between Hells Canyon Dam and the northern boundary of the HCNRA (Hells Canyon National Recreation Area) were catalogued according to location and bar type. Locations were determined in relation to the distance upstream from the confluence of the Snake and Columbia Rivers, in accordance with the standard practice of the U.S. Army Corps of Engineers. Tabulated data for each inventoried site in each year are appended to the report of Grams (1991, Degradation of Alluvial Sand Bars along the Snake River below Hells Canyon Dam, Hells Canyon National Recreation Area, unpublished undergraduate thesis, Middlebury College Geology Department, 98 pp.). Estimates of the area of subaerially exposed sand were based on measurements on air photos calibrated by field measurements. A field inventory of sand bars, using the classification of Schmidt (1990), was conducted in 1990 during two river trips. The subaerially exposed sand at that time was directly measured; the

TABLE 4. Aerial Photograph Series Covering Snake River in Hells Canyon.

Year	Date	Approximate Scale	Discharge (m^3/s)	Variability (m^3/s)	Elevation of Water Surface Above 1973 Water Surface* (m)
1955	August 20-September 4	1:20,000	310	14	0.9
1964	August 17-24	1:12,000	303	–	0.8
1970	July 31-August 10	1:14,000	292-337	3-18	0.9-1.1
1973	March 25	1:12,000	142	Steady Release	0
1977	September 9	1:12,000	150	7	0.1
1982	August 19	1:12,000	399	–	1.3

*At U.S. Geological Survey gaging station at Hells Canyon Dam, using rating relation.

estimated area of subaerially exposed sand, as interpreted from the 1964 photos, was measured in the field by co-locating landmarks (e.g., boulders) identifiable in the 1964 photographs and in the field. These data were used to establish size categories for classification of bar size in all photograph series, and the size class was determined at 221 sites in every series. Five categories were used: no exposed sand, less than 930 m^2, 930 to 1860 m^2, 1860 to 2790 m^2, and 2790 to 3715 m^2. Aggregated statistics about the area of exposed sand in each year were computed by multiplying the number of sand bars within each size class by the midpoint of each size class.

Logistical restrictions and gaps in photograph coverage prevented measurements in the entire study reach for every year. Therefore, the study area was divided into three subreaches, and data for a subreach in a particular year are only reported if comprehensive data were available. These subreaches are Hells Canyon Dam to Pittsburg Landing (no data for 1990), Pittsburg Landing to the Salmon River, and the Salmon River to the northern boundary of the HCNRA (does not include 1982 or 1990 data).

Comparison of subaerially exposed sand in 1982 as interpreted from aerial photography with the area observed in the field in 1990 indicates that some very small (less than 1000 m^2) sand bars can not be detected on aerial photography. Fourteen percent of the inventory sites that were interpreted as being devoid of sand in 1982 had subaerially exposed sand in 1990, a period during which there is no other evidence of sand bar deposition. Other errors in these methods arise from the bias introduced from errors in scale transfer and from differing river stage. The magnitude of error associated with differences in river stage was estimated by Kearsley and Warren (1993); they showed that the area of exposed sand at 125 large alluvial bars in Grand Canyon decreased by 18 percent when discharge increased from 141 to 424 m^3/s. This range of discharges is similar to the maximum range of discharges during the photography of Hells Canyon evaluated in this study.

The detailed characteristics of large bars that have not been completely eroded were measured at four sites in Hells Canyon. Topographic surveys were completed using an electronic distance meter, and bar sedimentology was studied by excavation of shallow trenches. Changes in the areal extent of sand bars and high terraces was measured in reference to features that have been stationary since 1955.

Grand Canyon

Inventory data for Grand Canyon are reported for two time periods: 1889 to 1993 and 1963 to 1990. Oblique ground-level photographs first taken in 1889 by Robert Brewster Stanton (Smith and Crampton, 1987) were replicated at 439 sites in Grand Canyon (Webb, in press). Photograph replication was completed between 1989 and 1993. The original camera stations were spaced at 1.7-km intervals over 446 km of the Colorado River, and sand bars occur in 298 of the views. At each camera station, the observed size of each bar was compared with the size visible in the 1889 photograph, and bars were categorized as aggraded, about equal, or eroded. Each sand deposit was classified as a separation bar, reattachment bar, or channel-margin deposit. River discharge was approximately 150 to 170 m^3/s in 1889 and fluctuated between 170 and 420 m^3/s during the repeat photography.

The number of reattachment bars in 838 large eddies within 375 km downstream from Glen Canyon Dam determined from aerial photographs taken in 1973 and 1984 were compiled from Zink (1989, Effects of Glen Canyon Dam on Sand Bars of the Colorado River in Grand Canyon, unpublished undergraduate thesis, Middlebury College Geology Department, 53 pp.) and Schmidt and Graf (1990). The area of exposed sand could not be meaningfully compared because discharge differed too greatly in the photographs. The maximum extent of post-dam erosion was estimated by assuming that all eddies had reattachment bars in 1963.

RESULTS

Small Scale Changes of Sand Bars

Several studies have described small-scale changes in sand bar volume and size in Grand Canyon, as well as processes that cause these changes (Beus *et al.*, 1985; Rubin *et al.*, 1990; Schmidt and Graf, 1990; Beus and Avery, 1992; Bauer and Schmidt, 1993; Budhu and Gobin, 1994). Analysis of change at detailed study sites in Hells Canyon confirms that there is variability in geomorphic response of alluvial bars, and reconstruction of the detailed history of sand bar change at Grand Canyon sites shows that inventory methods only detect large-scale changes; many details of erosional response are not detected. However, large-scale assessments of sand bar change are useful in determining average geomorphic response.

The variability in response of different sites is illustrated by the differing styles of geomorphic change at four study sites in Hells Canyon. There was no measurable change at China Bar between 1964 and 1990, but terrace banks of silty alluvium, which typically occur shoreward from sand bars, eroded at high rates at three other sites (Table 5). In each of these cases, the highest erosion rates occurred between 1970 and 1973. Despite high rates of cutbank erosion, in only one case did the adjacent sand bar also erode (Figure 3a). Figure 3b shows changes at Salt Creek Bar where the subaerially exposed bar did not change in area despite significant shoreward retreat of the cutbank.

Rephotography of sand bars at Badger Creek Rapids in Grand Canyon shows that measured changes in the number or area of subaerially exposed sand bars are sensitive only to large magnitude changes in bar topography (Figure 4). Although the average elevation of the surface of both separation bars at Badger Creek Rapids has decreased by about 1 m, the area of exposed sand, at low discharge, has changed little. Inventories of bar number or area would not detect changes of these bars. In contrast, reattachment bars further downstream have been completely eroded; in this case, inventory methods would detect these changes. Therefore, the changes described below represent significant and large-scale geomorphic response.

Longitudinal Patterns of Sand Bar Change in Hells Canyon

There was significant erosion of sand bars upstream from the Salmon River confluence following closure of the Hells Canyon Complex, and the rate of erosion declined with time. These changes are demonstrated by comparing the number or area (Figure 5) of subaerially exposed sand bars. The area of exposed sand decreased by about 50 percent between 1964 and 1973. Downstream from the Salmon River, the magnitude of erosion was small in relation to the changes upstream. There was a lag time prior to initiation of erosion downstream from the Salmon River; erosion did not occur in this reach between 1964 and 1973. Reattachment bars and channel-margin deposits upstream from the Salmon River eroded more extensively than did separation bars between 1964 and 1973 (Figure 6).

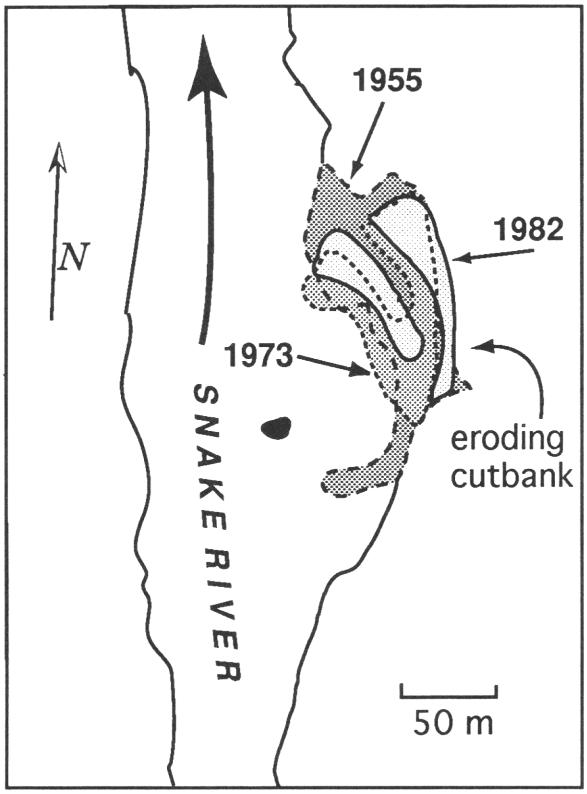
Longitudinal Patterns of Sand Bar Change in Grand Canyon

Many studies have described geomorphic changes of alluvial banks and bars in Grand Canyon over different spatial and temporal scales. These studies show that sand-bar size and number decreased rapidly after closure of Glen Canyon Dam (Schmidt and Graf, 1990; Kearsley *et al.*, 1994) and that at least two post-dam events have resupplied sediment to eddies, thereby initiating erosional cycles where rates decline with time. High annual peak flows between 1983 and 1986 caused temporary storage of fine sediment at high elevations, and erosion rates were high immediately after recession from these flows (Beus *et al.*, 1985; Schmidt and Graf, 1990). Erosion rates between 1986 and 1992 declined as the mass of high-elevation sediment available for erosion decreased. Floods on large tributaries, such as occurred on the Little Colorado River in January 1993, caused mainstem discharge to increase and led to deposition of high-elevation sand (Beus *et al.*, 1993); erosion rates of bars downstream from the Little Colorado River after January 1993 were initially high but declined with

TABLE 5. Summary of Change at Detailed Study Sites in Hells Canyon.

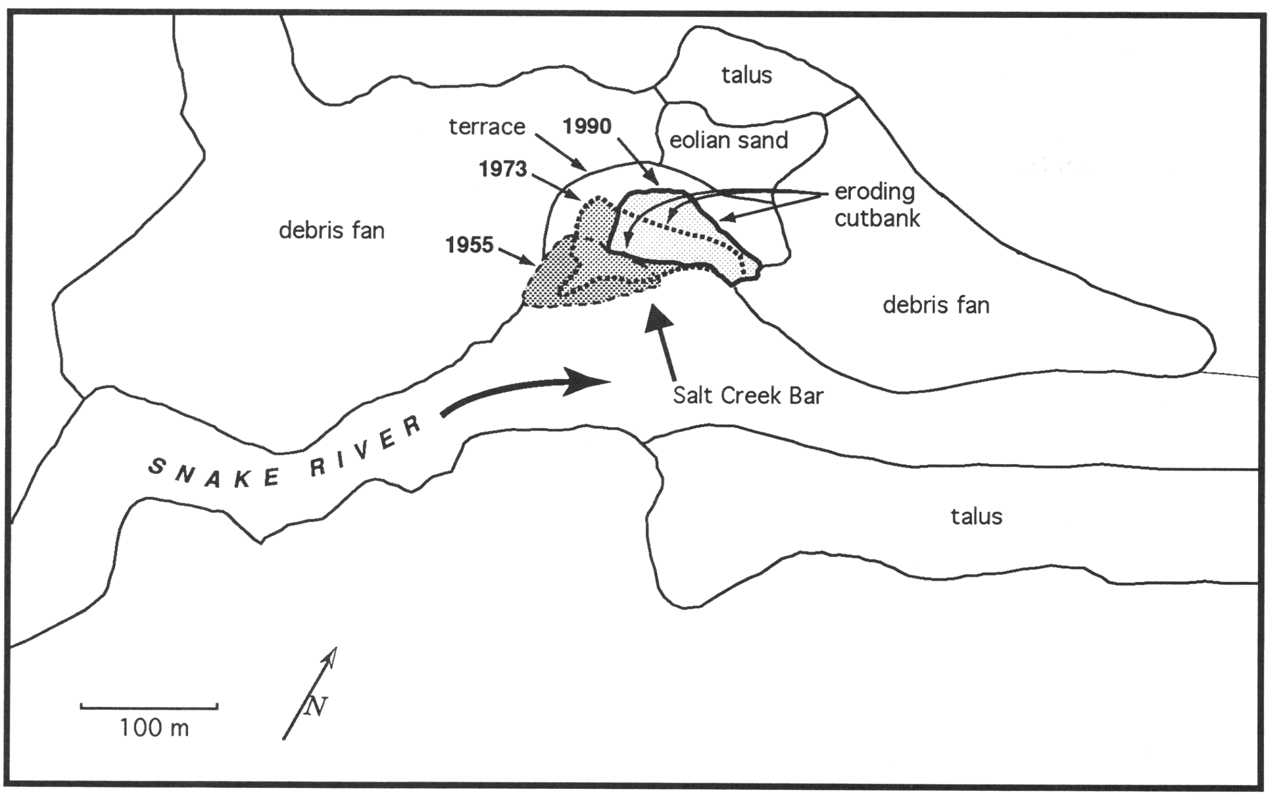
Site Name	Location*	Type of Deposit	Percentage Change in Area of Sand, 1964-1982** (percent)	Maximum Rate of Cutbank Erosion	Time Period of Maximum Erosion
Pine Bar	227.5	Reattachment	–35	3 m/yr	1970-1973 and 1977-1982
Salt Creek Bar	222.5	Reattachment	+33	6 m/yr	1970-1973
Fish Trap Bar	216.4	Reattachment	+30	3 m/yr	1970-1973
China Bar	192.4	Channel Margin	0	–	–

*In river miles above the Columbia River confluence, U.S. Army Corps of Engineers.
**Area exposed at low discharge.



(A)

Figure 3. Maps Showing Changes in Area of Exposed Sand at (A) Pine Bar, and (B) Salt Creek Bar. Note that the area of sand has greatly decreased at Pine Bar, but has changed little, despite change in location, at Salt Creek Bar. Dark shaded area bounded by long dashed lines indicates subaerially exposed bars in 1955. Intermediate shaded areas bounded by short dashed lines indicates area of sand in 1973. Lightest shaded area bounded by solid lines shows area of exposed sand in 1982 and 1990, respectively.



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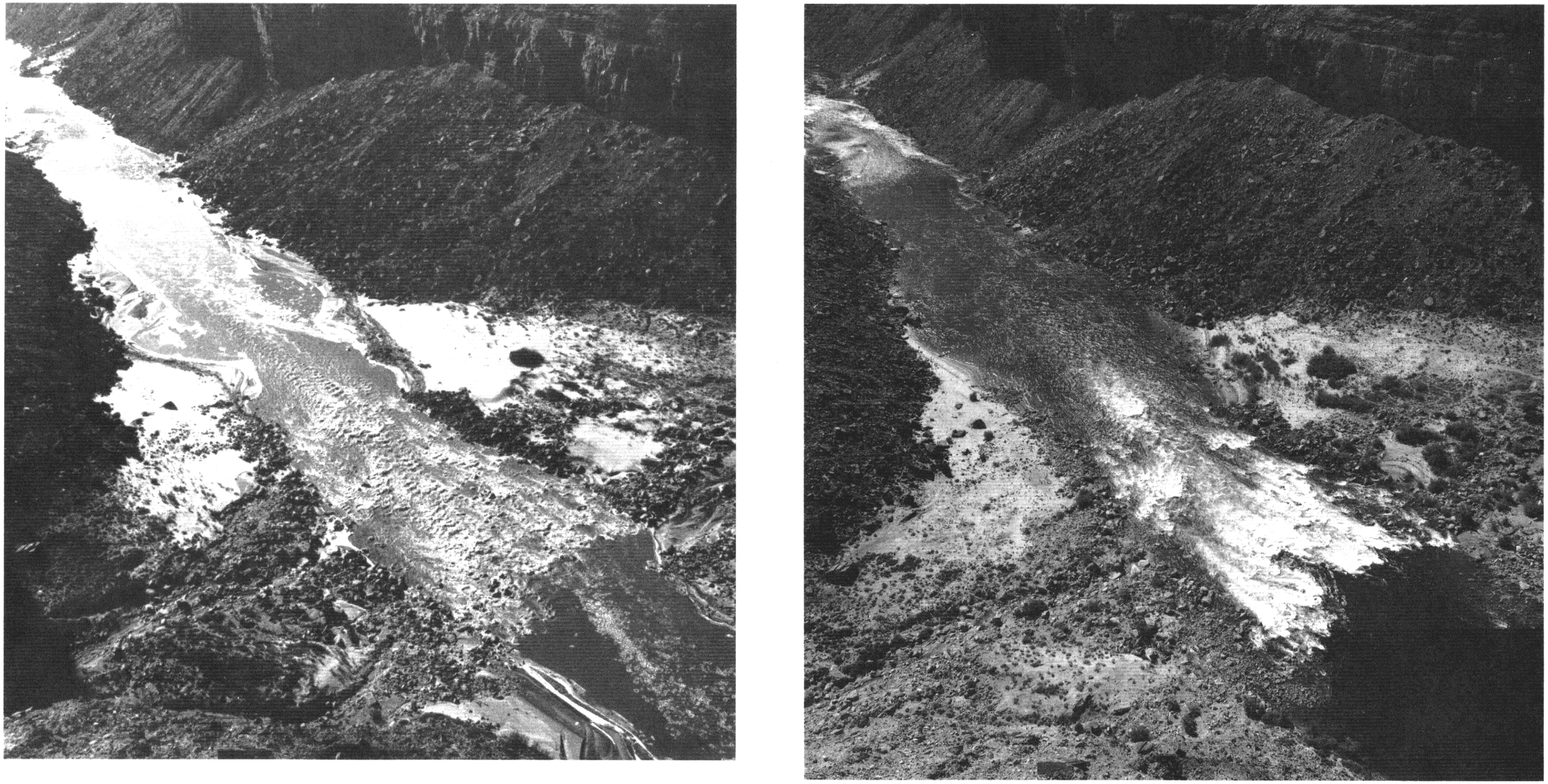

(A) (B)

Figure 4. Repeat Photography of Separation and Reattachment Bars Downstream from Badger Creek Rapid on the Colorado River in Grand Canyon, located 13.3 km Downstream from Lees Ferry, Arizona. Flow is from lower right to upper left. Separation bars are located on either side of channel opposite tail waves of rapid. Reattachment bars are located further downstream. (A) January 2, 1954, discharge 130 m^3/s (note ice along shoreline) (photograph by P. T. Reilly). (B) October 1991, about 230 m^3/s (note that many boulders are exposed on the surfaces of the separation bars). Surveys of vertical degradation indicate about 1 m of erosion, but the surface area is about the same in both photos. The reattachment bars located at the downstream end of the channel expension no longer exist above the water surface in 1991. The separation bars on river left and right are still considered large campsites.

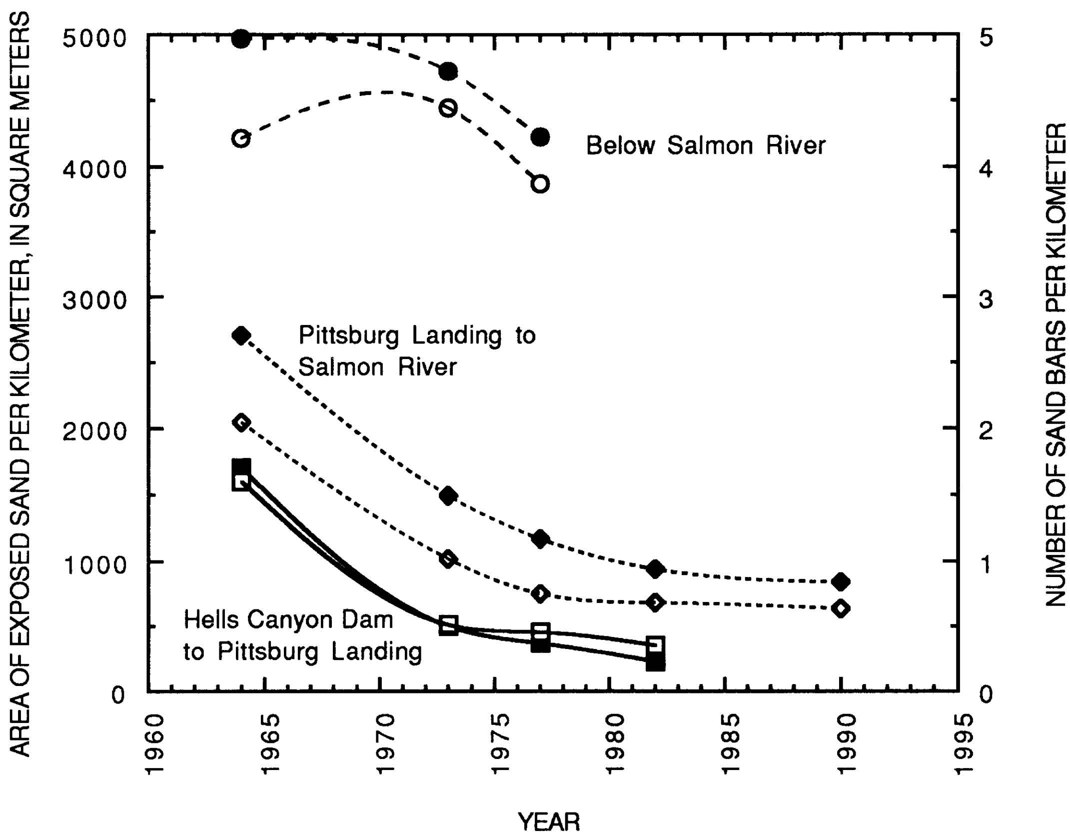

Figure 5. Graph Showing Change in Area (open symbols) and Number (solid symbols) of Sand Bars in Hells Canyon in Three Reaches. Locations of reach endpoints are shown in Figure 1.

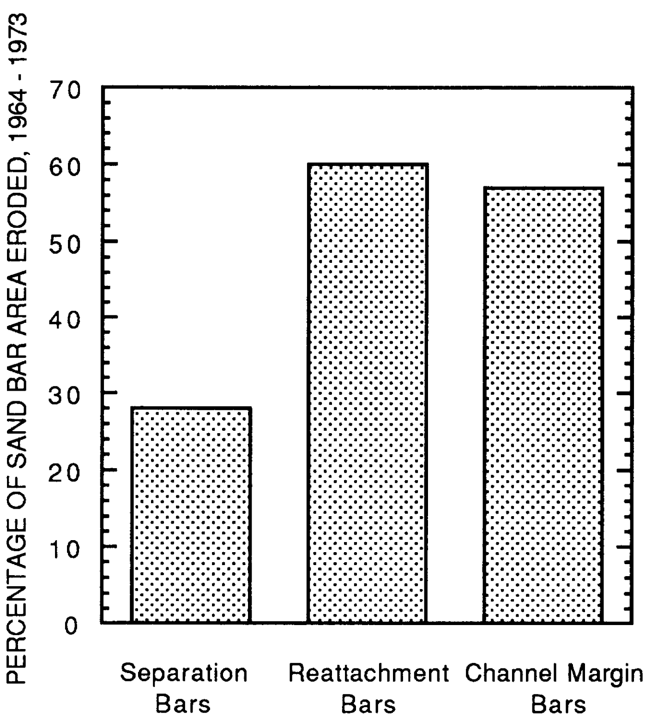

Figure 6. Graph Showing the Percentage of the Total Exposed Sand Bar Area in 1964 That Had Eroded by 1973 (by type of alluvial bar).

time (Hazel *et al.*, 1993). Bars are subject to fluctuations in volume over periods of days or months that are caused by changes in water release from Glen Canyon Dam (Beus and Avery, 1992; Budhu and Gobin, 1994) or by the inherent instability of eddy deposits (Cluer, 1991).

Compiled data concerning number and size of reattachment bars show that sand bar erosion has been less extensive than in Hells Canyon. These data show that the number of sand bars in some parts of Grand Canyon decreased by about 40 percent between 1963 and 1984, but that erosion in most parts of Grand Canyon has been much less (Figure 7). Erosion has been concentrated within 83 km of Glen Canyon Dam, where the number of bars has typically decreased by less than 20 percent. Comparison of the size of sand bars exposed in photography taken in 1889 and at present also show that the number of eroded bars is greatest near Glen Canyon Dam (Figure 8). For all of Grand Canyon, 65 percent of the sand bars observed in Stanton views subsequently eroded.

In Grand Canyon, the relative susceptibility to erosion of different types of bars is similar to Hells Canyon. A greater percentage of channel-margin deposits eroded than did other bar types, based on comparison of bar changes determined from the

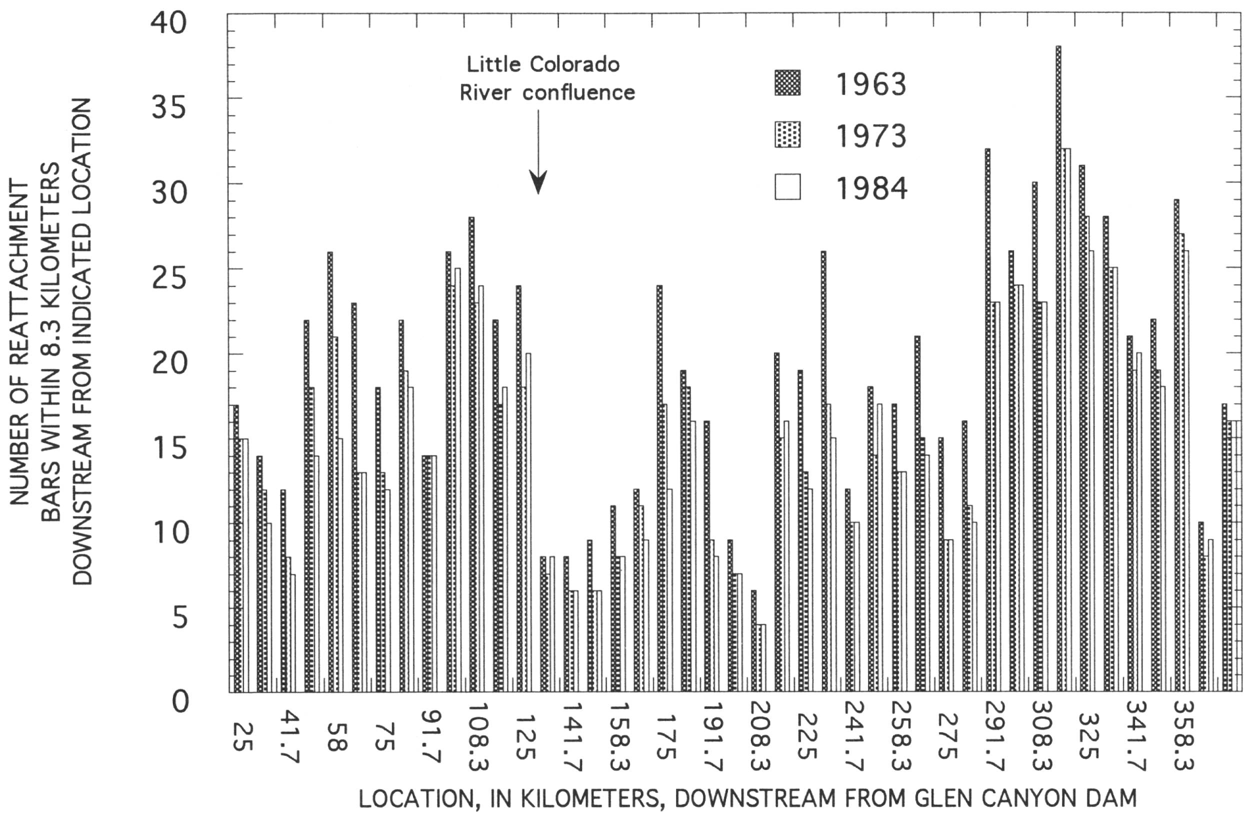

Figure 7. Graph Showing Sand Bar Frequency in 8.3-km Reaches of Grand Canyon Downstream from Lees Ferry Determined from Aerial Photography Taken in 1973 and 1984. Data for 1963 assumes that all eddies had reattachment bars.

Stanton repeat photography (Figure 9). Only 10 percent of all channel-margin deposits are larger than they were in 1889. Separation bars are the most stable type of bar; about 58 percent have eroded in the last century, compared with 17 and 25 percent, respectively, that have aggraded or remained about the same size. Tabulation of air photo data shows similar patterns of change for the period since closure of Glen Canyon Dam.

DISCUSSION

Sensitivity of Changes Detected by Inventories

These inventories of bar frequency are sensitive only to large-scale changes. Topographic changes must be of sufficient scale that erosion or deposition shifts a particular bar from the status of exposure to submergence or vice versa at comparable river discharge. Nevertheless, these inventory methods detect major differences in system response. Somewhat different inventory procedures applied to the same river, such as the inventories of sand bar number and area in Hells Canyon and the inventories of number (1963-1990) and style of change (1889-1993) of Grand Canyon sand bars, detect similar erosional patterns.

The Varying Magnitude of Geomorphic Change

Erosion in Grand Canyon has been less extensive than in Hells Canyon. The large differences in reservoir size and in the patterns of reservoir release suggest that there is linkage between the frequency of mainstem flooding, sediment resupply by tributaries, and geomorphic response. Although no data are presented here regarding the mechanics of flow or sediment transport, the different post-regulation flood frequencies of the two rivers suggest that more frequent clear-water flooding causes greater erosion.

The changes in Hells Canyon upstream from the Salmon River show that high rates of erosion can occur in response to a succession of high discharges in a sediment-depleted river. Most of the change in Hells Canyon occurred between 1964 and 1973, during an interval when all annual floods exceeded maximum

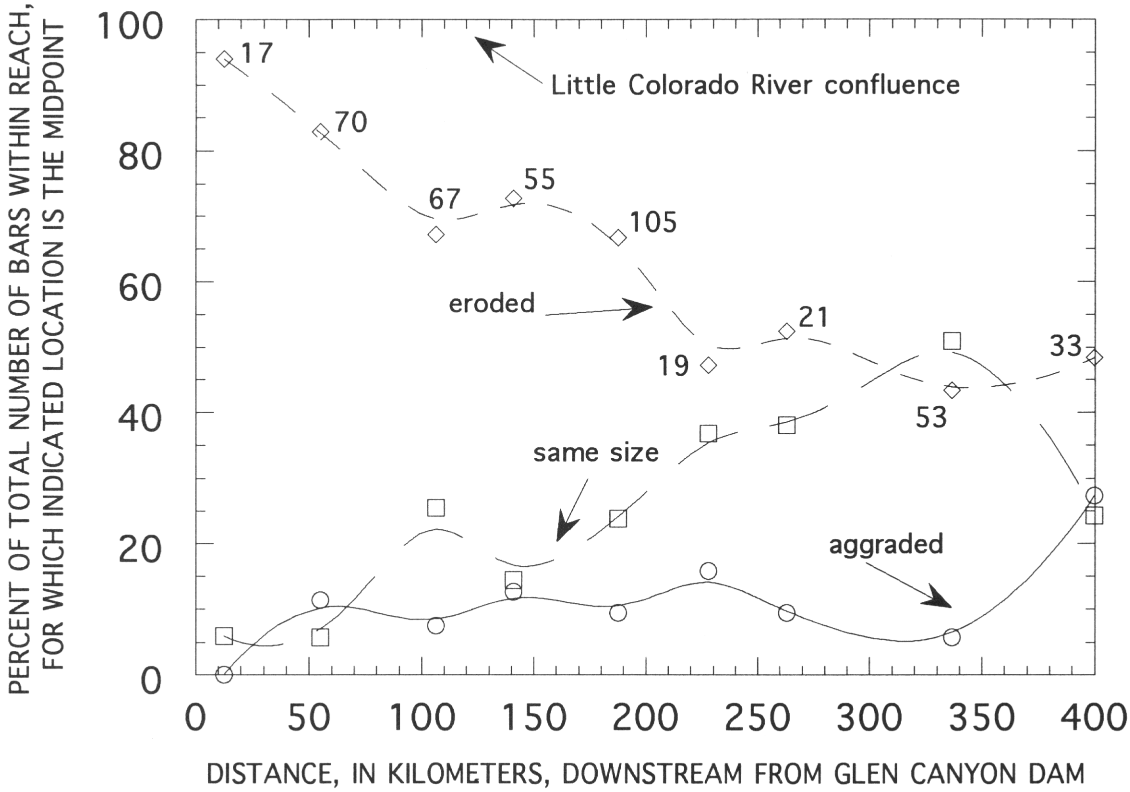

Figure 8. Graph Showing Percentage of Photographed Bars That Have Aggraded, Eroded, or Remained About the Same Size Between 1889 and the Present, Determined by Analysis of Stanton Rephotography. Values of the x-axis are the mid-point of the reach, and reaches are those proposed by Schmidt and Graf (1990). Numbers indicate total number of bars in each reach that were analyzed.

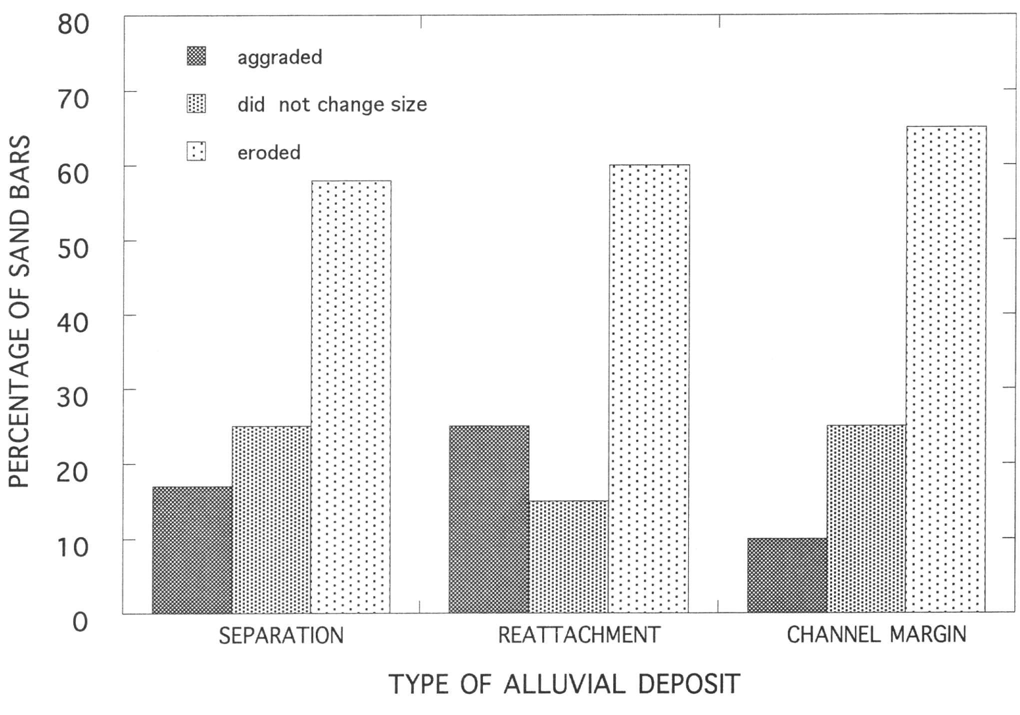

Figure 9. Graph Showing Percentage of Different Type Bars in Grand Canyon That Changed in Size Between 1889-1993 Based on Repeat Photography.

powerplant discharge and when two were among the highest of record. In contrast, less erosive change, and even localized aggradation, can occur where there are (1) less-frequent high discharges in a channel resupplied with sediment from unregulated tributaries (Grand Canyon), or (2) more frequent high discharges in a channel resupplied with sediment (Hells Canyon downstream from Salmon River).

In both canyons, reattachment bars and channel-margin deposits have eroded more than separation bars. Separation bars are entrained less easily because they are located in low-velocity flow near the separation point; reattachment bars are exposed to the higher velocity of eddy circulation and reattachment point migration (Schmidt *et al.,* 1993). Reattachment bars and channel-margin deposits may be subject to erosion when recirculation zones thin or disappear at high discharge.

The geometry of the channels and constricting debris fans differ between the two rivers, and in each canyon over short reaches. These differences are probably an important factor in explaining minor differences in geomorphic response and likely explain some of the differences in the geomorphic history of alluvial bars between Hells Canyon and Grand Canyon. It is unlikely that the large-scale differences in geomorphic response are due to these differences; no reach of Grand Canyon has eroded as much as the upstream parts of Hells Canyon.

CONCLUSIONS

These results show that there has been a significant difference in the temporal pattern of geomorphic change of alluvial bars during the past 30 years in Grand Canyon and Hells Canyon. Although the amount of available data concerning these two canyons differs greatly, comparison is possible because eddy bars occur in each canyon. These bars can be compared on photographs because the locations of these bars have not changed during 30 years of streamflow regulation. Even where river discharge in different photo series differs slightly, the number of exposed bars can be counted and historical changes compared. Results from bar frequency analyses detect significant differences in the magnitude of erosion in the two canyons investigated.

Inventories can be useful in assessing the relative magnitude of change downstream from large dams. In the case of Hells Canyon and Grand Canyon, inventories detect large-scale differences in alluvial bar change, despite the lack of availability of systematic topographic, bathymetric, and sediment-transport data in Hells Canyon. Although small-scale differences in channel and debris flow geometry exist, the most significant difference between the two regulated systems is the greater frequency of mainstem flooding in Hells Canyon. In Grand Canyon, the much higher storage-to-mean annual flow ratio results in less frequent high discharges.

There is a general need to develop national priorities for geographic focus of environmental restoration efforts. Hirsch *et al.* (1990) have shown that there is wide variation in the magnitude of flow regulation in the large drainage basins of North America. The inventory methods used in this study may be useful in a national assessment of the magnitude of geomorphic change and the appropriateness of environmental restoration of alluvial bars in canyons with abundant debris fans.

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