RESPONSE OF BEDROCK-GORGE ALLUVIAL SAND BARS TO OPERATIONS OF LARGE HYDROELECTRIC DAMS -- COLORADO RIVER IN GRAND CANYON, ARIZONA, AND SNAKE RIVER IN HELLS CANYON, IDAHO AND OREGON

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ABSTRACT

The area of sand exposed as sand bars and fine-grained alluvial banks at low discharge along the Snake River in Hells Canyon has decreased by about 75 percent since 1968. During a similiar period of time, changes downstream from Glen Canyon Dam on the Colorado River in Grand Canyon have been much less. The major differences between these two regulated rivers are that (1) high discharges are much more frequent on the Snake River, and (2) there are significant contributions of sediment from unregulated tributaries downstream from Glen Canyon Dam. The frequent high discharges on the Snake are related to the low reservoir capacity of this river system. The long interval between high discharges in Grand Canyon has allowed time for main-channel sediment storage that then is available for entrainment by occasional high discharges.

INTRODUCTION

Dams have been constructed on virtually every large river in the western United States. Federal Energy Regulatory Commission (FERC) relicensing of privately-owned dams and plans to change hydroelectric-generation capacity of federally-owned dams have resulted in environmental impact analysis and reevaluation of the operating criteria for water release from many of these facilities. Strategies for dam management in the 1990's have been based partly on mitigation of adverse impacts to downstream rivers. Improved understanding of the relation between different components of dam operations and related aspects of downstream river response can lead to improved dam-operation strategies.

Three changes induced by dams are (1) sediment trapping within reservoirs and release of clear water to downstream reaches, (2) flood control, and (3) hydroelectric peak-power generation. Sediment trapping is nearly complete above most large dams, and the magnitude of downstream floods is typically decreased (Williams and Wolman, 1984). Where hydroelectric peak power is generated, instantaneous discharge typically follows a diurnal cycle, with highest discharges on weekday afternoons or evenings and lowest discharges at night and on weekends.

This study was undertaken in order to evaluate the relative effects of large clear-water floods and of daily peak-power fluctuations by comparing geomorphic changes on two rivers with different regulated hydrologic characteristics. Substantial data is available about downstream geomorphic changes to the Colorado River in Grand Canyon caused by operations of Glen Canyon Dam (Burkham, 1987; Kieffer and others, 1990; Schmidt and Graf, 1990; U. S. Department of the Interior, 1988). The Hells Canyon reach of the Snake River was chosen for comparison because the Snake River has a similiar mean annual discharge and has recirculating-current alluvial deposits similiar to those of Grand Canyon (fig. 1). The regulating dams on the Colorado and Snake Rivers are similiar in their nearly complete sediment-trapping efficiency and their range of daily peak-power fluctuations. The operations of the regulating dams differ greatly, however, in the frequency of release of discharges in excess of powerplant capacity. Geographic differences give rise to different spatial patterns of sediment resupply from unregulated downstream tributaries. The purposes of this paper are to describe the similiarities and differences in dam operations on the two rivers and to relate these operational differences to differences in downstream geomorphic response of recirculating-current alluvial banks.

SEDIMENTATION AND SEDIMENT TRANSPORT IN BEDROCK GORGES

Although the downstream effects of large dams on alluvial rivers has been extensively studied (Andrews, 1986; Williams and Wolman, 1984), downstream geomorphic changes in bedrock gorges are not well understood. In these gorges, sand and finer sediments are stored on the channel bed and intermittently form banks. Recirculating currents develop within lateral flow-separation zones because downstream-directed current intermittently is separated from the banks. Such flow separation is typical downstream from debris fans that partially block the course of streams in bedrock gorges, but flow separation also occurs in the lee of bedrock obstructions and talus cones. Bars within these recirculating eddies form near the stagnation points that exist at the upstream and downstream ends of the separated flow zone (Rubin and others, 1990). Schmidt (1990) proposed a classification of recirculating current bars that distinguishes *separation bars* that form near the point of flow separation from *reattachment bars* that form near the point of flow reattachment. Schmidt and Graf (1990) noted that narrow alluvial banks not obviously associated with flow separation also exist; they called such banks *channel-margin deposits*. At low discharge, all of these deposits -- separation bars, reattachment bars, and channel-margin deposits -- intermittently form the fine-grained alluvial banks of these otherwise talus- and bedrock-lined channels.

Because flow separation is controlled by irregularities in the immovable (bedrock) or rarely-moved (boulders on debris fans) banks of the river, sand bars that form within recirculating currents do not migrate in the manner of alluvial river bars. Bars associated with eddies persist in specific locations because the channel obstructions that give rise to flow separation also persist. As the mass of sand stored in eddies changes, the size -- but not the location -- of these bars changes. This distinctive characteristic of recirculating-current bars permits comparison of sediment-storage changes in eddies by comparing the frequency and size of these bars.

Schmidt and Graf (1990) showed that high discharges in 1983 and 1984 typically scoured eddies in narrow reaches of Grand Canyon (average reach width-to-depth ratio less than 11), comparable in ratio to most of Hells Canyon. These high discharges caused net aggradation in local parts of some separation and reattachment bars. Schmidt and Graf (1990) showed that the greatest erosion took place in the narrowest parts of the river. Schmidt and Graf (1990) also suggested that reattachment bars were more susceptible to erosion than separation bars.

METHODS

U. S. Geological Survey gaging stations have operated at the same locations in Grand Canyon since the mid-1920's. However, gaging stations in Hells Canyon have been moved in response to dam construction. The station Snake River at Oxbow, Oregon, operated between 1926-71; the present station, Snake River at Hells Canyon Dam, has operated continuously since 1966. A long-term record for the Hells Canyon Dam station was computed by calculating a regression relation for mean daily discharge collected at the Oxbow and Hells Canyon stations for the 6-yr period of overlapping measurements. This relation, with a r^2 value of 0.97, was used to calculate daily flows and peak annual flows at Hells Canyon Dam prior to 1966 (Grams, 1991).

Sediment-transport measurements were made at Lees Ferry and near Grand Canyon between 1929-1972 and in 1983 and 1985. Sediment-transport data were collected on the Paria River between 1948-76 and the Little Colorado River between 1959-70, and at both stations in 1983. Randle and Pemberton (1987) analyzed these four records and calculated sediment-rating curves using regression analyses of log-transformed data (table 1). In this paper, the Lees Ferry station is used to characterize Glen Canyon Dam releases and the Grand Canyon station is used to characterize discharge and sediment transport downstream from unregulated tributaries.

Jones and Seitz (1980) summarized sediment-transport data collected between 1972-79 for Snake River near Anatone, Washington, downstream from the confluence of the Snake and Salmon Rivers and determined a non-linear best-fit line using a group-average method; no data for the Snake River in Hells Canyon has been collected upstream from the Salmon River.

In Hells Canyon, sand-bar occurrence and size were evaluated on 5 different air photo series taken between 1955-82 (Grams, 1991). All photos were at scales more detailed than 1:20,000 (table 2). Photos were converted to a common scale using a stereo-zoom transfer scope, and every sand bar or fine-grained alluvial bank along the river was catalogued by sand-bar type and size class. The most useful criteria in classifying bar type was the location of each bar in relation to the local channel constriction/expansion geometry. Bars that mantled downstream parts of debris fans or which were located immediately in the lee of obstructions were catalogued as separation bars. Bars that were located at the downstream end of channel expansions were classified as reattachment bars. Sand bars not clearly related to channel bank irregularities were catalogued as channel-margin deposits. Analysis of transport directions inferred from ripple-migration directions exposed in trenches indicates that many channel-margin deposits in Hells Canyon are formed by recirculating currents, probably by processes similiar to those that form reattachment bars.

Field surveying and measurement of bars in Hells Canyon, conducted on two river expeditions in July 1990, established the scale calibration for all photos. Size classes established for bars were 0, less than 930 m^2, 930-1860 m^2, 1860-2790 m^2, and 2790-3715 m^2. The category of "zero" size was used for bars that originally existed but were subsequently completely eroded. Bar frequency and size were summarized by 8.3-km subreach by multiplying the midpoint value for each size class by class frequency. The discharge at the time of each photo at different locations along the Snake River was determined using instantaneous gaging records for the Hells Canyon Dam gage and time-of-travel estimates determined by Koski (1974).

HYDROLOGIC CHANGES CAUSED BY THE HELLS CANYON COMPLEX AND BY GLEN CANYON DAM

The controlling dams of the two study reaches have been in operation for similiar periods. Three large dams, collectively called the Hells Canyon Complex, were completed between 1958-68 and completely regulate flow of the Snake River through Hells Canyon (table 3). The largest of these is Brownlee Dam, which was completed in 1958; the most downstream of these, Hells Canyon Dam, was completed in 1968. The unregulated Imnaha and Salmon Rivers join the Snake River about 100-km downstream from Hells Canyon Dam. Glen Canyon Dam on the Colorado River was completed in 1963 and is located 25 river-km upstream from the confluence with the unregulated Paria River. The Little Colorado River, another unregulated stream with a high sediment load, joins the Colorado River 125-km downstream from the dam.

Comparison of the ratio of reservoir storage to mean annual discharge of the two rivers shows the greater extent of flow regulation in the Colorado River basin (Hirsch and others, 1990). The ratio is 0.08 for the Hells Canyon Complex, similiar in magnitude to the value of 0.26 for the entire Columbia River basin. Lake Powell reservoir, formed by Glen Canyon Dam, is much larger than the reservoirs of the Hells Canyon Complex. The storage-to-mean annual flow ratio for Lake Powell is 2.1, and that of the entire upper Colorado River watershed is 2.3.

These differences in storage-to-mean discharge ratio affect the magnitude and frequency of dam releases that exceed powerplant capacity. Figure 2 shows that the magnitude and frequency of peak discharges on the Snake River has not changed despite dam construction; in contrast, there has been a great decrease in the magnitude of peak discharges downstream from Glen Canyon Dam. Time-series graphs of dimensionless annual peak discharge further illustrate these contrasts (fig. 3). One cannot detect when the Hells Canyon Complex became operational from the time-series data for the Snake River. In contrast, peak discharges have dramatically decreased since closure of Glen Canyon Dam; only the 1983 flood exceeded the pre-dam mean annual flood. The difference in peak discharge recurrence is due to the much longer filling time of Lake Powell. Except for a Colorado River high discharge in 1965, there was no discharge on either river that exceeded powerplant capacity prior to reservoir filling.

There has been very little change in the durations of mean daily discharge downstream from Hells Canyon Dam (table 4). In contrast, the magnitude of the 5-percent duration mean daily discharge has decreased greatly at Lees Ferry, consistent with peak flow changes described above. Changes in the magnitude of the 50-percent and 95-percent duration of mean daily discharge reflects the range between typical daily and weekend discharge. An indication of the differences in daily peaking-induced fluctuations can be obtained by comparing the difference between maximum powerplant discharge and minimum required discharge (table 3). This difference is less at Hells Canyon, indicating that instantaneous discharges fluctuate more widely in Grand Canyon than in Hells Canyon.

REGULATED SEDIMENT TRANSPORT, BED DEGRADATION, AND BANK DEPOSITION

Sediment-budget calculations based on the sedment-rating / flow-duration method (Randle and Pemberton, 1987) or on regional sediment-transport relations (Howard and Dolan, 1981) predict that the bed of the Colorado River downstream from Lees Ferry aggraded during the period of Lake Powell filling. In contrast, Pemberton (1976) and Burkham (1987) showed that the Colorado River channel upstream from the Paria River degraded after closure of Glen Canyon Dam; the gaging cross-section was irreversibly scoured about 4 m by the 1965 high discharge. Comparable data is not available for the

Hells Canyon reach, although there have not been significant changes in the stage/discharge relation of the Hells Canyon Dam gage (R. W. Luscombe, hydrologist, U. S. Geological Survey, Boise, pers. comm., 1991).

Regulated sediment-transport of the Colorado River is about one order of magnitude greater than of the Snake (table 1). The disparity between transport is even greater than that represented by these relations because the Snake River data is for all suspended sediment and the Colorado River data is for sand-sized sediment between 0.0625-2 mm. Jones and Seitz (1980) reported that between 68-92 percent of all transported sediment of the Snake River near Anatone was finer than 0.0625 mm.

Comparisons between the mass of stored and transported sediment of the Colorado River in Grand Canyon illustrates the limited sediment storage in gorges. The mass of sand stored in the bed and in eddies of the Colorado River between Lees Ferry and the Grand Canyon gaging station in 1984 was about 38 million Mg (U. S. Department of the Interior, 1989; Wilson, 1986). The mean annual suspended sediment load of the Colorado River between 1941-57, prior to construction of Glen Canyon Dam, was 60.0 and 77.9 million Mg/yr at Lees Ferry and near Grand Canyon, respectively. Assuming that pre-dam annual suspended sediment loads were typically about 30-35 percent sand, the mass of sand stored on the bed of the Colorado River in 1984 was less than twice the annual mass of sand transported by the pre-dam river.

Comparable amounts of fine-grained sediment were stored along the banks of the Snake prior to completion of Hells Canyon Dam as were stored along the Colorado River in 1984. In 1964, there were 1900 m^2/km stored in this reach, a value similiar to the amount reported for narrow reaches of Grand Canyon (670-3500 m^2/km) and about 5 times less than that for some wide reaches (2000-10,000 m^2/km) (Schmidt and Graf, 1990, table 7).

Schmidt (1990) showed that bar sediments in the Grand Canyon are similiar in size distribution to the distribution of the suspended load transported by the bar-forming discharges. The d_{50} of five samples of bar sediments in Hells Canyon ranged between .22-.5 mm, similiar to the d_{50} of a composite sample of Snake River sand bars near Lewiston (Jones and Seitz, 1980). Sand bars along the Snake River are therefore similiar in size to the coarse component of the suspended load.

DOWNSTREAM CHANGES IN SAND BARS

Hells Canyon

Since 1964, there has been significant erosion of fine-grained alluvial banks and bars upstream from the Salmon River confluence. The area of sand exposed at low discharge was reduced by about 50 percent between 1964-73, and the rate of change has decreased with time (fig. 4). Total decrease in area since 1968 has been about 75 percent. The same magnitude of change is indicated by changes in the frequency of bars; between 1964-73, 120 small- (0-930 m^2) and moderate-sized (930-1860 m^2) bars were completely eroded from Hells Canyon. The greatest changes upstream from the Salmon River confluence have occurred by the scour of channel-margin and reattachment bars (fig. 5). Separation bars have experienced less erosion than the other, more numerous and areally expansive, types of bars. Downstream from the Salmon, erosion of bars has been much less than in upstream reaches; in one reach, net aggradation was measured.

Changes at Pine Bar illustrate these patterns. The sequence of maps of this reattachment bar shows that reattachment-bar degradation occurs by erosion of upstream parts of the bar and by horizontal retreat of other areas (fig. 6). Since 1982, the surface of the parts of this bar have been replaced by fine gravel, a trend observed at some other sites. Although erosion of most sand bars has decreased with time, the toes of some higher terraces have continued to erode. Between 1964-90, horizontal retreat of these toe slopes was 30 and 140 m at two monitored sites.

Grand Canyon

Erosional changes in bars have been much less in Grand Canyon. During the Lake-Powell filling period, bank erosion associated with the initiation of daily peak power fluctuations occurred (Dolan and others, 1974), but only intermittent erosion and deposition was reported by Howard and Dolan (1981) by the end of the filling period. Howard and Dolan (1981) reported that most bars had developed slopes and sediment sizes adjusted to local swash and nearshore current conditions. In wide reaches of Grand Canyon, former bars were overgrown by dense stands of riparian vegetation, and flow-separation areas were eliminated at some sites at low discharge. Changes at a reattachment bar upstream from Kwagunt Rapids (Rubin and others, 1990) are representative of this historical pattern (fig. 7), although in narrow reaches, there was much less vegetation encroachment.

High discharges in 1983 and 1984 reactivated these bars, scoured vegetation and upper bar surfaces, and redeposited well-sorted very fine to medium sand. In most reaches of Grand Canyon, there was a decrease in the total number of sand bars after recession of the 1984 high discharges, with most of the change occurring due to reattachment erosion (fig. 8B). Although these changes are of local importance to environmental managers in Grand Canyon, the proportional change is less than the scale of changes that has occurred in Hells Canyon upstream from the Salmon River.

LARGE FLOODS AND SEDIMENT RESUPPLY

The contrasting style of bar response in the two reaches indicates that a succession of high discharges occuring in a sediment-depleted river channel can cause significant erosion of recirculating-current bars and banks. In contrast, less frequent high discharges cause less geomorphic change and can cause localized aggradation. The limited degradation of bars in Grand Canyon, relative to changes in Hells Canyon, is likely due to the availability of accumulated bed sediment that is subsequently entrained by occassional high discharges.

A cumulative sand balance for the Colorado River channel near the Grand Canyon gage for the period since dam closure was calculated using the transport relations of Randle and Pemberton (1987) and mean daily discharge data for the Paria, Little Colorado, and

Colorado Rivers. Cumulative sediment storage was calculated by cumulating the annual value of the sum of Paria and Little Colorado inputs to the Colorado River minus the computed value of sand transported past the Grand Canyon gage. Randle and Pemberton (1987) have shown that actual sediment transport during peak-power fluctuations is greater than that calculated using mean daily values, because most transport occurs during periods of highest discharge. Despite this problem, figure 9 illustrates shows the magnitude of sediment accumulation that occurred in the absence of high discharges. High discharges between 1983-86 scoured sediment of a magnitude approximately equal to the amount that had accumulated between 1965-82. These high discharges caused relatively little erosion, compared to Hells Canyon, because of the large reservoir of bed sediment available for entrainment. Less sediment was available for entrainment upstream from the Little Colorado River, and more erosion did occur in these upstream narrow reaches (fig. 8, river km locations 33.3-58.3)

In Hells Canyon upstream from the Salmon River, there has been little sediment resupply from unregulated tributaries and sediment is only available from the nonrenewable bed and bank. As the bed supply is diminished, only bank sediments are available for erosion. As these bank sediments are eroded, successively larger floods are required to entrain the remaining sediments and erode high-terrace toe slopes (fig. 5). This relationship is illustrated in figure 10 where maximum peak discharge within each photo analysis time interval is plotted in relation to the annual rate of bar area change for the same time intervals. The geomorphic effectiveness (Wolman and Gerson, 1978) of Hells Canyon floods is therefore diminishing in response to the infinitely long recovery times that exist in this sediment-depleted river system.

IMPLICATIONS FOR RIVER MANAGEMENT AND CONCLUSIONS

Preservation of fine-grained alluvial banks and bars is an objective of river management in Grand Canyon National Park. The focus of most discussion has been on the range of daily hydroelectric peak-power fluctuations. This study shows that a succession of high discharges in a sediment-depleted river system causes widespread erosion. Although the range of daily fluctuations is greater in Grand Canyon than in Hells Canyon, erosion has been much greater in Hells Canyon because floods have been more widespread. In Hells Canyon, there is effectively no sediment replenishment, and the erosional effect of floods dominate. If the operational strategy of Glen Canyon Dam shifts to more frequent high discharges or to simulation of pre-dam hydrographs in the absence of artificial augmentation of sediment, greater erosion of reattachment bars and channel margin deposits can be expected because of decreased periods during which channel-bed sediment can accumulate.

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Table 1. -- Sediment-transport relations for Colorado River and selected tributaries (from Randle and Pemberton 1987)

Paria River at Lees Ferry

Q_s=0.00000010531$Q^{3.1342}$ (discharge less than 2.3 m^3/s)

Q_s=0.00135$Q^{1.8319}$ (discharge between 2.3-31.1 m^3/s)

Q_s=9.9402Q (discharge greater than 31.1 m^3/s)

Little Colorado River near Cameron

Q_s=0.00114$Q^{1.4777}$(December - May)

Q_s=0.03994$Q^{1.2769}$ (June - November)

Colorado River near Grand Canyon

Q_s=0.0000000002727$Q^{3.3326}$ (discharge less than 708 m^3/s)

Q_s=0.00000000494$Q^{2.1117}$(discharge greater than 708 m^3/s)

Snake River near Anatone, Washington

Q_s=0.0000085$Q^{2.8}$ (discharges between 567-1980 m^3/s)

Q_s=0.00000025$Q^{3.4}$ (discharges between 1980-5660 m^3/s)

Q_s = sediment load, in Mg/da

Q = discharge, in m^3/s

Table 2. -- Aerial photograph information, Snake River.

Date of photography	Scale	Mean daily discharge[1]	Discharge range[2]
		in cubic meters per second	
1955	1:20000	306-314	7-14
1964	1:12000	292-311	--
1973	1:12000	142,218,340,510[3]	0
1977	1:12000	150	4
1982	1:12000	399	--

[1] In some cases, photos were taken during a period of several days
[2] Range of discharge during the 6 hrs preceding the assumed time when photos were taken, based on chart records.
[3] Four series were taken at different steady flow levels.

Table 3. -- Reservoir data summary.

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	1209[1]	--	991[1]
Oxbow	February 1961-March 1961	6.7[1]	--	750[1]
Hells Canyon	October 1967-November 1967	121.9[1]	142[1]	849[1]
		Colorado River		
Glen Canyon	March 1963-June 1980	33299	28-85[2]	892

[1]U. S. Department of Energy, 1985

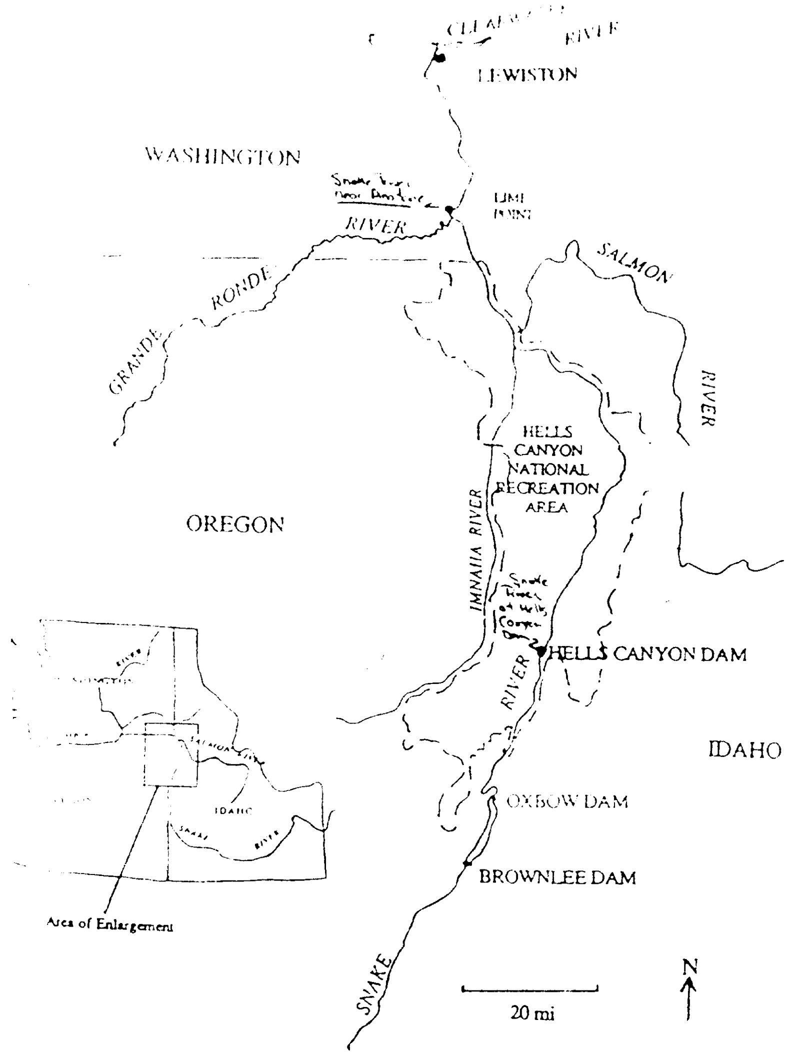
[2] winter and summer discharges, respectively

Table 4. -- Hydrologic summary

Mean annual discharge, in cubic meters per second	Dimensionless discharge[1] at indicated duration		
	5 percent	50 percent	95 percent
	Snake River, pre Brownlee Dam		
531	2.24	0.85	0.45
	Snake River, post Brownlee Dam		
538	2.37	0.85	0.39
	Colorado River, pre Glen Canyon Dam		
470	3.79	0.48	0.24
	Colorado River, post Glen Canyon Dam		
412	1.92	0.82	0.10

[1] Discharge divided by mean annual discharge for indicated period.

A.



B.

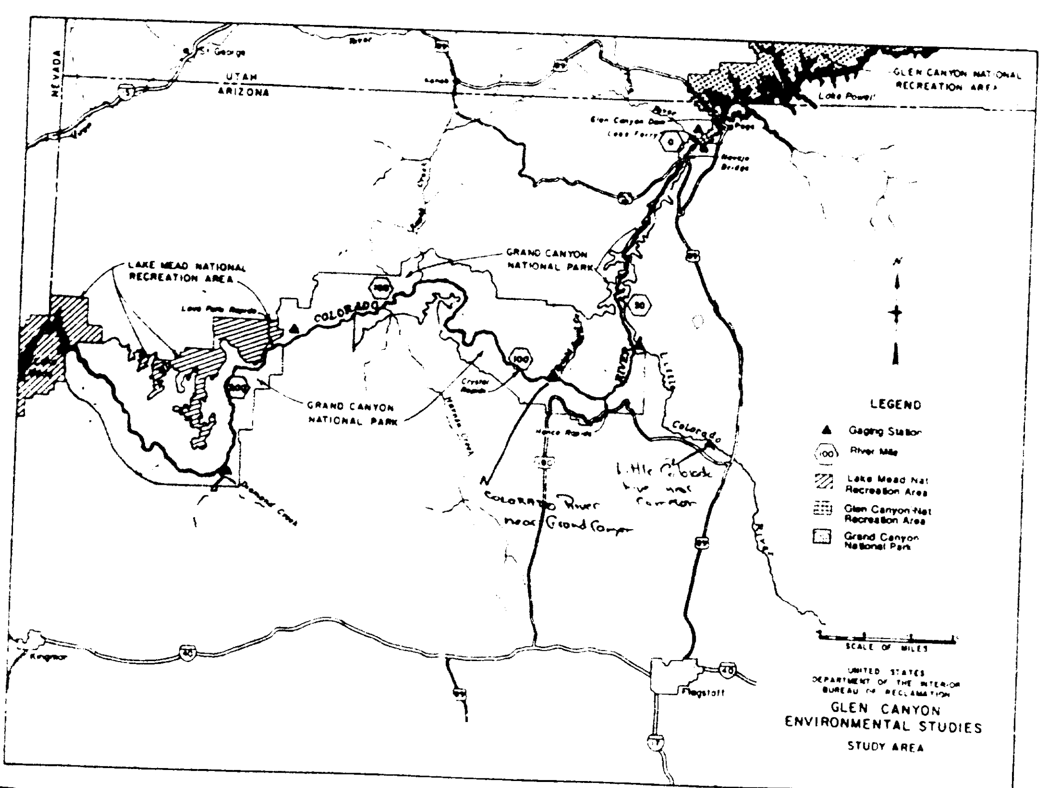


Figure 1. Study Areas. A. Hells Canyon B. Grand Canyon

Figure 2. -- Recurrence of annual peak discharge, Snake River at Hells Canyon Dam and Colorado River at Lees Ferry

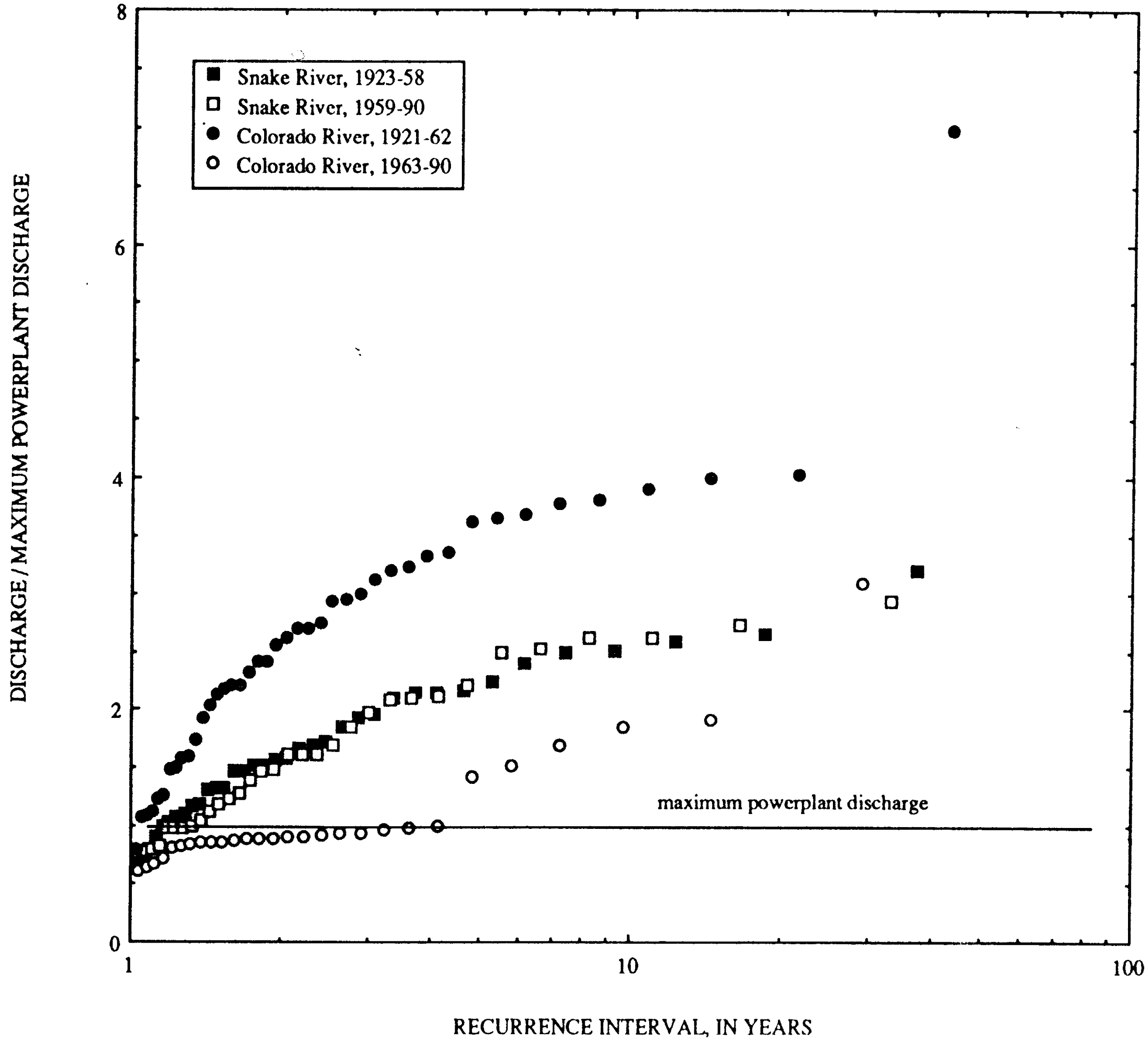
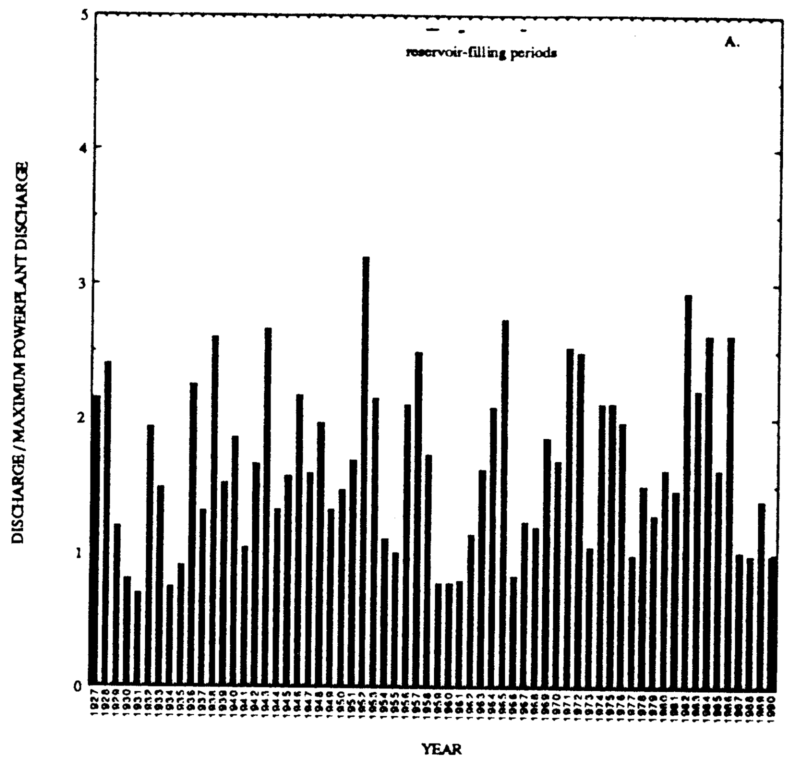


Figure 3. -- Dimensionless annual peak discharge. A. Snake River at Hells Canyon Dam. B. Colorado River at Lees Ferry



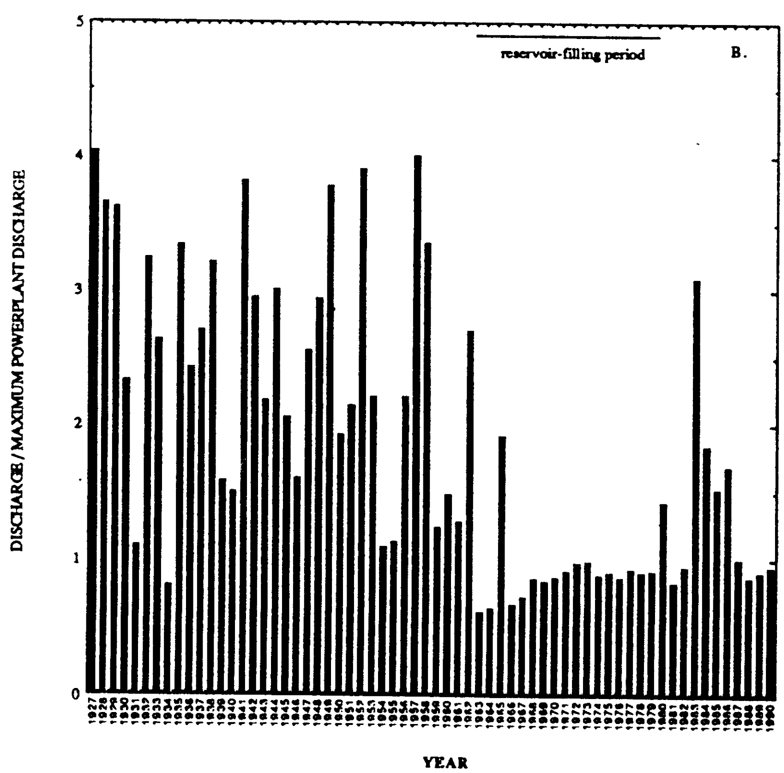


Figure 4. -- Area of sand exposed at low discharge along Snake River

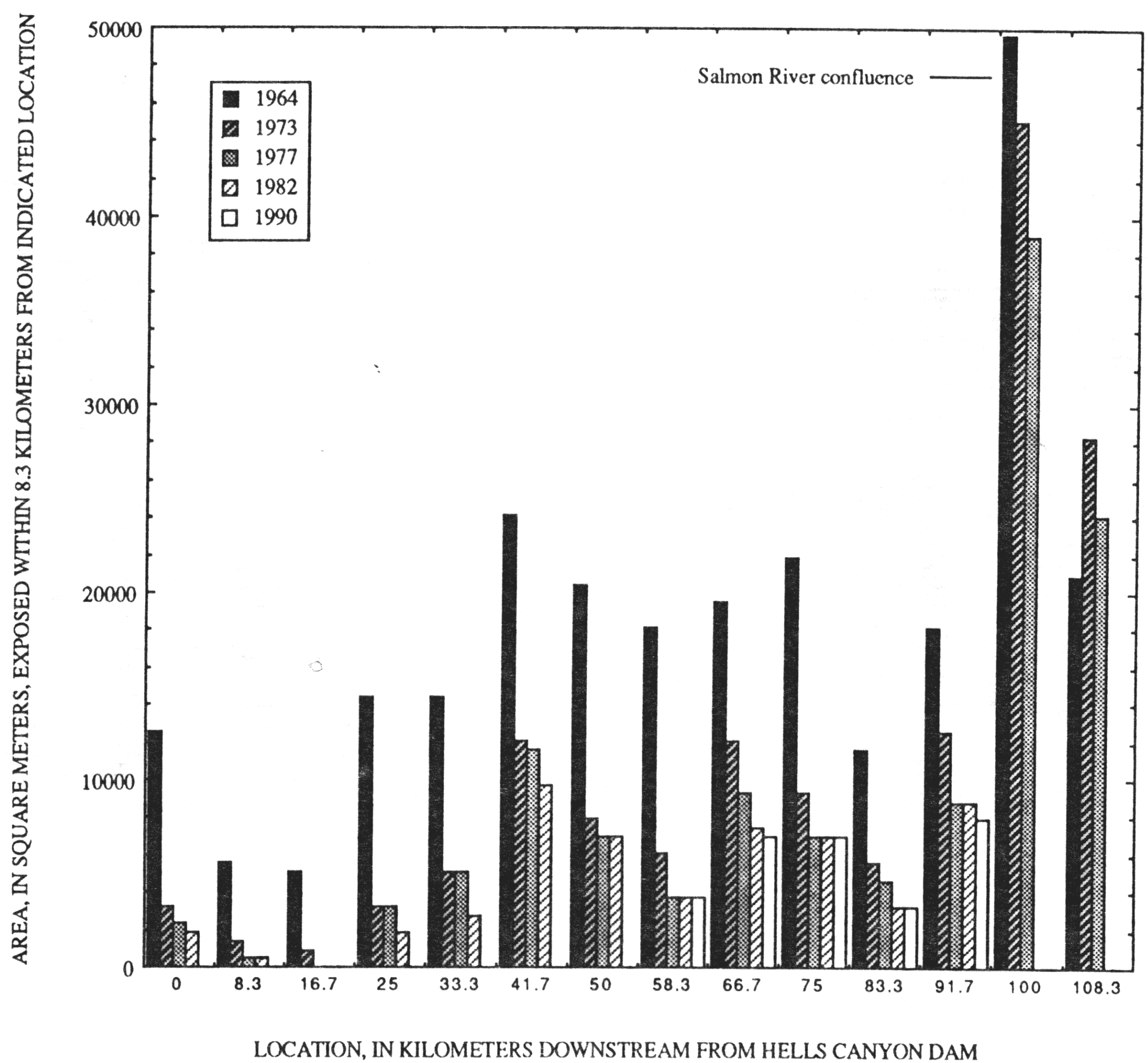


Figure 5. -- Annual peak discharge and area of sand exposed at low discharge, Snake River between Hells Canyon Dam and Salmon River

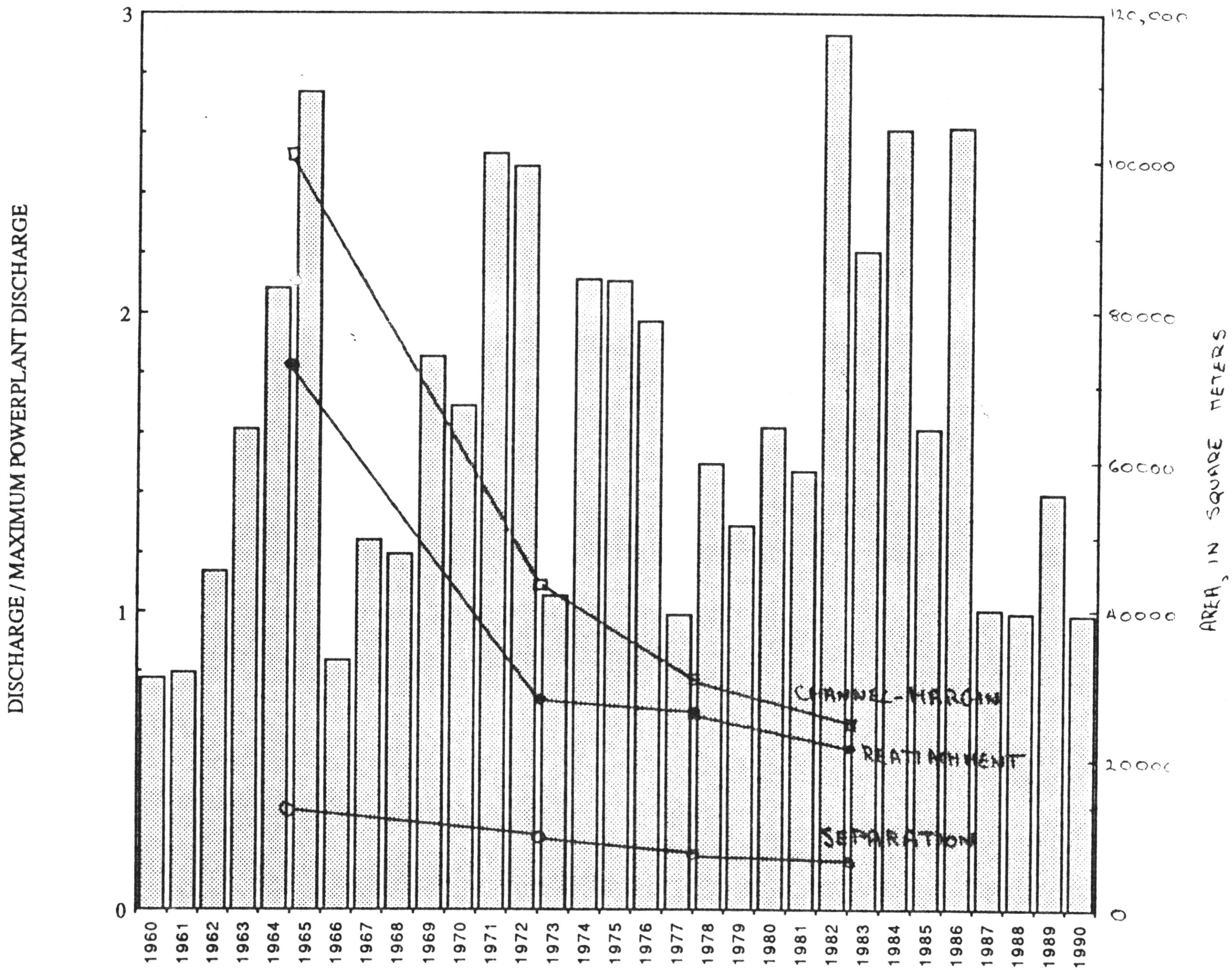


Figure 6. -- Landforms and exposed sediment at Pine Bar, Snake River in Hells Canyon between 1955 - 1990. A. 1955, 311 m^3/s. B. 1964, 334 m^3/s. C. 1970, 337 m^3/s. D. 1973, 142 m^3/s. E. 1977, 198 m^3/s. F. 1982, 396 m^3/s. G. 1990, 195 m^3/s.

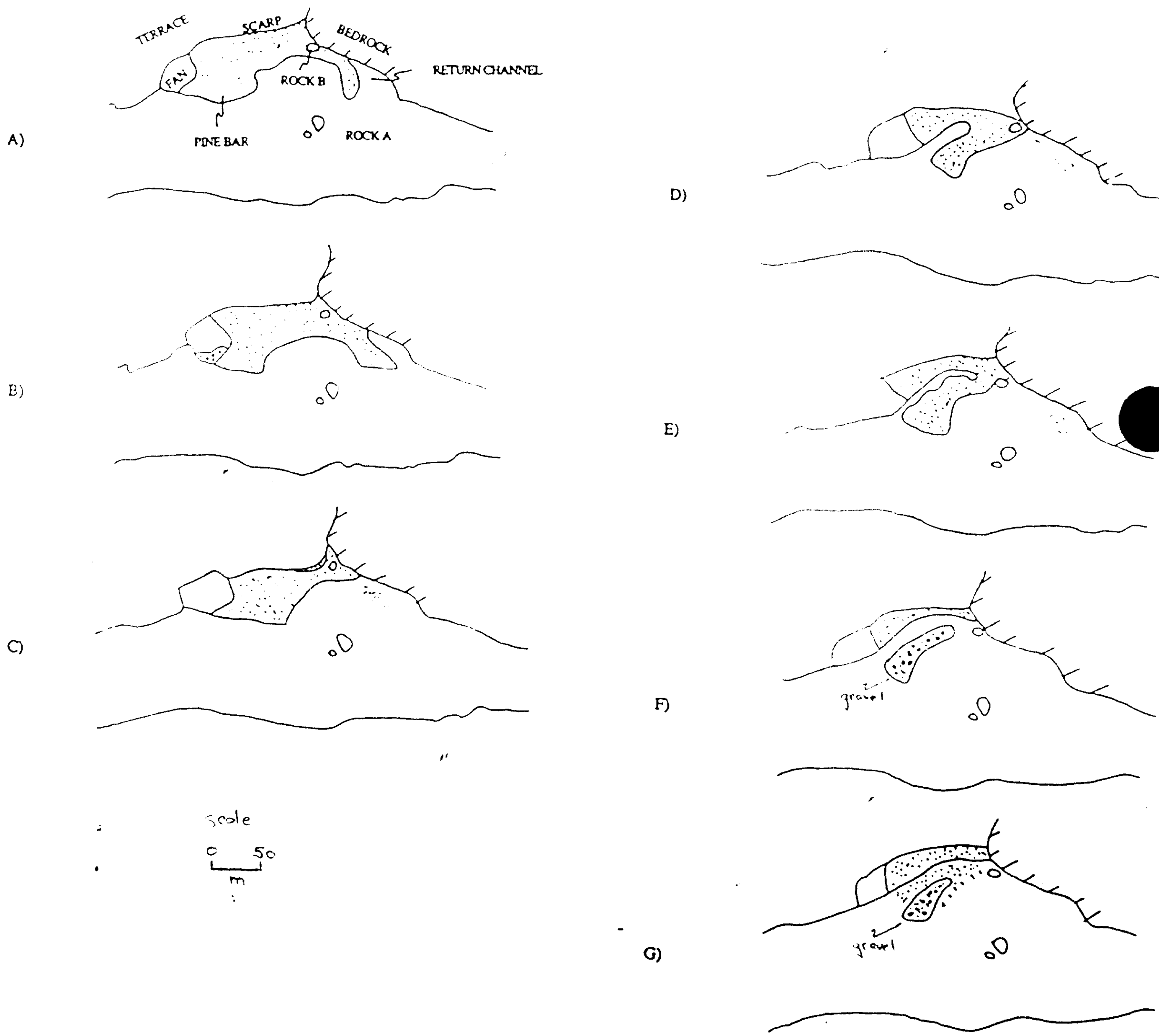


Figure 7. -- Alluvial deposits and vegetation at Upper Kwagunt Rapids marsh in selected years. River flow is left to right. Darkest area is marsh vegetation. Moderately-dark areas are tamarix. Lighest areas are bare sand. R=reattachment bar. S=separation bar. rcc=return current channel. A. May 14, 1965, 740-760 m^3/s. B. June 16, 1973, 250-370 m^3/s. C. July 11, 1980, 740-760 m^3/s. D. October 22, 1984, 160 m^3/s.

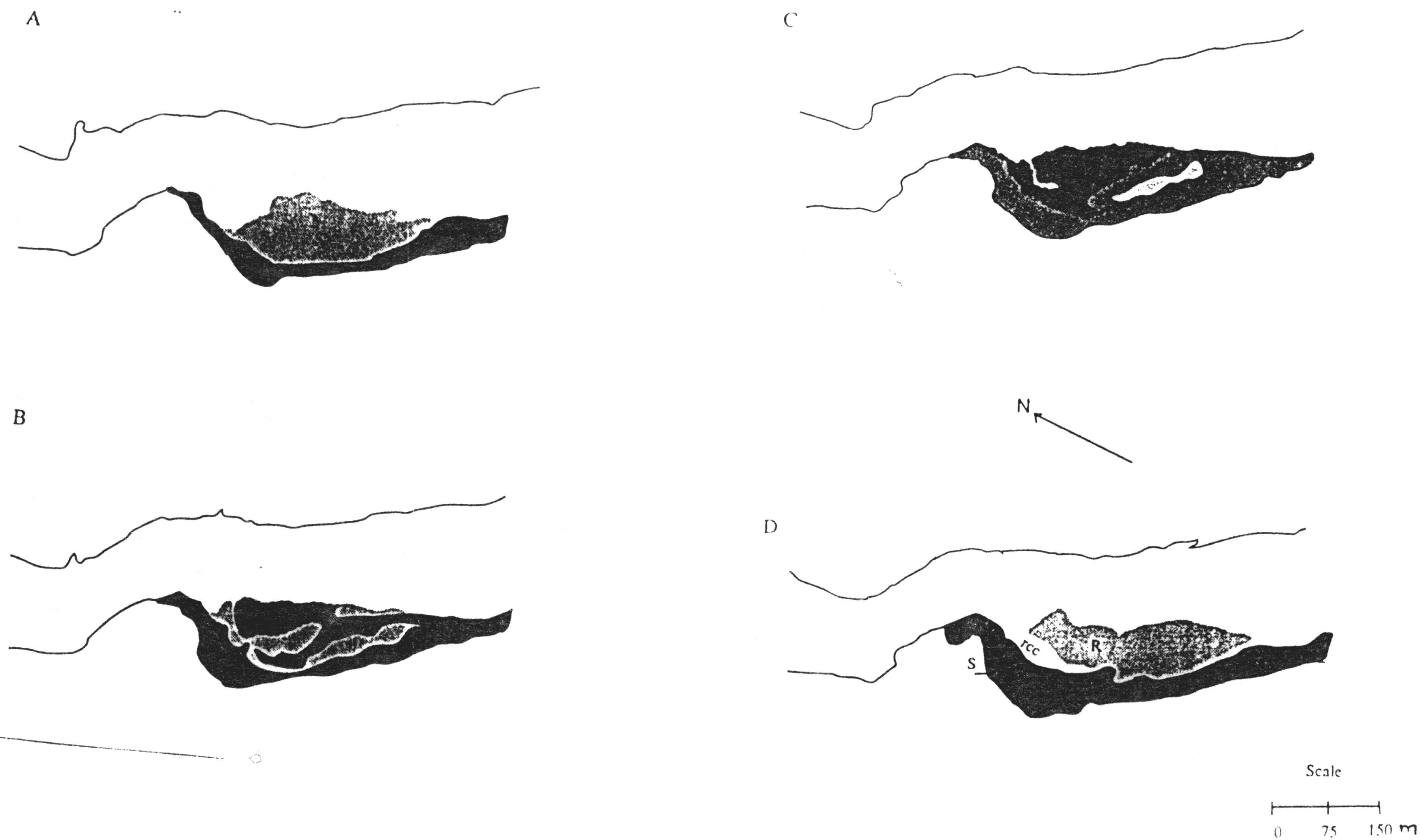


Figure 8. -- Frequency of sand bars. A. Snake River. B. Colorado River

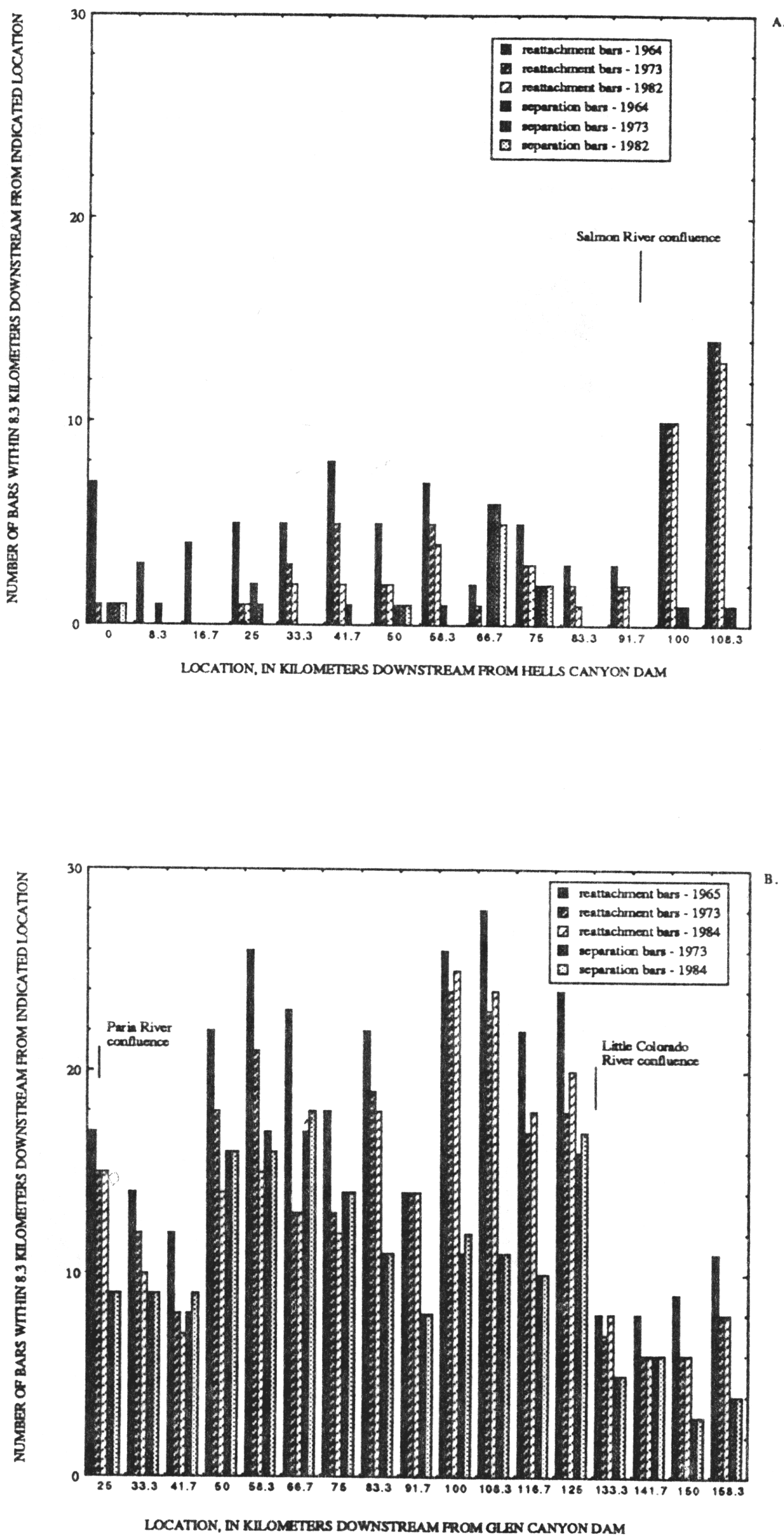


Figure 9. - Cumulative sand storage in Colorado River near Grand Canyon following closure of Glen Canyon Dam

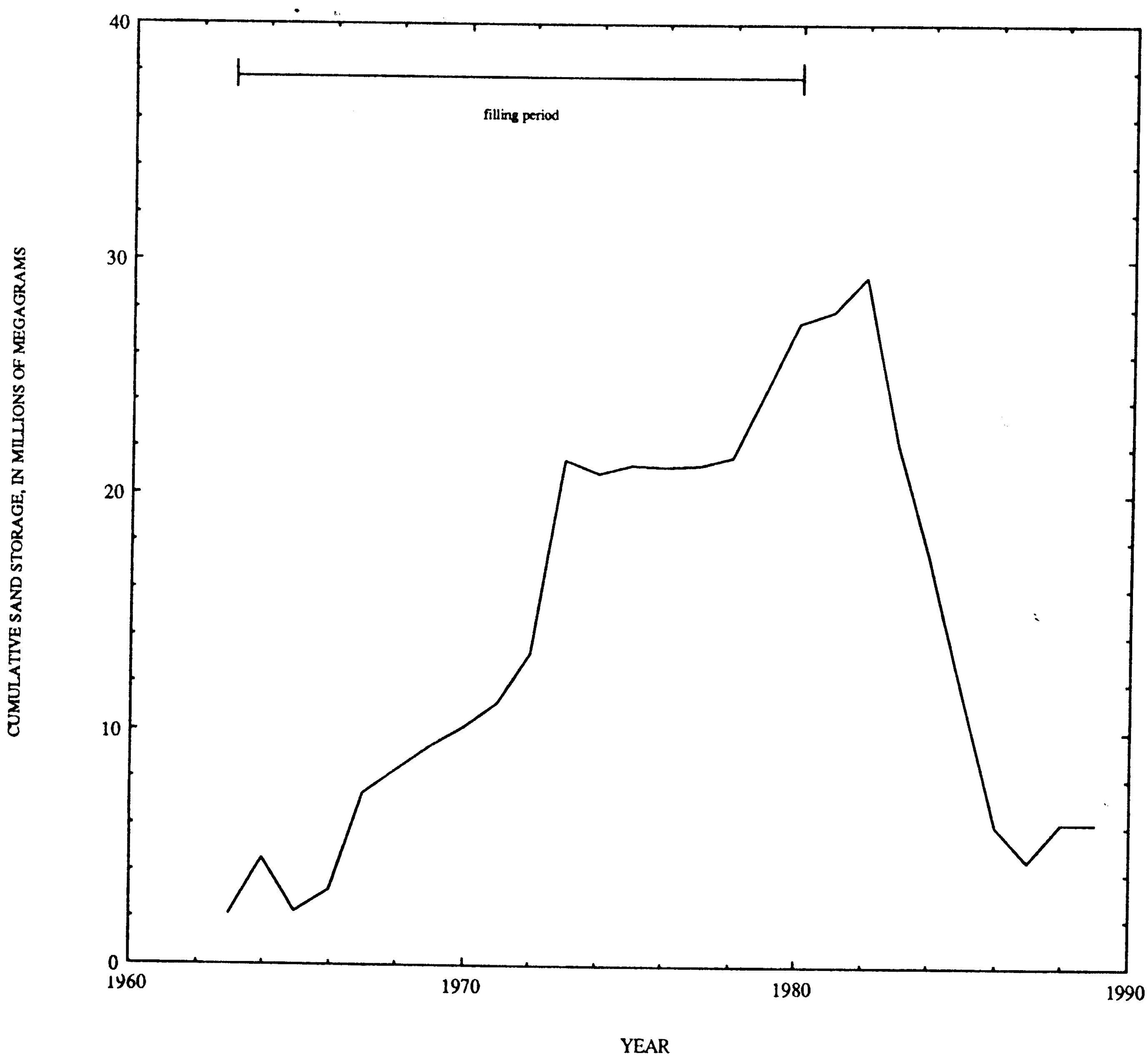


Figure 10. -- Annual change in area of sand exposed at low discharge along Snake River