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GEOMORPHOLOGY OF THE COLORADO RIVER IN THE GRAND CANYON[1]

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ABSTRACT

Sediment supplied to the Colorado River within the Grand Canyon has been sorted into distinct deposits of three grain size ranges. The major rapids are formed by boulder deposits from side-canyon tributaries. As a result of a fourfold reduction in peak discharge when Glen Canyon Dam was closed in 1963, new fan debris may increase the gradient through some of the rapids by a factor of 1.8. Cobbles and gravel, transported only during flood stages, are preferentially deposited in the wider sections of the river as bars and riffles and are, for the most part, inactive during post-dam discharges. Fine-grain (largely sandy) terraces occur throughout the canyon, especially along the banks of the large reverse eddies above and below the rapids. The lower terraces are being reworked into beach-like shores by diurnally-varying, post-dam discharges. A slight net lateral erosion of the terraces has resulted. Prior to construction of the dam, sandy bed deposits underwent scour averaging about 1 m during spring floods, balanced by deposition from tributary sources during the summer. Downstream from rapids, decreased turbulence due to lower discharges has resulted in deposition averaging 2.2 m on the bed within the upper portions of the canyon. Differences in rock types along the river determine overall channel morphology. Rocks of low resistance result in a wide valley, a meandering channel, and abundant cobble bars and sand terraces. Narrow channels with rapids and deep pools are most frequent within the sections of the canyon where Precambrian crystalline rocks dominate.

INTRODUCTION

The Colorado River within the Grand Canyon (fig. 1) is special among North American rivers due to its spectacular geology, inaccessibility, and treacherous course. The river is also unusual from a geomorphological standpoint because of its narrow width, numerous rapids, and the large load of fine-grain sediment it transported before the construction of Glen Canyon Dam in 1963.

Leopold (1969, p. 132) suggested that despite the varied rock types throughout the Grand Canyon, the river exhibits a uniform morphology along its length, including regular riffle and pool spacing and an essentially uniform gradient. In addition, he said that most of the rapids are caused by bars not necessarily associated with tributary fans or structural control. We have presented evidence that most rapids are structurally controlled and that the frequency of rapids varies along the canyon due to variation in the regional and local fracture patterns and the stratigraphy of the Colorado Plateau (Dolan et al. 1978). In this paper we will confirm that the downstream variation of rock type and channel characteristics are associated with the frequency of rapids, channel width, frequency of bars and alluvial

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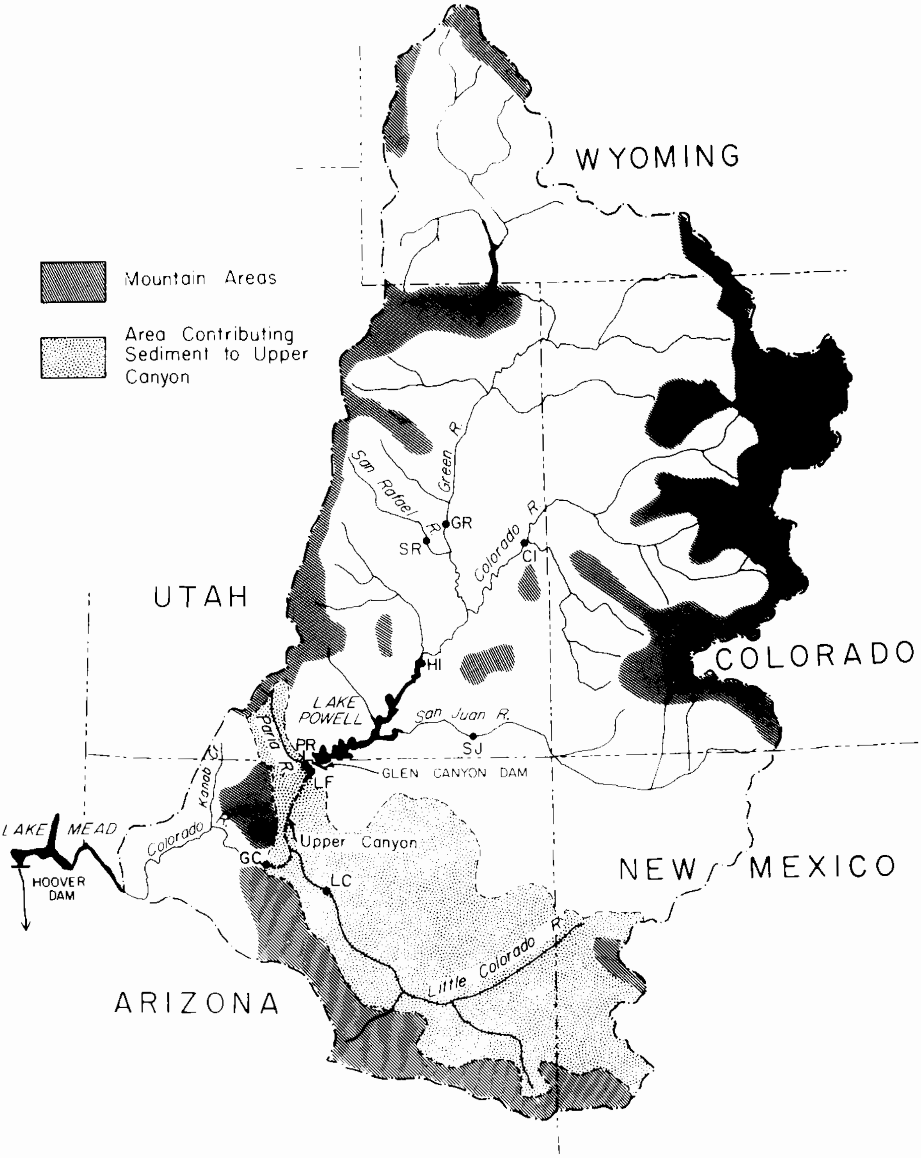

Fig. 1. – The Colorado River basin above Lake Mead. Snowmelt in mountain areas produces the yearly spring flood peak, but most sediment is contributed from the desert areas (unpatterned or dotted) by summer thunderstorms. Gaging stations identified as follows: GC = Colorado River at Grand Canyon; LF = Colorado River at Lees Ferry; LC = Little Colorado River at Cameron; HI = Colorado River at Hite; PR = Paria River; SR = San Rafael River; SJ = San Juan River at Bluff; GR = Green River at Green River, Utah; CI = Colorado River at Cisco. The Upper Canyon is defined as the 140 km reach between the Lees Ferry and Grand Canyon gaging stations (dashed line).

TABLE 1
Pre- and Post-Dam Statistics for the Glen Canyon Dam Area of the Colorado River

	Lees Ferry Gaging Station		Grand Canyon Gaging Station	
	Pre-Dam	Post-Dam	Pre-Dam	Post-Dam
Median Discharge (m^3/s)	210	350	230	360
Mean Annual Flood (m^3/s)	2440	760	2440	790
10-Year Recurrence Interval Flood (m^3/s)	3480	850	2460	1130
Discharge Equaled or Exceeded 95% of Time, Based on Average Daily Flows (m^3/s)	100	160	110	170
Median Sediment Concentration (ppm)	1500	7	1250	350
Sediment Concentration Equaled or Exceeded 1% of Time (ppm)	21000	700	28000	15000

Note: – Data based on U.S. Geological Survey Records.

fans, river gradient, and other channel characteristics. Differential transport of sediment according to size has produced three types of sedimentary deposits in the Grand Canyon: locally derived alluvial fan debris, cobble bars, and sandy alluvium. We will discuss each of these deposits in terms of distribution and morphology, and we will examine the process of sediment addition and removal. Finally, we will consider the effect of Glen Canyon Dam upon the sediment budget. During the course of this investigation, both authors made six two-week float trips through the Grand Canyon.

HYDROLOGICAL AND GEOLOGICAL FRAMEWORK

Two types of flood peaks occurred in the regime of the Colorado River before the construction of Glen Canyon Dam. Spring and early summer snowmelt from the headwaters caused annual peak discharges averaging 2400 m^3/sec and occasionally exceeding 3100 m^3/sec (table 1). Little new sediment was introduced by the watershed so that the suspended load consisted of moderate concentrations of sand and coarse silt scoured from the bed and banks of the channels. Spring floods were the only flows that reworked the cobble bars and tributary fan deposits. During late summer and early fall, thunderstorms in the Colorado Plateau created secondary peak discharges which seldom exceeded 850 m^3/sec; however, these flash floods contributed large concentrations (up to 15% by weight) of suspended sediment and bed load. Some of this sediment load was deposited on the channel bed (sand sizes) and as discontinuous terraces of sand, silt and clay. The fine-grain deposits were constantly reworked by floods with spring snowmelt causing erosion and the summer floods resulting in deposition. Low discharges in late fall, winter, and in early spring had little impact on the balance of the sediment budget.

The regulated flow has had a major effect on the fluvial morphology of the river. Construction of Glen Canyon Dam began in 1956. The river was first routed through the diversion tunnels early in 1959, and regulation of flow began in March, 1963. Between March, 1963, and May, 1965, water releases were very low – about 30 m^3/sec. In May and June, 1965, discharges up to 1800 m^3/sec were released, the diversion tunnels were closed, and the present pattern of diurnal releases in response to demands for power was established. Daily peaks now average about 600 m^3/sec and lows about 140 m^3/sec, with extremes from 30 m^3/sec to 760 m^3/sec (table 1).

Prior to 1956, the discharges and sediment flow through the Grand Canyon could be considered natural, with only minor influences due to small reservoirs and diversions of the headwaters. Some storage of sediment occurred at the Glen Canyon Dam during the period 1956–1963, resulting in limited bed scour immediately below the dam (Pemberton 1976). However, major alterations of the fluvial regime started when controlled flows began in March, 1963.

The pre-dam regime varied systematically during the period starting in 1922 when detailed records commenced (Smith et al. 1960, p. 234–238). Five-year averages of discharges and flood peaks show little trend until completion of the dam. However, measurements of sediment yield and sediment concentration declined during the pre-dam years (fig. 2). This long-term decrease in sediment transport through the Grand Canyon may be due to variations in seasonal rainfall distribution (Smith et al. 1960, p. 234–238; Bradley 1976), to increased upstream diversions and dam construction, or to the gradual termination of stream entrenchment which had started in the late nineteenth century. Sediment measurement techniques have evolved greatly during the period of measurement, consequently all or part of the trend may be apparent rather than real (W.B. Garrett, personal comm.). Nevertheless, bed elevations at the Grand Canyon gaging station also decreased systematically during the pre-dam period, suggesting that the decreased sediment yields were real.

As a result of the changes in river regime, pre-dam high water terraces are no longer inundated but are being modified by rapid growth of riparian vegetation and eolian reworking (Dolan et al. 1974). Sandy terrace deposits within the zone of water fluctuation have been remolded by currents and swash (small waves generated by turbulence in rapids) into sloping shorefronts colloquially called beaches (fig. 3).

Only a small percentage of the river banks in the Grand Canyon are fine-grain terraces. Most of the banks consist of bedrock or talus deposits which account for the generally narrow channel (averaging about 100 m wide) for a river with this discharge. For comparison, the width of the Colorado River at Yuma, Arizona, below the canyon was about 160 m prior to construction of Hoover Dam (Leopold and Maddock 1953, p. 28).

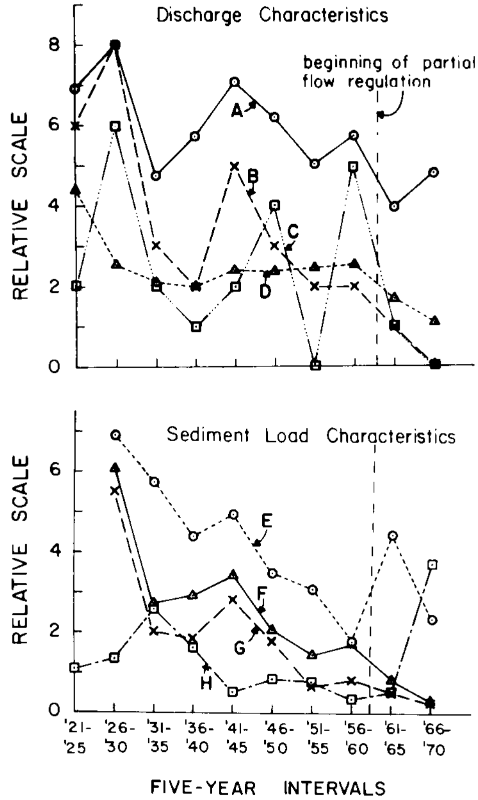

Fig. 2. – Long-term trends in discharge and sediment load characteristics for the Grand Canyon gaging station of the Colorado River for 5-year intervals beginning in 1921. Key to curves of discharge characteristics: (A) average yearly discharge; (B) number of spring flood peaks greater than 80 000 cfs (2266 m^3/sec); (C) number of summer flood peaks greater than 30 000 cfs (850 m^3/sec); (D) peak discharge during period. Key to curves of sediment load characteristics: (E) peak sediment concentration during period; (F) average yearly total sediment load; (G) maximum daily sediment load during period; (H) average bed elevation of the Grand Canyon gaging station. Unit values for the relative scale for each curve: (A) 2×10^6 acre-feet or 2.5×10^9 m^3; (B) 1 occurrence; (C) 1 occurrence; (D) 50 000 cfs or 1416 m^3/sec; (E) 2% by weight; (F) 50×10^6 tons or 45.3×10^6 metric tons; (G) 5000 tons or 4536 metric tons; (H) 2 feet (0.61 m) relative to a gage height of – 8 feet (– 2.44 m).

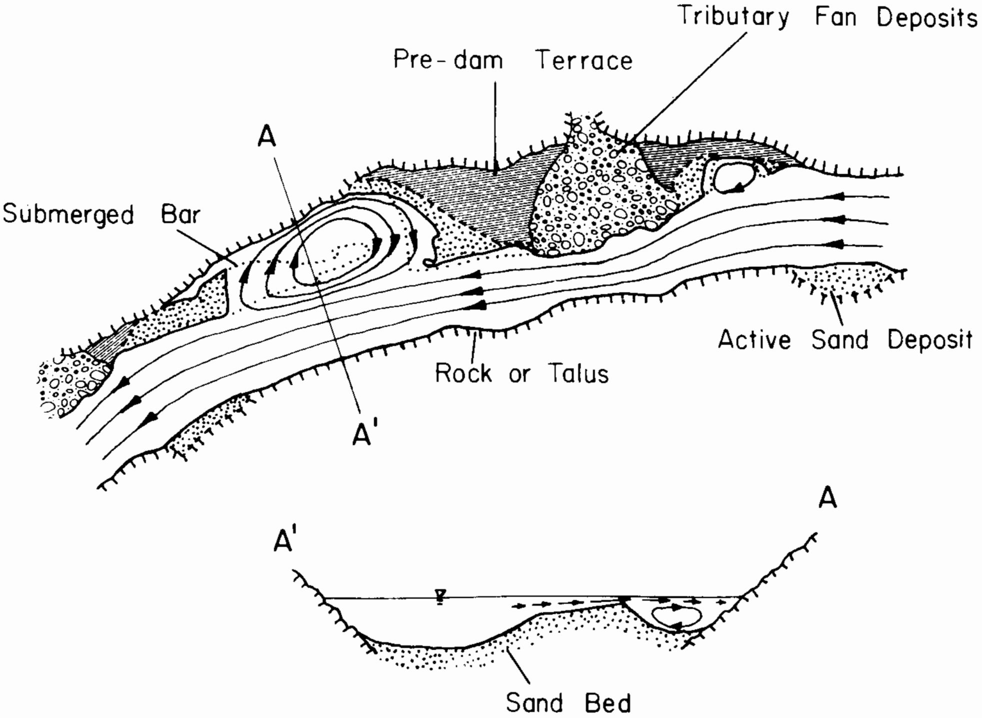

Fig. 3. – Map and cross section showing typical morphology of fluvial deposits associated with tributary fans. Arrows on plan view show inferred surface flow streamlines, and arrows in cross section show cross-river components of secondary circulation.

STRUCTURAL CONTROL OF CHANNEL PATTERN: DOWNSTREAM VARIATION

John Wesley Powell noted many changes in the dominant "mood" of the Grand Canyon during his journey in 1869, such as the change from the open expanses below Desert View Overlook (miles 65–75) to the "oppressive constriction" of the granite gorges. To illustrate the variation in the pattern of fluvial features within the canyon, seven attributes were measured from aerial photos and topographic maps along the first 225 miles below Lees Ferry. The first two indices are 1) the flood-stage valley width, and 2) the channel gradient. The remaining five are the occurrence of 3) cobble bars, 4) deep pools (channel depth gradient for post-dam discharges), 5) alluvial fans, 6) tributary entrances, and 7) sand terraces large enough to serve as campsites for river float trips (fig. 4, table 2). These measures indicate covariant response to downstream differences in lithology and structure. The effect of lithology is primarily reflected by the valley width; resistant rocks exposed near river level create a narrow valley. Valley width, in turn, is strongly related to the other variables shown in table 2, and is the major cause of the variation pattern. Differences in bedrock resistance affect channel morphology not only through variations in channel width, but also through fracturing of the bedrock which affects the frequency of tributary fans and deep pools (Dolan et al. 1978).

Despite this complex pattern of structural control, downstream variation in the channel can be characterized by four major channel types which alternate throughout the canyon (fig. 4).

A wide valley with freely-meandering channel. – Sections of the Colorado River

TABLE 2

Correlation between Fluvial Attributes of the Colorado River within the Grand Canyon

	Rapids[a]	Width[b]	Fans[c]	Bars[d]	Pools[e]	Slope[f]	Low Terraces[g]
Width	−.32						
Fans	. . .	.37					
Bars	. . .	.73	.31				
Pools	. . .	−.33	−.19	−.29			
Slope	.47	. . .	. . .	. . .	. . .		
Low Terraces	. . .	.33	.29	.32	−.33	. . .	
Tributaries[h]	. . .	−.21	. . .	. . .	.27	.19	. . .

NOTE: – Multivariate observations made on 78 2.5-mile (4 km) segments of the river. Correlations less than 95% l.o.s. are omitted, although caution should be exercised in interpretation of significance due to non-normality of frequency data.

[a] Number of rapids per 4 km segment. Occurrence of rapids taken from U.S. Geological Survey maps reproduced in Belknap (1969).

[b] Average flood-stage channel width measured by prominent line of mesquite and acacia growth.

[c] Number of exposed tributary canyon fans per 4 km segment.

[d] Number of cobble bars per 4 km segment exposed during normal post-dam discharges.

[e] Number of deep pools (> 20 m) per 4 km segment, measured from depth soundings with discharges ranging from about 140 to 570 m^3/sec.

[f] Average channel gradient for 4 km segment.

[g] Number of large low terraces estimated by the number of campsites per 4 km segment (campsites determined from listing by Weeden et al. 1975).

[h] Number of tributaries with drainage basins greater than about .15 km^2 entering river per 4 km segment.

valley are relatively wide where easily eroded shales occur near river level. Prominent features of these sections are wide, shallow flow and a meandering channel (fig. 8), as well as abundant cobble bars, few deep pools, tributary fans, and terraces. The meandering pattern appears to be related to modern channel processes, because the wavelength of the meanders is about eight times the flood-stage valley width, as is observed in most other actively meandering channels. Deeply entrenched meanders occur elsewhere in the canyon, particularly in Marble Canyon, with wavelengths much larger than in the freely-meandering portions of the river and lack the usual sedimentary features of meanders.

Valleys of intermediate width. – Where the valley is constricted by resistant sandstone or limestone, free meandering stops. If tributary fans are abundant, the channel pattern is dominated by alternating rapid-pool sequences, and cobble bars are limited to the widest valley sections, commonly just below one rapid-pool sequence and above the next (fig. 6). Characteristic of these river sections is the association of large channel width with deep pools. These occur because the jet flow and associated secondary circulation below the rapids have high scouring capacity.

Narrow valleys in fractured igneous and metamorphic rocks. – The "granite narrows," bordered by rugged, uneven slopes and cliffs (miles 77–112) are created by highly fractured and stratigraphically heterogeneous Precambrian schists and intrusives. In response to variable rock types the channel width is quite variable, although narrow, so that many small riffles occur at local constrictions as "deep water waves of convergence" (Leopold 1969). However, the major rapids occur at tributary entrances, although in some places the narrow channel may limit the fan to a boulder accumulation on the channel bed (fig. 5*B*). Deep pools are common, due to localized ease of scour in fracture zones and less resistant bands of schist. Tributaries flow into the canyon along these fracture zones (Dolan et al. 1978). Cobble bars are rare and the average channel gradient is high (fig. 5*B*).

Narrow valleys in massive limestone. – Contrasting with the granite narrows, the exposure of massively-bedded Muav limestone at river level (miles 140 to 165) creates nearly continuous vertical cliffs of constant width. The result is a sluiceway with few rapids, tributary fans, or cobble bars, and, correspondingly, a low gradient and few deep pools (fig. 5*C*). Even where

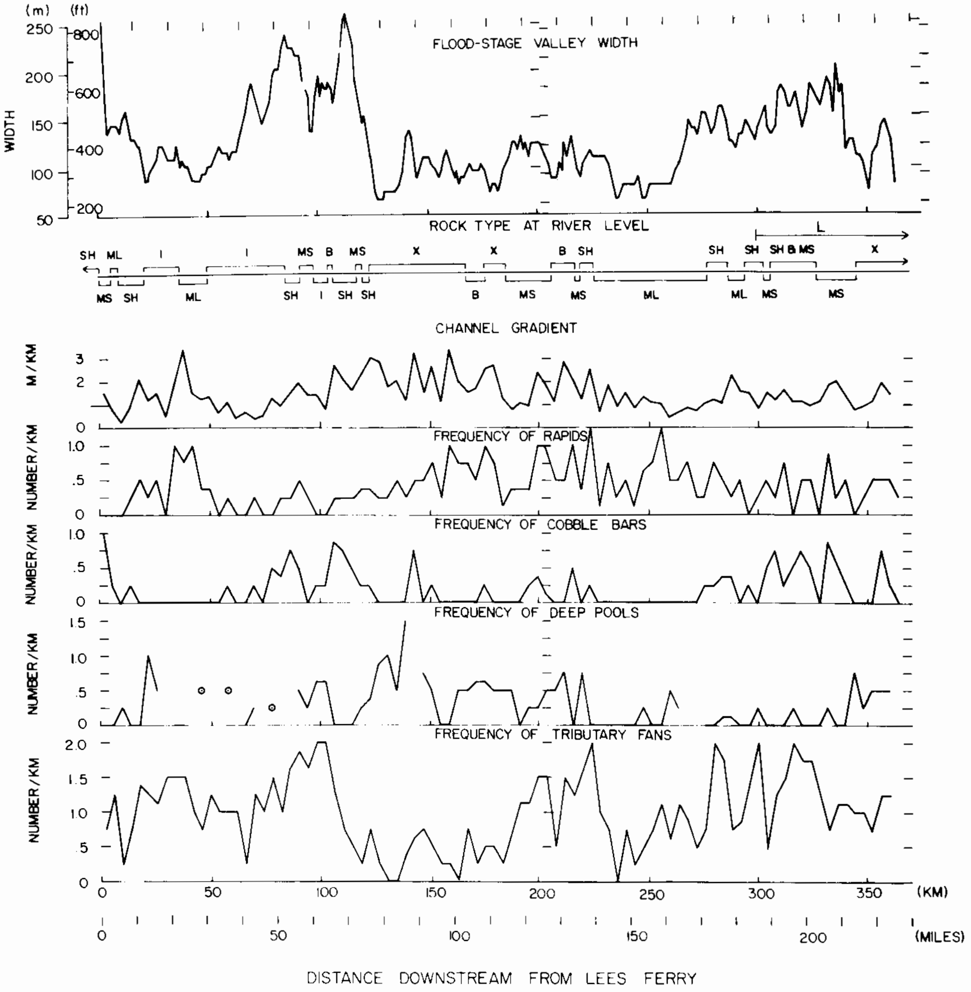

Fig. 4. – Multivariate relationship between channel attributes of the Colorado River in the Grand Canyon for the 225 miles downstream from Lees Ferry. See table 2 for explanation of measurements. Key to rock types exposed at river level: SH = shale; MS = massive sandstone; ML = massive limestone; I = Rocks of intermediate resistance or interbedded hard and soft rock; B = mafic dikes and sills; X = fractured and intruded schist and gneiss; L = lava flows at river level locally from one bank of channel. Histogram of the frequency of deep pools is broken where data is missing.

larger tributaries enter there are only minor rapids, small fans, and no deep pools. The minor impact of larger tributaries is due to the small fraction of cobbles and boulders delivered by the flow of the tributaries through the Muav coupled with an enhanced transporting capacity of the narrow main channel.

Even less affected by tributary fans are the cliff-bordered reaches near the upper part of the canyon (miles 1–10) and parts of Marble Canyon (fig. 5*A*). In these reaches, channel bottom profiles are nearly flat and dominated by sand. Similar flat, sandy channel bottoms apparently characterized much of the low gradient reaches upstream from Lees Ferry, including the now inundated Glen Canyon.

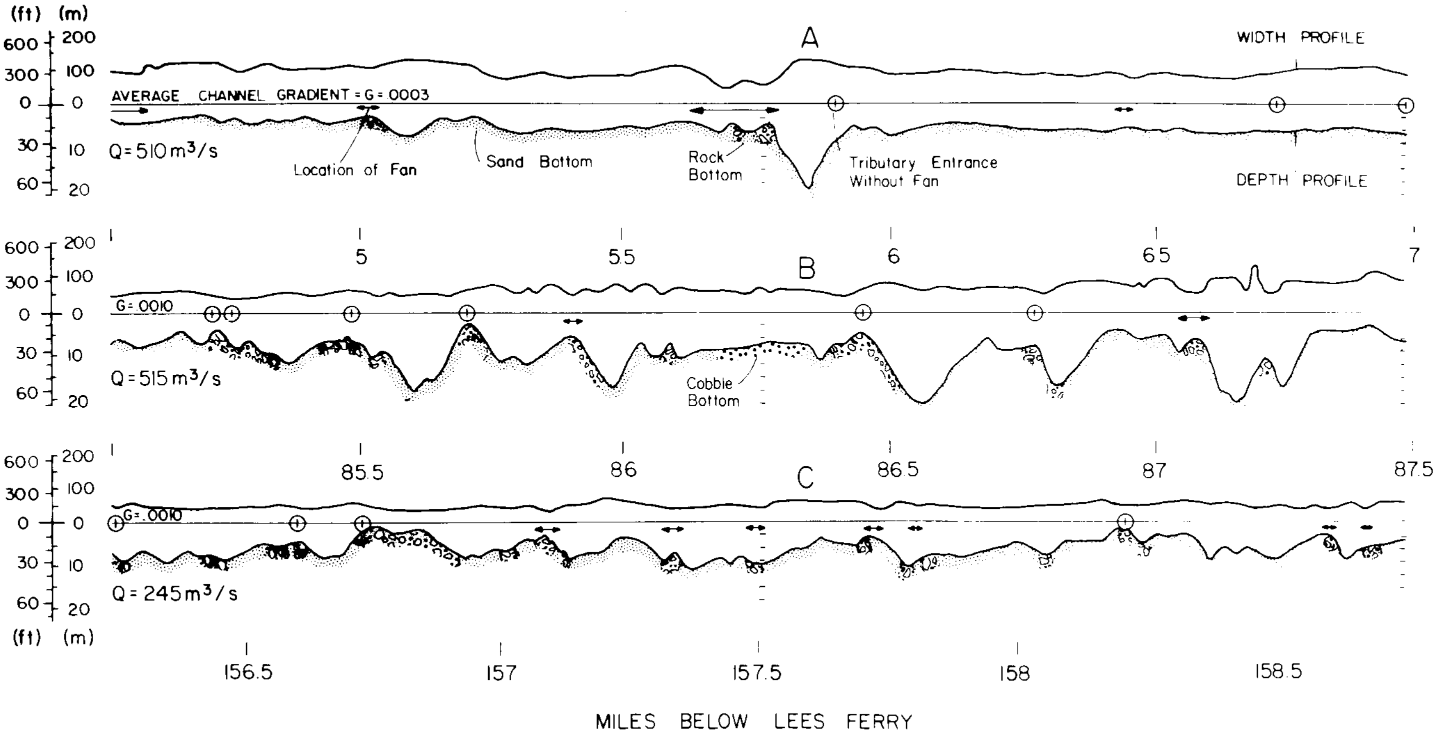

Fig. 5. – Representative depth profiles and channel widths for channel types of the Colorado River in the Grand Canyon: A. Moderately wide, shallow channel in massive limestone and sandstone with few tributary entrances and few deep pools (note deep pool downstream from tributary fan); B. Narrow, variable width channel in highly fractured Precambrian schists and intrusives with numerous tributary entrances and deep pools, but few subaerial tributary fans; C. Narrow, uniform width channel in massive limestone with numerous small tributaries and small fans, but few deep pools. Width and depth profiles are measured relative to horizontal datum. The discharge prevailing during the depth measurements is indicated.

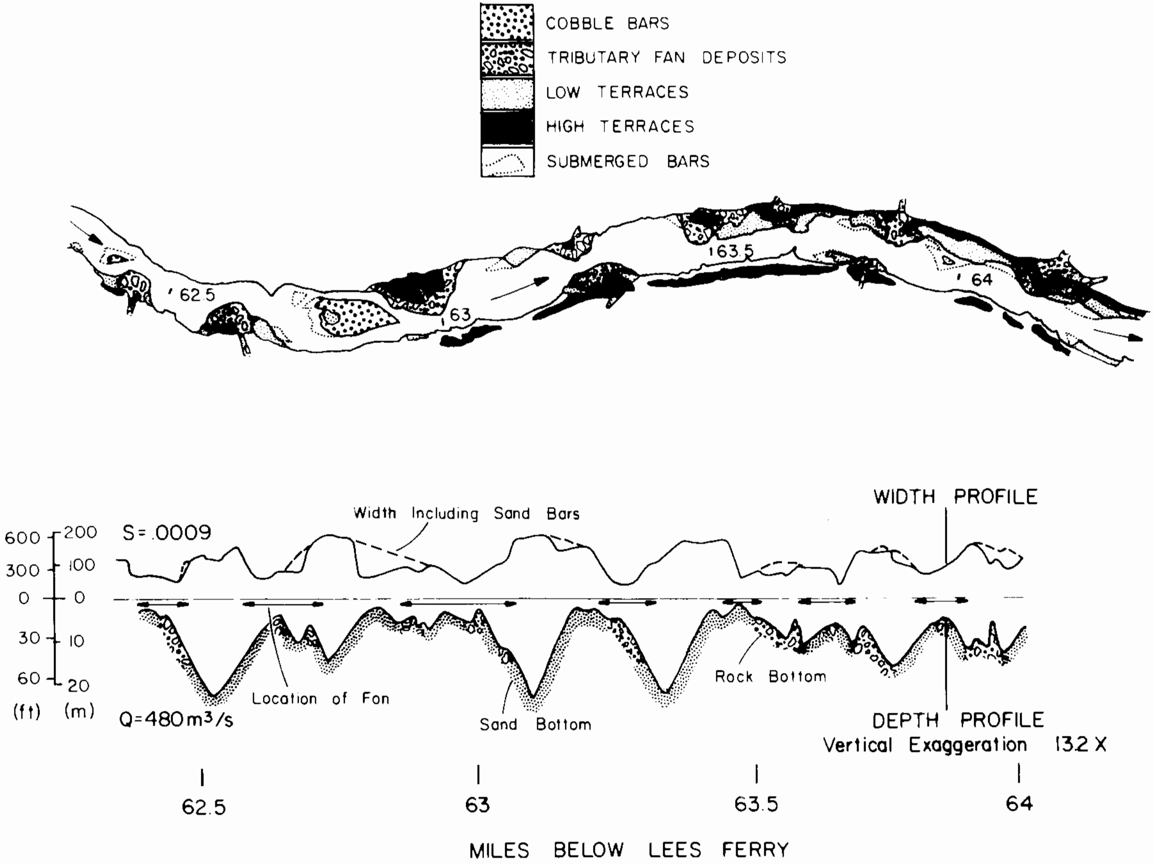

Fig. 6. – Geomorphic map and width and depth profile for a channel segment of intermediate width and well-developed, side canyon tributary fan deposits and associated deep pools. Rock and talus are uncolored. Low terraces include sandy post-dam deposits, pre-dam fine-grain vegetated deposits, and low pre-dam silty sand terraces. High pre-dam terraces are overgrown with mesquite and acacia. See figure 5 for further explanation.

MORPHOLOGY AND DYNAMICS OF FLUVIAL DEPOSITS

Although the physiography of the Grand Canyon varies markedly along the Colorado River, the fluvial deposits are composed of three intergrading components: (1) tributary alluvial fan deposits, (2) cobble bars, and (3) fine-grain sediments. Each size has been areally and vertically sorted into distinct but related deposits. Characterized by different sources, sinks, and dynamics, each has responded in a different manner to the changed regime due to Glen Canyon Dam.

Alluvial Fan Boulders. – Most rapids in the Grand Canyon occur at channel constrictions caused by the deposition of coarse alluvial debris by side-canyon tributaries (figs. 3, 6). The tributaries, with very steep gradients within narrow canyon walls, move boulders up to several meters in diameter. Some of the fans are more properly described as debris avalanche deposits derived from alcoves in the massive cliffs. The Colorado River, despite its much greater discharge, can only move debris of this calibre during flood peaks at relatively steep gradients through its narrowest channels. The rapids formed in this way account for most of the elevation decrease along the river through the canyon.

At tributary entrances the debris fans form one bank of the river, while bedrock or talus generally forms the other. In some cases fans lie opposite each other where tributary entrances are structurally controlled. If the bedrock is more easily eroded than the coarse alluvium, the channel may slowly migrate away from the tributary entrance, forming a pronounced meander.

Because the coarsest tributary debris cannot be transported by the Colorado River at gradients characteristic of between-rapids reaches, large debris covers the river bottom only in the rapids (fig. 7). This implies that the quantity of debris supplied by tributaries is too little to force the entire river into a gradient steep enough to transport coarse material. However, sufficient quantities are supplied to account for the rapids that dominate the gradient of the river. Debris supplied by floods is, therefore, balanced over time by its removal after comminution by abrasion, breakage, or solution (Schumm and Stevens 1973). The size of debris covering the bottom of a given rapid is determined by several factors, including the size and quantity of the debris supplied, the maximum main stem post-depositional flood peaks, and the local river width. Fine detritus is sorted out, leaving a pavement of the coarsest debris delivered in sufficient quantity to form a coherent bed.

Side-canyon floods merging into the Colorado River lose competence and deposit coarse debris as a localized obstruction in the main channel. The main stream reworks this debris, sorting and removing the finer detritus, widening the river, and reducing the gradient to a value consistent with the threshold of motion of the coarsest debris (fig. 7). Maximum mainstem discharges determine the channel gradient and width through the debris fans. Graf (1979) cites evidence that the highest flood peaks are barely competent to transport the fan debris, and that the coarse lag boulders are relatively immobile.

The multifold reduction of maximum post-dam flood peaks from 3400 m^3/sec to 850 m^3/sec raises the possibility that rapids in tributary fans may increase in gradient and decrease in width as side-canyon flooding adds new debris. Formulas for threshold-of-motion channels in coarse debris presented by Henderson (1966, p. 454) suggest that a fourfold reduction in peak discharge could allow an increase in rapid gradient by a factor of 1.8 under such circumstances. This raises the possibility of rapids too steep for navigation by float trips (Dolan et al. 1974). The intense tributary flooding in December, 1966 (Cooley et al. 1977) added debris to many tributary fans, steepening rapids and narrowing the channel. One of these rapids, Crystal Rapids (mile 98), is now barely navigable.

Cobbles and Gravel. – Bars of well-rounded and well-sorted cobbles up to 50 cm occur throughout the canyon (figs. 6, 8),

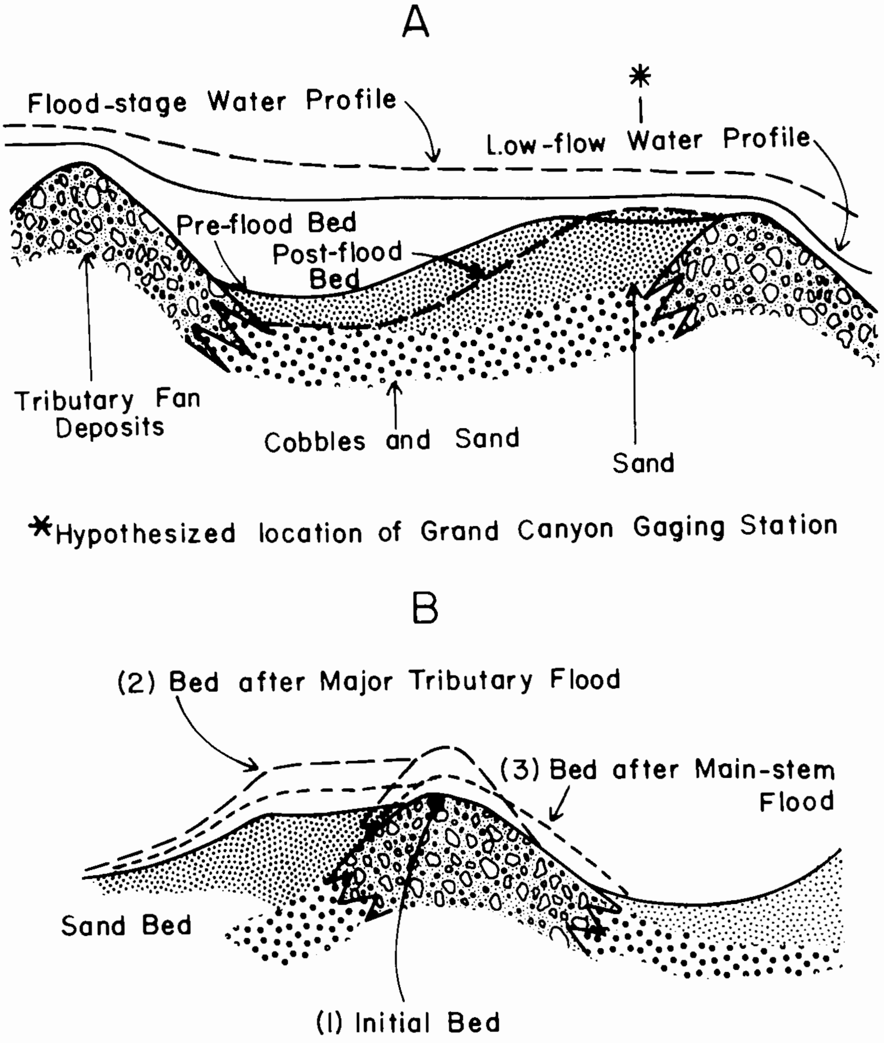

Fig. 7. – Schematic illustration of sedimentary dynamics in a rapid-pool sequence under pre-dam regime. Vertical dimension greatly exaggerated. A) Seasonal changes in sand deposits within a pool between tributary fans and associated rapids. During early spring months the low flows are marked by nearly ponded water within pools. A moderately deep pool is maintained below the rapids by turbulence and jet flow generated within the rapids, but the channel bed just upstream from the next tributary fan is shallow and flat. The annual late spring flood causes enhanced scour in the pools, locally eroding them to the underlying coarser deposits. Some of the eroded sand is temporarily deposited just above the next rapid (leading to the fill during rising stages as observed at the Grand Canyon gaging station), but most of the eroded sand is transported out of the Upper Canyon. During the late summer and fall, reworking of the bed and deposition of sediment contributed by tributary floods restores the initial profile on the average. Rare intense floods completely scour the sand, and the underlying cobbles are actively transported, with subsequent redeposition of a sand cover. Smaller debris on the tributary fan deposits may also be moved. B) Changes in tributary fan deposits. Initial conditions are as above (A). A catastrophic local rainstorm causes the tributary to deposit a local plug of mixed coarse and fine detritus at the tributary mouth, building up the bed, steepening the rapids, and causing an accumulation of sand in the upstream pool (2). A large main-stem flood reworks the fan debris, eroding the finer debris and depositing the coarser debris just downstream, producing a net lowering of the brink of the rapids and a gentler gradient through the rapids (3). Long-term comminution of the remaining coarse debris may eventually return the fan and upstream sand deposits to the original level.

forcing the flow into riffles (the small size of the cobbles precludes the formation of true rapids). The bars are primarily composed of rock from within the canyon.

Along the 225 miles of canyon between Lees Ferry and Diamond Creek, the average flood stage (3500 m^3/sec) width of the river is 129 m. The average width is 213 m where cobble bars are present and less than 125 m where they are absent.

Decrease in competence of flood flow where the river spreads into the wide sections of the canyon is the factor controlling cobble deposition. This deposition is generally aided by a downstream constriction, such as bedrock or a tributary fan, which acts to pond water upstream (fig. 6). Bars also occur as a mantle over coarser fan debris on the inside bend of broadly curved rapids and as isolated bars below the plunge pools of short, steep rapids (figs. 6, 8). Strong jet flow during floods keeps the pools swept clear of cobble deposits, whereas these pools are filled during lower stages by fine sediment (fig. 7).

Although cobble-size detritus forms a conspicuous component of the fluvial deposits in the Grand Canyon, it is poorly represented (less than 0.1%) downstream in the deposits of Lake Mead (Smith et al. 1960). Cobbles are a relatively slow-moving component of the sediment load; in fact, they are immobile under the present controlled flow and were moved only by the largest pre-dam flood peaks. Cobbles are abundant in the lower portions of the channel fill but are usually covered by 2–6 m of sand (Bureau of Reclamation 1950, 1970; Pemberton 1976), thus moving only during flood peaks when the overlying sand has been scoured (fig. 7).

Cobble-size debris is a through-flowing component of the sediment load, as is attested by well-rounded shapes. The larger cobbles are presently immobile but smaller particles are probably still in motion locally. Under pre-dam conditions, much debris that would be added to the cobble component by selective sorting of new fan deposits and by comminution of older fan boulders now remains on the alluvial fans. Because of their large size and composition, the cobbles should be rapidly broken down by solution, breakage, and abrasion, but losses are made up, on the average, by local side-canyon contributions of cobbles. Thus individual cobbles may not, in general, move the length of the canyon before being reduced to sub-cobble size. Comminution is thus a contributing factor to the poor representation of cobbles in Lake Mead sediments.

Fine-Grain Terraces. – Sandy terraces have been deposited in areas of slack water throughout the Grand Canyon. Their depositional patterns are similar to those of the cobble bars in that terraces are more common along wider sections of the river in locations with slower flood-stage currents (figs. 3, 6, 8). The terraces, deposited and reworked by pre-dam spring floods, form a discontinuous mantle over the alluvial fan and cobble bars, as well as being locally deposited on banks of bedrock or talus. Current intensity low enough to encourage deposition of terraces occurs under several circumstances: (1) Reverse eddies caused by channel constriction at tributary fans may occur both upstream and downstream from the constriction (figs. 3, 6, 8). The downstream eddy is usually better developed because separation occurs most readily in divergent flow. The reverse eddies involve complex three-dimensional flow patterns, including horizontally-oriented helicoidal flow upstream along the channel bank, so that the terrace deposits have a corresponding pattern (fig. 3). The depositional pattern is also locally complicated by secondary and tertiary eddies in concave corners near the shore and by changes in the size, number, and strength of the eddies with change in river stage. Up to 1 m of diurnal scour and fill occurs locally as a result of stage variation. (2) Small terraces occur in protected alcoves even in the narrowest sections of the canyon along zones of weak rock, fractures, or at the entrance of small tributaries. (3) Along some of the wider sections of the river both banks are lined with steep, narrow banks of fine sand and silt (fig. 6). These silty deposits were left

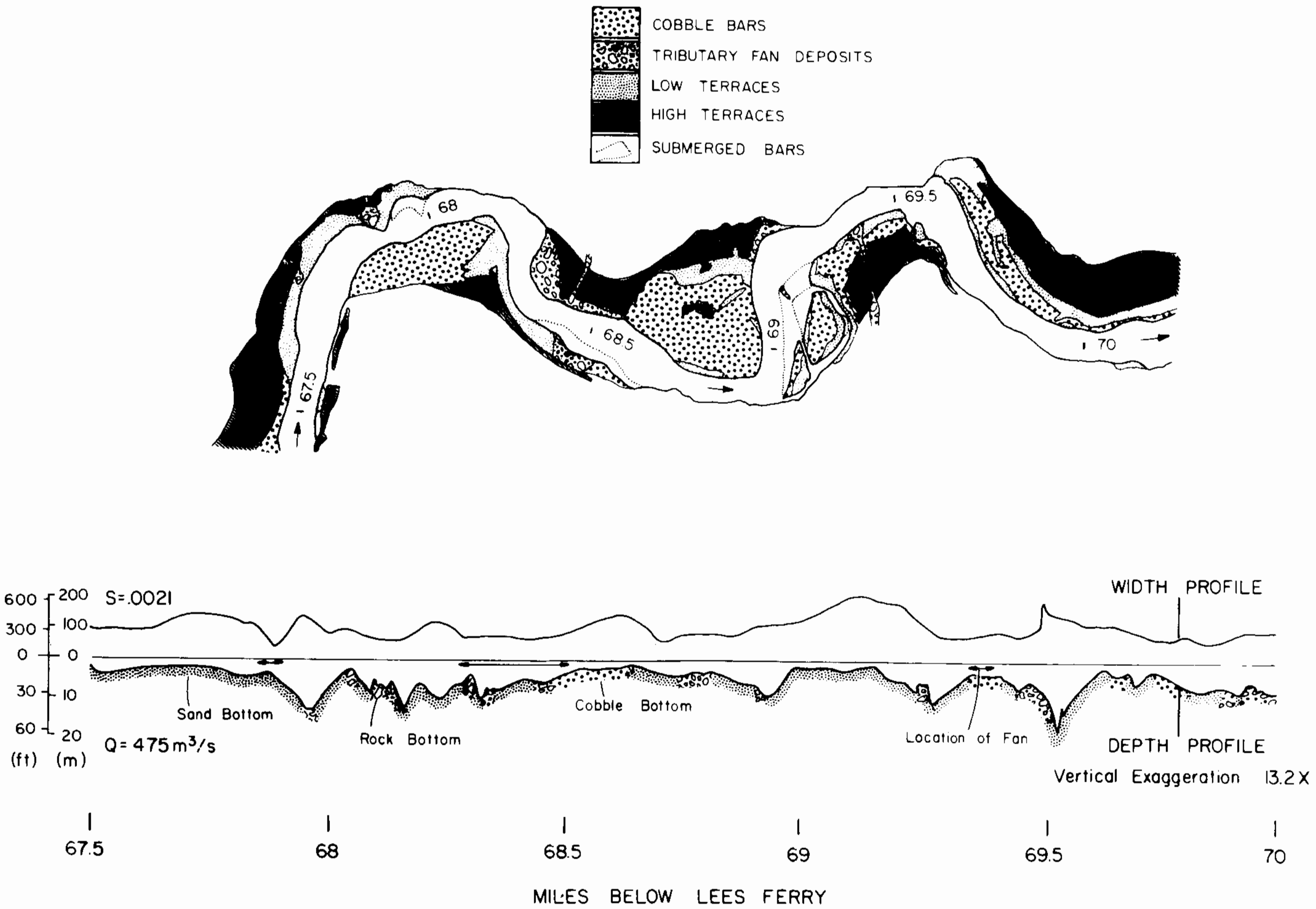

Fig. 8. – Geomorphic map and width and depth profiles for a wide, meandering section of channel with abundant cobble bars developed in shale bedrock. See figures 5 and 6 for additional explanation.

during the pre-dam summer flood peaks and have a universal association with a dense cover of vegetation under both pre- and post-dam conditions. The vegetation has encouraged deposition of fine material and, conversely, the fine-grain deposits offer moisture, nutrients, and a firm substrate for the vegetation.

Limited bed sampling and drilling at dam sites suggest that sand forms the majority of the channel bed with short interruptions at the boulder-filled rapids and the cobble bars. This is supported by the smooth fathometer traces and gradual changes of channel depth. Both the Lees Ferry and Grand Canyon gaging stations were sand-bed channels under natural conditions and were subject to seasonal scour and fill often exceeding 2 m.

Based upon drill hole records in the vicinity of the Glen Canyon and Hoover dam sites, the sand and gravel fill beneath the channel bed ranges from 9 to 45 m, averaging 20 m (Bureau of Reclamation 1950, 1970). Extremes range from 0 to more than 60 m. The uppermost 2–6 m of this fill is sand underlain by interbedded sandy gravels and sand (Pemberton 1976).

SEDIMENTOLOGY OF FINE-GRAIN SEDIMENT

Grain Size Characteristics. – The grain size characteristics of the suspended sediment carried by the Colorado River under the pre-dam regime varied with stage and sediment source. The grain size distribution of the sediment accumulating in Lake Mead (fig. 9-*15*) is a close approximation of the composition of the sediment transported through the Grand Canyon. It is almost exclusively sand size or finer detritus (Smith et al. 1960, p. 199). Superimposed on this was a wide temporal variation in grain size. Under pre-dam conditions the suspended load at the Grand Canyon gaging station during the spring flood peaks was relatively coarse, with about 70% of the load in the sand-size range (fig. 9-*1*). Most of this suspended sand was derived from temporary scour of the channel bed (fig. 9-*6*) and the flood terraces (fig. 9-*9*, 9-*11*). Summer thunderstorms caused flash flooding in the desert tributaries and the resulting high sediment concentrations at moderate discharge were predominantly silt and clay (fig. 9-*3*). Sand deposits left by the spring flood peak (fig. 9-*9*) are coarser grained than the silty terraces deposited by the upper watershed tributaries (fig. 9-*11*).

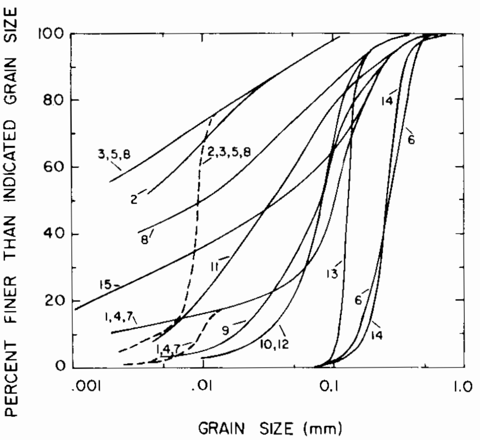

Fig. 9. – Representative grain-size distributions for fine-grain fluvial deposits and suspended sediment load of the Colorado, Paria, and Little Colorado rivers. Gaging station grain size information from published U.S. Geological Survey records. Lake Mead curve from Smith et al. (1960). Dashed lines show grain size distribution of naturally flocculated suspended sediment (Sherman 1953). Other data from samples collected along the river. Key to curves. *Grand Canyon Gaging Station* – Suspended load, pre-dam: (1) High discharge, moderate sediment load, (2) low discharge, low sediment load, (3) moderate discharge, high sediment load. Post-dam: (4) Low sediment load, and (5) high sediment load. (6) Bed sediment. *Paria River* – Suspended load: high discharge: (7) High sediment load. *Little Colorado River* – Suspended load: (8) High discharge, high sediment load. *Flood terraces*: (9) High pre-dam, (10) post dam, (11) fine-grain, vegetated. *Post-dam beach deposits*: (12) Low energy environment, (13) moderate energy environment, (14) high energy environment. *Colorado River deposits in Lake Mead* (15).

Effects of Glen Canyon Dam. – *Post-Dam Deposits*: The normal post-dam sediment load (fig. 9-*4*) has a grain size distribution similar to the pre-dam spring floods, and the sand in suspension is exchanged with terraces, banks, and the channel bed. Thus moderate suspended sediment concentrations accompany the daily peak post-dam discharges, but these sands are redeposited further downstream during low water.

At present, sediment concentrations in the Colorado can be almost as high as during pre-dam conditions (table 1) due to the flooding of below-dam tributaries. The grain sizes transported during tributary floods (pre- and post-dam) are dominated by clay and silt (fig. 9-5) which is carried as wash load and generally transported through the canyon without deposition. During periods of high sediment load, thin but short-lived clay deposits are, at times, left on the beaches within the zone of daily fluctuations of water level. In some locations of weak currents, the clay accumulations are thicker and resist erosion so that they form distinct layers in the bank deposits.

Infrequent tributary floods may increase the daily post-dam discharges by 280 m^3/sec or more. One such flood in 1973 deposited a sandy terrace which was as much as 0.6 m thick and extended discontinuously from below the entrance of the Little Colorado River to Lake Mead (table 3 and fig. 9-*10*). Most of the sand in this terrace was probably derived from the scour of the banks and especially the bed.

Post-dam Bank Morphology and Sediment: The sandy deposits in the zone of daily water level fluctuation are constantly molded by currents and by wave and swash action associated with the rapids. These shorefront sands are analogous to coastal beach deposits in morphology, composition, and depositional environment. Both environments undergo daily fluctuations in water level superimposed upon currents and swash. Not surprisingly, the deposits are similar both in grain size and morphology, leading to the loose description of the shorefront as a beach.

The beaches of the Colorado River are subjected to a wide range of intensities of current and wave action. High energy beaches occur along narrow or shallow sections of the river where currents are strong, and below rapids where high turbulence generates waves and swash action. Contrasted with these are low energy beaches along wide, deep sections of the river or in protected alcoves.

TABLE 3

Size Characteristics of Fine-Grain Fluvial Deposits of the Colorado River in the Grand Canyon

Type of Deposit	Median Grain[a] Size (mm)
Post-Dam Beaches – Low Gradient (0–9°)	.191
Post-Dam Beaches – Medium Gradient (10–20°)	.140
Post-Dam Beaches – Steep Gradient (> 20°)	.116
Post-Dam Flood Deposits	.110
Pre- and Post-Dam Deposits Supporting Dense Vegetation	.063
Pre-Dam Flood Terraces	.099

[a] Based upon microscopic sampling which was calibrated using sieve analysis.

During a float trip in 1974, we collected 105 sediment samples from beaches along the 250 mile length of the canyon (table 3). At the sample sites and at additional locations the beach gradients were measured by a Brunton compass, and the intensity of current and swash were rated on a subjective scale. Nearshore currents exceeding about 0.3 m/sec were characterized as "rapid," whereas runup exceeding about 1 m was labeled as intense (although small compared to oceanic beaches). Beach gradient is inversely related to both the intensity of swash and that of longshore currents, with high swash or high currents producing gradients in the range of 3° to 9°, while in low energy environments the gradient approached the angle of repose of the sand (table 4). No statistical tests of association were performed due to the subjective nature of the classification. In particular, perception of swash intensity is inversely related to beach gradient, for the swash penetrates further on low gradients.

Grain size also responds to energy gradient, being coarser on the high energy beaches (fig. 9-*12*, 9-*14*, and table 3). Similar relationships between beach gradient, grain size, and energy input have been noted on coastal beaches (Dolan 1965; Bascom 1951).

TABLE 4

Relationship between Gradient of Post-Dam Beaches and Activity of Swash and Current

	Beach Gradient		
	0–9°	10–20°	> 20°
A. Effect of Current Velocity[a]			
Slow	3[b]	7.5[c]	10
Medium	5	11.5	3
Rapid	6	6	4
B. Effect of Swash Intensity[a]			
Low	1.5	12	16
Medium	4.5	11	1
High	11	10	0

[a] Subjective classification.
[b] Number of observations in category.
[c] Fractional numbers result from splitting of borderline observations.

The shorefront deposits in the Grand Canyon are well-sorted (fig. 9-*12*, 9-*13*, 9-*14*) and the highest energy beaches are nearly as coarse as the sandy bed material. No downstream trend in sorting or grain size of beach sands was noted (also see Laursen et al. 1976).

Channel Width: Channel width can be dramatically altered downstream from a dam, either widening or narrowing depending on the relative changes in peak discharge, sediment supply, and vegetation. The dramatic decrease of suspended sediment following construction of Glen Canyon Dam led Dolan et al. (1974) and Laursen et al. (1976) to predict a net scour of sandy banks, as was observed in the reach just below the dam. In fact, during the first ten years since the dam, sandy channel banks have suffered only a very slight erosion, with individual cases of both pronounced erosion and marked deposition (Howard and Dolan 1979). In this regard, Petts (1979) has emphasized that the large number of interacting variables affecting channel response to dam construction complicate the prediction of width changes and scour and fill.

Counteracting the expected erosional tendency are two factors: decreased peak flows and stable vegetation. Prior to construction of the dam, few *tamarix* (salt cedar) occurred along the Colorado River in the Grand Canyon due to the large seasonal variations of both water stage and scour and fill of the bank deposits. *Tamarix* has spread widely along the river since flow regulation, aiding sediment entrapment on the banks (Turner and Karpiscak 1980). The less-confined channels of the Colorado and Green rivers upstream from the Grand Canyon apparently narrowed an average of 27% since the late 1800s as a result of the spread of *tamarix* (Graf 1978; dissent by Everitt 1979). The possibility exists that the slight post-dam bank erosion in the Grand Canyon may change to narrowing if *tamarix* increases in extent and density, assuming no change in regime of dam releases.

However, neither bank narrowing nor erosion can be of the same order of magnitude as that observed elsewhere due to the confined channel. Most of the banks are rock or talus. Where sand banks occur, slight erosion or deposition would decrease or increase bank shear stress more rapidly than in stream channels with unconfined widths. Thus minor width changes should balance large variations in peak discharge, suspended sediment loads, and bankside vegetation.

Prior to construction of Glen Canyon Dam, additions from tributaries below Lees Ferry accounted for only 20.4% of the suspended sediment load at the Grand Canyon gaging station. Because of the dramatic reduction of sediment load caused by the construction of the dam, Dolan et al. (1974) and Laursen et al. (1976), predicted that net scour of the bed and widespread net erosion

TABLE 5

Sediment Yields, Runoff, and Drainage Areas of the Colorado River and Tributaries

	Drainage Area (km^2)	Sediment Yield (metric tons/km^2-yr)	Annual Runoff (m^3/km^2-yr)
	Reach 1		
Colorado River above Cisco, Utah	62400	142	102000
Green River above Green River, Utah	105200	148	52200
San Rafael River	4400	298	31100
Ungaged Tributaries	26400	376[a]	. . .
	Reach 2		
Colorado River above Hite, Utah	198400	185	60100
San Juan River	59600	291	31300
Ungaged Tributaries	21500	524[a]	. . .
	Upper Canyon		
Colorado River above Lees Ferry	279500	237	51900
Paria River	4100	784	5900
Little Colorado River	68600	124	2600
Ungaged Tributaries	5100	776[a]	. . .
	Lower Canyon		
Colorado River above Grand Canyon	356900	235	41100
Kanab Creek	2800	307	2400

SOURCE. – Based upon U.S. Geological Survey records for years prior to completion of Glen Canyon Dam.

[a] Estimated value: See text.

of the terraces would result. However, detailed analysis of the post-dam sediment budget does not confirm these expectations thus far. Since flow regulation, net *deposition* has occurred on the channel bed although this has been accompanied by a slight net lateral erosion of sandy beaches (Howard and Dolan 1979).

Pre-dam Sediment Budget: During the decade 1948–1957, prior to appreciable influence from the construction or operation of Glen Canyon Dam, detailed sediment records were collected at the head and end of an 87-mile segment of the Colorado River between the Lees Ferry and Grand Canyon gaging stations (this river segment is referred to here as the Upper Canyon). In addition, sediment records were collected on the Paria River just upstream from its junction with the Colorado, and on the Little Colorado at Cameron, 26 miles upstream from the Colorado River. Table 5 summarizes the sediment yield and drainage area characteristics of these tributaries, the main stem, and the ungaged tributaries of the Colorado River in Utah and Arizona. A detailed input-output balance of the sediment budget of the Upper Canyon was conducted using monthly totals of water and sediment discharge. Net storage change, ΔS (measured in metric tons), occurring within the reach during a given time interval is equal to the difference between input and output. A simple model of this budget is:

$$\Delta S = LF + LC + PR + M(LC + PR) - GC, \tag{1}$$

where LF, LC, PR, and GC are sediment loads of the Lees Ferry, Little Colorado River, Paria River, and Grand Canyon gaging stations, respectively. The contribution of the ungaged tributaries is estimated by multiplying the measured tributary input by a weighting factor, M. Although the estimated sediment yield of ungaged tributaries may result in appreciable error for individual runoff events, it becomes more accurate for monthly and yearly yields for the proper value of M.

The weighting factor can be estimated *a priori* by assuming an appropriate sediment yield by comparison with similar gaged tributaries or *a posteriori* by assuming a value which gives the best comparison with observed scour and fill behavior of the Grand

Canyon and Less Ferry gaging stations. Setting the sediment yield of the ungaged tributaries to those of the Little Colorado River, the Paria River, and Kanab Creek (a tributary which enters below the Upper Canyon) gives values of the weighting factor of 0.05, 0.34, and 0.13, respectively. A value near the upper end of this range seems reasonable, due to the very steep relief and sedimentary geology of much of the ungaged drainage area, implying sediment yields of about 780 metric tons/km-yr for the ungaged tributaries (table 5).

DYNAMICS OF FINE-GRAIN SEDIMENT

The sand-size and finer sediment transported by the Colorado River is the most important size range both in terms of the extent of deposits and its relative abundance in the sediment load (> 99% of the total load). Furthermore, the fine-grain sizes are the most conspicuously affected by Glen Canyon Dam. Therefore, a discussion of the sediment budget of the fine-grain sediment forms the bulk of the subsequent presentation.

The sedimentary budget of this component is well documented by suspended sediment concentration measurements made by the U.S. Geological Survey in 1922. These measurements were made on the main stem at Lees Ferry and Grand Canyon gaging stations and from 1948 on the major tributaries, the Little Colorado and Paria rivers (fig. 1). Regular measurements were discontinued in 1970.

The Colorado River is a suspended load river; that is, most of the sediment in the size range characteristic of the channel bed is carried in suspension, at least at high flows. About 30% of the sediment transported during pre-dam spring flood peaks was as coarse as the size range of the bed sands (> 0.1 mm). As a result of the dominant role of suspended load transport and the normally high sediment concentrations of the river, the sandy deposits of the bed, banks, and terraces were and are subject to continuous reworking in response to changes in flow conditions, serving as both source and sink of sand and coarse silt. The dynamic character of the sandy deposits is illustrated by the large magnitude of scour and fill (up to 1.5 m in average bed elevation; larger for local bed elevation) that occurred at the Grand Canyon and Lees Ferry gaging stations in response to seasonal and long-term variation of discharge and sediment load (figs. 10, 11).

Changes in the sediment budget were estimated on a yearly basis in a similar manner for two reaches of the Colorado River above Lees Ferry, however availability of sediment load records limited these estimates to the years 1949–1958. The lower reach (Reach 2) extends to Lees Ferry from Hite, Utah, approximately 163 miles upstream, and includes measured input from the San Juan River, the Colorado River upstream from Hite, and unmeasured contributions from 21500 km^2 (fig. 1 and table 5). The upper reach (Reach 1) extends from Cisco, Utah, on the Colorado River and from Green River, Utah, to Hite (about 151 miles on the Colorado River and an additional 117 miles on the Green River) and includes measured contributions from upstream reaches of the Colorado and Green rivers, from the San Rafael River, and unmeasured contributions from 26 400 km^2 (fig. 1 and table 5).

Because of the relatively high contributions from ungaged tributaries in Reaches 1 and 2 and because of the necessity to use estimates based partly on measured contributions for drainage basins outside the reach in question, the estimated storage changes for these reaches are not as accurate as for the Upper Canyon; however, the similar patterns (fig. 11) suggest that the estimates are reasonable.

Changes in sediment storage within the Upper Canyon should be reflected primarily in changes in average bed elevation, because of the minor changes in channel width and in overbank deposition within this rock-confined river. The average bed elevation change, ΔE, on sand-bed portions of the channel which result from changes in sediment storage, ΔS, is a function of the length

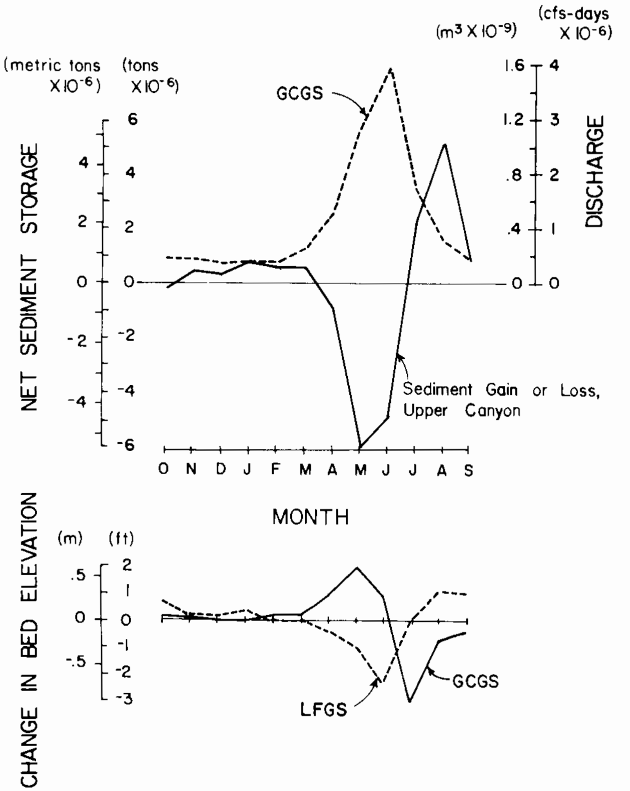

Fig. 10. – Changes in monthly averages of discharge, sediment storage, and bed elevations of gaging stations for the Upper Canyon section of the Colorado River in the Grand Canyon. Values represent averages for the 10-year period beginning in October, 1947. GCGS = Grand Canyon gaging station; LFGS = Lees Ferry gaging station.

of the Upper Canyon (140 km), the proportion of the total channel length that is sand bed, P, the average channel width, W, and the density of sediment, D:

$$\Delta E = K\,\Delta S, \text{ where } K = \frac{10^6}{140\,000\; D\cdot P\cdot W}, \qquad (2)$$

where ΔE and W are measured in meters, ΔS in metric tons $\times 10^{-6}$, and the density in metric tons/m^3. Assuming that the average channel width is about 95 m (depending upon stage), the sand bed density about 1.5 metric tons/m^3, the proportion of sand bed about 0.75, then the constant, K, should have a value of about 0.066.

Estimated storage changes in the Upper Canyon have been correlated with year-to-year bed elevation changes at the Grand Canyon and Lees Ferry gaging stations for various assumed values of the weighting factor, M (table 2). Storage changes correlate best ($r = 0.9$) with pre-dam elevation changes at the Grand Canyon gaging station for $M = 0.3$, which, as discussed above, corresponds to a reasonable sediment yield for the ungaged tributaries. This suggests that bed elevation changes at the Grand Canyon gaging station are representative of average changes within the Upper Canyon. This is further confirmed by the slope of the regression line predicting bed elevation changes from storage changes (0.055), which is very

TABLE 6

Correlation between Changes of Bed Elevation and Changes in Sediment Storage for the Grand Canyon and the Lees Ferry Gaging Stations

			Value of Estimating Parameter			
			M = 0	M = .3	M = .44	M = .65
Grand Canyon						
	1948–57	r[b]	.15	.91	.88	.71
		b[c]	.007	.054	.037	.017
	1948–70	r	−.31	.83	.77	.68
		b	.010	.054	.024	.010
Lees Ferry						
	1948–57	r	.66	.65	.27	
		b	.013	.020	.007	
	1948–70	r	.74	−.53	−.80	−.83
		b	.044	−.074	−.054	−.010

[a] Correlation of yearly average bed elevations, Grand Canyon with Lees Ferry Gaging Station: 1948–57 .38; 1948–70 −.64.

[b] Pearson correlation coefficient of yearly averages of bed elevations versus estimated yearly averages of sediment storage.

[c] Least-squares regression slope of bed elevation estimated by sediment storage. Bed elevation in meters, sediment storage in metric tons $\times 10^{-6}$.

close to the value of 0.066 estimated by equation 2. This correspondence also confirms that equation 1 provides a reasonable estimate of storage changes within the Upper Canyon for the appropriate value of M. Finally, equations 1 and 2 provide a close prediction of the post-dam changes in bed elevation at the Grand Canyon gaging station (table 6 and fig. 11), as is discussed below.

Storage changes in the Upper Canyon are not as well correlated with the pre-dam behavior of the Lees Ferry gaging station (table 6) due to its location above the Paria and Little Colorado rivers. Rather, its bed elevation changes are more closely related to storage changes in Reach 2 (fig. 11) lying just above the gaging station. Equations 1 and 2 cannot be used to predict the post-dam behavior of this station, because of its location above the Paria and Little Colorado rivers and the negligible sediment contribution from ungaged tributaries between the gaging station and the dam.

Within the Upper Canyon, the basic pattern of storage changes in response to discharge and sediment input variations is essentially the same for the range of possible values for M discussed above. In figure 10, monthly values of discharges, change in sediment storage, and bed elevations of the Grand Canyon and Lees Ferry gaging stations have been averaged over the pre-dam decade from 1948–1957 to show seasonal patterns of storage changes and scour and fill behavior. Figure 11 summarizes yearly variations in peak discharge, average bed elevations, and estimated changes in sediment storage over the years of record from 1922–1970 (storage changes could only be estimated for the period from 1948–1970, years for which suspended sediment measurements were taken on the Little Colorado and Paria rivers).

During the unregulated years from 1948–1957 and the years marginally affected by dam construction (1958–1962), the large March–June flood peaks eroded much bed and bank sand from the Upper Canyon, resulting in large net sediment removal or negative storage (fig. 10). The flood peak net storage loss averaged above 10.3×10^6 metric tons/yr during the years 1948–1957 with a peak value of 22.6×10^6 in 1957, corresponding to values of bed scour throughout the Upper Canyon of approximately 0.7 and 1.5 m respectively (see discussion below). On the average this loss of sediment was made up by input from desert tributaries, including the Paria and Little Colorado rivers, during the rest of the year, particularly during the summer thunderstorm season from July through September (fig. 10). Also adding to

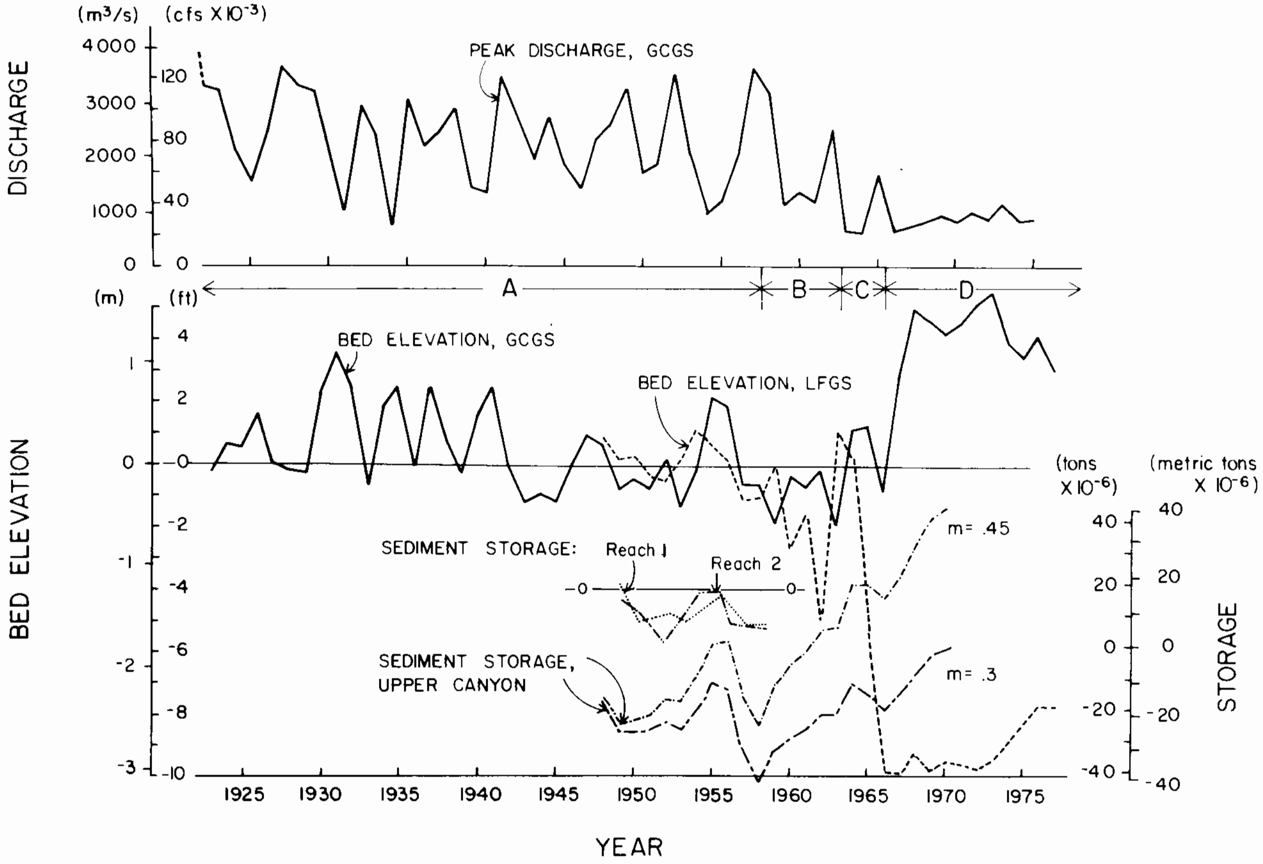

Fig. 11. – Yearly variation in 1) peak discharge, 2) average gaging station bed elevation, and 3) estimated average values of sediment storage for the Upper Canyon section of the Colorado River in the Grand Canyon for the period 1948–1970. Year-end values of sediment storage are shown for two upstream reaches (Reach 1 and Reach 2) with the origin displaced by + 2 tons × 10^{-6}. GCGS = Grand Canyon gaging station; LFGS = Lees Ferry gaging station.

this accumulation was the lower transport capacity at the Grand Canyon gaging station than at the Lees Ferry gaging station during low flow months (fig. 12).

The magnitude of sediment storage or removal accompanying flood-stage runoff is affected by the past history of storage changes. For example, past episodes of pronounced scour lead to lower velocities for a given stage, tending to reduce future scour associated with high discharge and, conversely, encouraging deposition during tributary floods. Thus if two consecutive months have nearly equal flood peaks, the first removes much more sediment from the Upper Canyon than does the second. This produces a strong hysteresis during flood peaks with stronger net sediment removal during the rising stage. Conversely, large net scour can occur during a moderate flood peak if substantial sediment accumulation has occurred due to tributary floods since the last major spring flood peak.

Patterns and cause of scour and fill: In this paper we use *scour* and *fill* in a broad sense to refer to any temporal change in mean bed elevation at a cross section over time scales up to several years. *Aggradation* and *erosion* are used for net changes in bed elevation over time scales of a few years or more (i.e., trends superimposed upon scour and fill). Scour and fill may occur as a result of two processes: local redistribution of bed sediment and net storage changes through long segments of the river. The former will be termed "local" processes, and the latter "general." Recent research, particularly by Colby (1964) and Lane and Borland (1954), suggests that general processes are rare in short-term scour and fill in natural streams due to the large volume changes in sediment storage necessary to produce appreciable bed elevation changes. Thus they suggest that observed scour and fill is due primarily to local causes. The extreme scour and fill behavior of the Colorado River in the Grand Canyon was documented by Leopold and Maddock (1953, p. 33–43), and Leopold et al. (1964, p. 227–241). They suggested that the observed scour and fill is due to changes in bed roughness with stage rather than changes of energy gradient within the reach.

Our study suggests that observed scour and fill behavior in the Colorado River within the Grand Canyon is due to a complex combination of short-term local processes and general processes acting over a longer time scale of weeks, months, or years. The importance of the general processes is documented by the large sediment storage changes in the Upper Canyon which sufficiently account for the year-to-year variations in bed elevation of the magnitude observed at the Grand Canyon and Lees Ferry gaging stations and which correlate closely with these bed elevation changes. Also, the similar patterns of year-to-year sediment storage changes in the three reaches representing several hundred miles of the Colorado River (fig. 11) indicate river-length processes of scour and fill. On the other hand, the importance of local processes is indicated by the opposite reaction of the two gaging stations to the passage of the spring flood peak (the Grand Canyon cross section initially filling, and the Lees Ferry scouring) such that, in the case of the Grand Canyon cross section, the month-by-month fluctuations in bed elevation are nearly opposite to changes that would be expected from net storage changes (fig. 10).

Local scour and fill: Local processes of scour and fill may include one or more of the following mechanisms: 1) Narrow channel sections tend to scour during the rising stages and fill during decreasing stages, with the bed sediment displaced during the rising stage accumulating downstream from the constriction (Colby 1964; Silverston and Laursen 1976; Andrews 1979). The short-term behavior of the Lees Ferry gaging station follows this pattern (fig. 10). Also, 2) the migration of bedforms through gaging station cross section can cause irregular variation of bed elevation (Foley 1978). Although such irregularity may occur, the pattern of changes at both the Grand Canyon and Lees Ferry gaging stations shows a consistent year-to-year pattern (fig. 10). 3) The supercritical control exerted by fixed-bed rapids may cause net scour of pools upstream from the rapids during the high stages, with possible accumulation at the head of the next pool downstream. Silverston and Laursen (1976) propose that this "weir effect" should cause complex, almost unpredictable patterns of scour and fill from one gaging station to another, but also presumably at any single gaging station through time due to routing of supplied and scoured sediment from one pool to another. However, such local routing effects are probably overshadowed by other mechanisms, as indicated by the observed regularity of scour and fill. Finally, 4) increased turbulence generated by rapids during flood stages may scour the pool immediately downstream, with possible concomitant fill further downstream in the same pool if it is sufficiently long. The scouring potential of the rapids is indicated by the numerous sand-floored deep pools found throughout the canyon. During high stages these pools may deepen and elongate, and adjacent channel banks may be eroded where composed of sand and silt. Adding to this effect is the increased energy gradient and bed shear through pools at high stages (Keller 1971; Richards 1976; Lisle 1979).

This latter mechanism has apparently gone unrecognized and seems capable of explaining not only local variations in scour and fill behavior and the observed month-to-month changes in net sediment storage, but also general patterns of scour and fill and the net storage increase that has occurred since the construction of the dam. In its local effect, rapids act much like a local channel constriction, except that the locus of maximum scour is displaced downstream due to the resistant bed in the rapids. The behavior of the Grand Canyon gaging station – filling during rising stages and excavating during falling and low water stages – may be due to its location at the lower end of a long pool below a major rapid. Scour of the pool during rising stages is probably accompanied by temporary fill further downstream at the gaging station where the rapids-generated turbulence has dissipated (fig. 7*A*).

General Scour and Fill: The long term, general process of scour and fill at the Grand Canyon gaging station very closely follows the pattern of estimated sediment storage changes in the Upper Canyon (fig. 11). The Lees Ferry gaging station varied less in bed elevation than the Grand Canyon station prior to 1959, and the pattern of bed elevation changes paralleled more closely storage changes in Reach 2 than those in the Upper Canyon.

Throughout the Upper Canyon from below Lees Ferry the river is characterized by numerous rapids (the 225 miles below Lees Ferry has an average gradient of .0016), whereas the 180 miles upstream, including the Lees Ferry gaging station, have very few rapids and an average gradient (.0003) of 5.3 times less than that within the Grand Canyon. This change in channel type below Lees Ferry affords an explanation for the relatively large magnitude of scour and fill occurring in the Upper Canyon as compared to upstream reaches. Not only are year-to-year storage variations greater in the Upper Canyon than for Reaches 1 or 2, but the upstream reaches are twice as long with greater average channel width than the Upper Canyon, implying a lesser average amplitude of bed scour and fill in the upstream reaches.

The large magnitude of scour during rising and high water stages within the Upper Canyon seems best explained by the increase in turbulence generated within the rapids and the large increase in velocity within the pools between rapids as the flow stage increases. Scour due to turbulence should also persist further downstream within pools during flood discharges. The higher velocity and greater turbulence below rapids during high stages are easily recognized during float trips by the presence of rougher water and stronger eddies.

Turbulence-generated scour is not localized to the few rapids closest to Lees Ferry, but is distributed throughout the canyon. During rising stages, bed material transport falls short of capacity throughout the Grand Canyon, and scour occurs. This tendency for

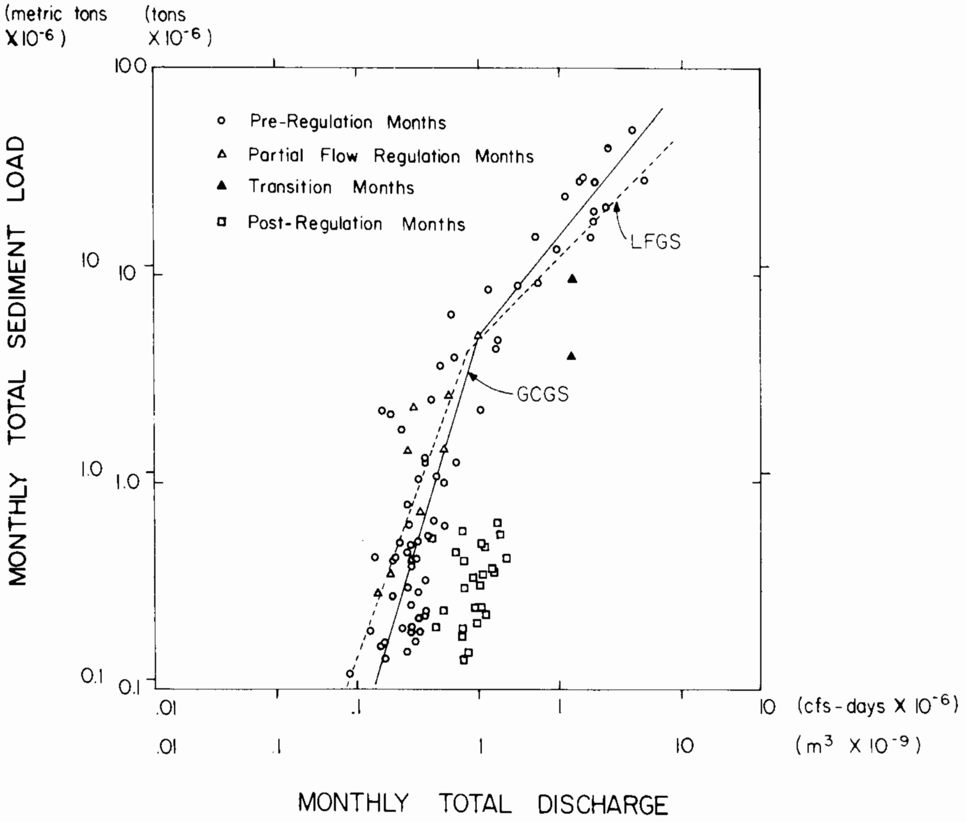

Fig. 12. – Relationship between monthly values of sediment load and discharge for the Grand Canyon (GCGS) gaging station for the period from October, 1947 to October, 1970. Values are shown only for those months when the desert tributaries (Little Colorado and Paria rivers) contributed negligible sediment to the river. The solid line shows a broken regression line fit to the pre-regulation months for the Grand Canyon gaging station. The dashed line is a similar relationship for the Lees Ferry gaging station (data not shown).

net scour during high flows and net deposition during low flows is further attested by comparing suspended sediment transport (monthly values) for the two gaging stations for months without appreciable sediment input from tributaries (fig. 12). The Grand Canyon gaging station data further confirm that the long-term changes in bed elevation at this cross section are representative of bed changes throughout the Upper Canyon.

Effect of Glen Canyon Dam on the Sediment Budget: In general, marked changes in discharge or sediment load result in alterations in channel characteristics such as width, depth, gradient, roughness, and bed elevation. The imposition of a dam on a suspended load, dominantly sand-bed channel in general causes profound changes downstream. At the Yuma, Arizona, gaging station on the Colorado River, 350 miles downstream from Lake Mead, the drastic decrease of sediment coupled with flow regulation caused net bed scour, with accompanying channel narrowing and deepening (Leopold and Maddock 1953, p. 37–39).

The changes in hydraulic regime below a dam are partly offsetting; the drastic reduction in bed-material load (tending to cause net scour) is opposed by the effect of flow regulation which, by eliminating flood peaks, reduces transport capacity. Overall, the former exceeds the latter, leading to net scour. The same process should have occurred in the Grand Canyon.

At the Grand Canyon gaging station the dam caused a reduction in sediment load by a factor of about 3.9. Further upstream the reduction is greater, reaching about 15 just below the entrance of the Paria River. Predam and post-dam flow duration curves can be used to estimate relative capacity of the pre- and post-dam flows if it is assumed that total load capacity is proportional to the 1.8 to 2.0 power of the discharge, and that changes in channel width and gradient within the pools have been negligible. A reduction of transport capacity by a factor of about 1.7 and 2.1 would be predicted.

Such considerations led Dolan et al. (1974) and Laursen et al. (1976) to predict net scour of sand below the dam throughout the Grand Canyon. Indeed, at the Lees Ferry gaging station and other cross sections in the 15 miles between this station and the dam, scour has been dramatic to the extent that coarse bed armoring has developed (Pemberton 1976). However, the bed armoring ceases below the entrance of the Paria River 15 miles below the dam. Contrary to the above prediction, the bed elevation of the Grand Canyon gaging station has *increased*, and sediment budgeting strongly suggests a net storage increase throughout the Upper Canyon since the beginning of flow regulation in 1965 (fig. 11).

The final peak discharge at 1800 m^3/sec in 1965 prior to closure of the diversion tunnels caused a large net scour throughout the Upper Canyon. From that time until cessation of suspended sediment recording in 1970 there was net storage corresponding to an estimated average bed aggradation within the Upper Canyon of 1.8 to 2.6 m, for estimated values of the factor M, between 0.3 and 0.45, respectively. Correspondingly, average bed elevations at the Grand Canyon gaging station increased by about 1.9 m from the end of 1965 to the end of 1970 (fig. 11), reaching a record gage height for the period of measurement starting in 1922. Approximately 0.6 to 0.7 m of this aggradation may have been due to a stage rise of the same magnitude as that at the gaging station due to the debris accumulation at the tributary fan of Bright Angel Creek, which was subjected to a major flash flood in December, 1966 (Cooley et al. 1977).

Although post-dam aggradation within the Upper Canyon runs counter to the predictions using straightforward application of bed material transport formulas, the aggradational behavior does follow pre-dam patterns. The post-dam flow regime is similar to pre-dam, low-water discharges, during which aggradation occurred due to sediment supplied by tributary floods. Thus, due to the lack of flushing action of turbulence generated by pre-dam flood peaks, sand has accumulated rather than scoured, except very close to the dam. The failure of total load transport equations to predict the observed post-dam deposition of fine sediment within the Upper Canyon appears to be due in part to the assumption of a constant energy gradient (which, in reality, should increase with stage in the pools) and in part to the reduction in rapids-generated turbulence with lowered stage.

Because of the lack of sediment records after 1970, long-term trends in sediment storage cannot be monitored. Bed elevation changes at the two gaging stations have been relatively small since 1968, but have been opposite in trend to the large immediate post-dam changes (fig. 11). At Lees Ferry, the initially strong degradation (about 3.4 m) has been followed by a slight recovery (about 0.7 m), and the bed is now about $\frac{1}{3}$ covered by slowly-migrating sand dunes (W. B. Garrett personal comm.). The source of this sand may be continued erosion of pre-dam terraces, but the present sand bed suggests that the complete scouring of these terraces (at least to an immobile pavement) may take many years, even immediately below the dam. Also, the post-dam scour has apparently reduced the bed elevation to the extent that sand transport rates are very low, particularly in sections just upstream from fixed control points at rapids. The recent degradational trend at the Grand Canyon gaging station of 0.4 m since 1968 may be due to more frequent peak releases from Lake Powell in the last few years, coupled with occasional winter flooding of the below-dam tributaries.

Part of the net sediment accumulation within the Upper Canyon may not be on the bed, but may have been deposited on low overbank terraces during occasional peak flows or by eolian deflation of sand exposed on the beaches during the diurnal low water (Dolan et al. 1974). In addition, buildup of some of the tributary fans due to addition of debris during flash floods may have caused local aggradation due to the backwater effects. Howard and Dolan (1979) estimate that 25% of the fans have had sufficient tributary deposition to noticeably narrow the main stem. However, given the magnitude of post-dam sediment storage, it seems unlikely that any or all of these alternative depositional sites can account for much of the post-dam storage. General channel aggradation must also have occurred.

One set of data seemingly contradicts the conclusion of net post-dam aggradation in the Upper Canyon. If, in fact, the post-dam bed were higher than normal pre-dam levels for a given discharge, the sediment transport rate should be higher, at least during those times when desert tributaries were not directly contributing fine-grain suspended sediment or wash load. However, quite the opposite is true. For a given overall monthly discharge, the sediment yield of the Grand Canyon gaging station has *decreased* by a factor of about 13 since the last high discharges of 1965 (see fig. 12). A similar decrease is also apparent in the daily discharge sediment-load relationship. In addition, there did not seem to be any trend towards increasing sediment discharges at the Grand Canyon gaging station during the period from 1966–1970 when channel beds were apparently aggrading in the Upper Canyon. Several possible reasons for the low post-dam sediment yields may be advanced. 1) The average grain size of the bed and banks has increased, reducing sediment yields. Limited bed sampling at the Lees Ferry and Grand Canyon gaging stations suggests a post-dam increase in average grain size of the bed by a factor of 1.6. 2) Due to the rather limited range of post-dam discharges, the channel bed may have been remolded by selective scour until it minimized sediment yields for the post-dam discharge range. During the widely varying range of pre-dam discharges, the constant reshaping of the bed at different discharges might never have permitted this equilibrium. 3) Low-water, pre-dam discharges of the Colorado River within the range of post-dam discharges included large amounts of very fine sediment derived from reworking of bed and bank deposits.

Three additional factors may also be involved, but are probably less important. 1) Some of the apparent post-dam storage of sediment has gone into overbank deposition or deposition behind aggraded rapids. 2) Post-dam sediment discharges at the Grand Canyon gaging station may have been underestimated, due to the daily fluctuation in discharge and the limited sampling (usually once a day). 3) Net channel widening due to post-dam scour of beach deposits has reduced velocities for a given discharge.

In conclusion, our studies indicate that the sand bed of the Colorado River in the Grand Canyon under the natural regime was subject to seasonal cycles of general scour and fill exceeding 1 m along the entire canyon. In pools below rapids and in narrows, local scour and fill may be several times the average. Severe floods (a peak flow in 1884 may have exceeded 8500 m^3/sec) may scour to much greater depths, as evidenced by a sawn board buried by 15 m of sand and gravel at the Hoover Dam site (Bureau of Reclamation 1950). The uppermost 2 to 6 m of sandy alluvium on the bed (Bureau of Reclamation 1950, 1970; Pemberton 1976) is probably reworked by the frequent spring floods in the range of 2500 to 3400 m^3/sec, whereas the underlying 4 to 40 m of gravelly sands probably are moved by the more intense floods that also rework the cobble bars (fig. 7*A*).

Greatly reduced flood peaks since completion of Glen Canyon Dam have decreased the turbulence generated by rapids and hence transport capacity to the extent that an average of more than 1.5 m of sand has accumulated on the bed of the Upper Canyon.

DISCUSSION AND CONCLUSIONS: TIME SCALES AND CONSTRAINTS ON EQUILIBRIUM

All rivers share the tendency toward balancing of input and output of sediment through self-adjustment of their morphology, a tendency described as "quasi-equilibrium" by Leopold (1969, p. 236). Any discussion of fluvial equilibrium must therefore include the definition of the elements to be examined for equilibrium (for example, supply and removal of sediment of a particular size range), the characteristic time scales of adjustment (rates of transport and comminution), the past history of system input (supply of sediment), and the constraints affecting the system response (fluvial morphology). Of these the characterization of system structure and operation (the constraints) seems least discussed within the context of equilibrium, yet these constraints are among the most obvious aspects in the balance of sediment flow through a canyon and the resultant fluvial morphology.

The major constraint on fluvial transport, both directly and indirectly, is structural control. As noted previously, in the Grand Canyon the extent of these constraints varies from the severely restricted channel width and alluvial fan development in Granite Gorge to minimal effect in the broad valley in the Upper Canyon. Where the channel is narrow, transport competency is enhanced relative to unconfined channels. Indirectly, structural control by canyon walls is important in providing the sources of alluvial fan debris.

Sediment transport through the Grand Canyon involves complex interactions between the grain sizes in transport, each with its characteristic time scale of supply and removal. The transport and deposit of each grain size form constraints on the transport of other size ranges of sediment.

Because most of the drop in the river occurs in rapids where debris is contributed by tributaries and rockfalls, the overall river gradient is primarily determined by the balance between addition and removal of coarse debris (fig. 7*B*). The rate of addition depends upon the size, quantity, and location of the supplied debris, together with the frequency of tributary flooding or rockfall. The rate of removal depends upon the in situ comminution of the boulders to a transportable size by abrasion, breakage, and chemical weathering. This equilibrium is statistical rather than exact, for both addition and removal of alluvial fan debris occurs sporadically during floods. The characteristic time scale of this balance of addition and removal must be on the order of a thousand years or more. The most distinguishing feature of the equilibrium of fan debris is that the balance is not between sediment input and its unmodified transport out of the system, as in the case of fine sediment, but rather between input and weathering or erosion to a finer grain size.

The morphological context of the debris-fan rapids along with the structurally controlled channel width constitute the major constraints upon transport and deposition of cobbles. The cobble bars, reworked primarily during major floods, have an intermediate time scale of adjustment, probably measured in hundreds of years. Both comminution and downstream transport are involved in the balance of removal of gravel, and additions are derived both from upstream and locally from tributary floods, rockfalls, and comminution of fan debris. The fans, bars, and channel width constraints, in turn, provide the morphological framework for transport and deposition of fine sediment.

Despite the large seasonal epicycles of scour and fill, the Lees Ferry and Grand Canyon gaging stations maintained essentially constant bed elevations during the period from initiation of measurements in 1922 until after completion of Glen Canyon Dam. This suggests a rough equilibrium of addition and removal of fine sediment from the portions of the bed and banks floored with fine alluvium, with a time scale for establishment of equilibrium measured in a few months.

Leopold (1969, p. 135) has suggested that rivers such as the Colorado River in the Grand Canyon tend to adjust their gradients and other morphological features for transport or supplied sediment with the least work or greatest efficiency. This least-work hypothesis has been successfully applied by several geomorphologists and most directly for sediment transport by Kirkby (1977). However, the existence of morphological constraints may severely limit the efficiency of transport (Chang 1979). The overall channel gradient is dominated by the fall in rapids, so that the river profile is not primarily adjusted for transport of the most abundant size components; that is, sand and finer sizes. By contrast, the former low gradient of the river system upstream from Lees Ferry suggests that section was, in fact, adjusted primarily for sand transport.

Although the detailed suspended sediment records indicate that input and output of sand-size sediment were roughly balanced in the natural river regime, the time scales of adjustment of the tributary fans and the cobble bars is too long to ascertain whether addition and removal have been in balance during past decades, particularly since the influence of Quaternary climatic changes is likely to have had a remnant influence on the rapids' morphology.

The Quaternary morphology of the river is uncertain due to limited alluvial deposits in the narrow canyon. Alluvial fans and attendant rapids may have been either more or less frequent, or possibly both in alternation, because the enhanced scouring potential of the glacial snowmelt may have been balanced by increased physical weathering of the canyon walls. The extent of flash flooding in tributary canyons during pluvial episodes is also uncertain. In some locations sand and gravel deposits extend 200 or more feet beneath present bed levels (Bureau of Reclamation 1950) suggesting that deep scour occurred occasionally during the Quaternary, probably associated with diminished development of tributary fan rapids. Scattered gravel terraces occur along some of the wider portions of the Upper Canyon, and these probably correlated with the extensive development of pluvial gravel terraces of Quaternary and Tertiary age farther upstream along the Colorado River and its tributaries.

The influence of Glen Canyon Dam on the equilibrium of sediment transport and fluvial morphology is occurring over the same range of time scales that is characteristic of the various grain size ranges. The transport of sand and the sandy alluvium have responded most rapidly and most completely to the diminished sediment delivery and diminished flood peaks. The net effects have been moderate, with slight lateral erosion of terraces and apparent net deposition on the bed. The characteristically rapid response of the sandy deposits of the Colorado River to change in supply or discharge suggest that future changes will be slight as long as the pattern of release remains the same. However, there has been a proposal to widen the range of daily variation of releases from the dam in 1990 to enhance peak power generation, with minima near 30 m^3/sec and maxima near 1200 m^3/sec. Under the present pattern, the diminished turbulence has more than compensated for reduced sand supply; however, increased discharges will considerably enhance transport capacity as well as bring additional terrace deposits within the zone of inundation. Appreciable scour can be expected. The wider range of discharge will also greatly enhance drawdown effects on the sedimentary terraces, increasing ground water sapping and possibly creating bank instabilities.

The effect of Glen Canyon Dam upon the tributary alluvial fan rapids has been felt more slowly and sporadically, since rapids in equilibrium with pre-dam discharges are stable under present flows. Debris deposited by post-dam tributary flooding is stable at steeper gradients and with a narrower channel. Our aerial photographic study suggests that about 25% of the alluvial fans along the canyon were noticeably enlarged between 1964 and 1973 (Howard and Dolan 1979), many probably associated with several intense thunderstorms during December, 1966. The same trend of steeper, narrower rapids as well as formation of new rapids will probably continue throughout the lifetime of Glen Canyon Dam. As individual rapids are steepened by tributary flooding, the sand bed will readjust, aggrading above the rapids and scouring below. These long-term, sand-bed adjustments are secondary responses superimposed upon the rapid overall primary response to Glen Canyon Dam (Howard 1965).

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