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Colorado River sediment transport
1. Natural sediment supply limitation and the influence of Glen Canyon Dam

David J. Topping
U.S. Geological Survey, Reston, Virginia

David M. Rubin
U.S. Geological Survey, Menlo Park, California

L. E. Vierra Jr.
Department of Civil and Environmental Engineering, University of Colorado, Boulder

Abstract. Analyses of flow, sediment-transport, bed-topographic, and sedimentologic data suggest that before the closure of Glen Canyon Dam in 1963, the Colorado River in Marble and Grand Canyons was annually supply-limited with respect to fine sediment (i.e., sand and finer material). Furthermore, these analyses suggest that the predam river in Glen Canyon was not supply-limited to the same degree and that the degree of annual supply limitation increased near the head of Marble Canyon. The predam Colorado River in Grand Canyon displays evidence of four effects of supply limitation: (1) seasonal hysteresis in sediment concentration, (2) seasonal hysteresis in sediment grain size coupled to the seasonal hysteresis in sediment concentration, (3) production of inversely graded flood deposits, and (4) development or modification of a lag between the time of a flood peak and the time of either maximum or minimum (depending on reach geometry) bed elevation. Analyses of sediment budgets provide additional support for the interpretation that the predam river was annually supply-limited with respect to fine sediment, but it was not supply-limited with respect to fine sediment during all seasons. In the average predam year, sand would accumulate and be stored in Marble Canyon and upper Grand Canyon for 9 months of the year (from July through March) when flows were dominantly below 200–300 m^3/s; this stored sand was then eroded during April through June when flows were typically higher. After closure of Glen Canyon Dam, because of the large magnitudes of the uncertainties in the sediment budget, no season of substantial sand accumulation is evident. Because most flows in the postdam river exceed 200–300 m^3/s, substantial sand accumulation in the postdam river is unlikely.

1. Introduction

River channels range in type from classical self-formed alluvial channels to bedrock channels. In self-formed alluvial channels the sediment supply is either in equilibrium or exceeds the transport capacity of the channel over long timescales, whereas in bedrock channels, the transport capacity of the channel exceeds the supply of sediment over long timescales. Most rivers fall between these two channel types and may be expected to show some evidence of sediment supply limitation with respect to some portion of the size classes of sediment in transport. The Colorado River in Glen, Marble, and Grand Canyons (Figure 1) is one such river. Though in many places the river bed consists of patches of erodible fine sediment (i.e., sand and finer material) overlying gravel and bedrock, in at least 10 reaches in Marble and Grand Canyons the river flows directly over bedrock (R. Anima, U.S. Geological Survey, personal communication, 1999). Therefore, although the bed of the river is, in many places, easily erodible, the river displays some geomorphic evidence of sediment supply limitation.

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In addition to this geomorphic signature, sediment supply limitation produces four effects found in sediment-transport, sedimentologic, and bed-topographic data: (1) seasonal hysteresis in sediment concentration, (2) seasonal hysteresis in sediment grain size coupled to the seasonal hysteresis in sediment concentration, (3) production of inversely graded flood deposits, and (4) development or modification of a lag between the time of a flood peak and the time of either maximum or minimum (depending on reach geometry) bed elevation. The Colorado River is a good natural laboratory for studying these effects of sediment supply limitation in a fluvial system because of the wealth of available flow and sediment-transport data collected both prior to and after the closure of Glen Canyon Dam in 1963. As in the postdam era [*Rubin et al.*, 1998; *Topping et al.*, this issue], sediment-transport rates in the predam era varied independently of discharge and as a function of the grain sizes of sediment present in the river. Seasonal decreases in the upstream supply of sediment during the annual snowmelt flood have been observed to produce significant hysteresis in suspended-sediment concentration at the Grand Canyon gage [*Leopold and Maddock*, 1953]. Decreases in the predam upstream supply of sediment have been interpreted to cause coarsening of the bed [*Colby*, 1964; *Burkham*, 1986] and scour

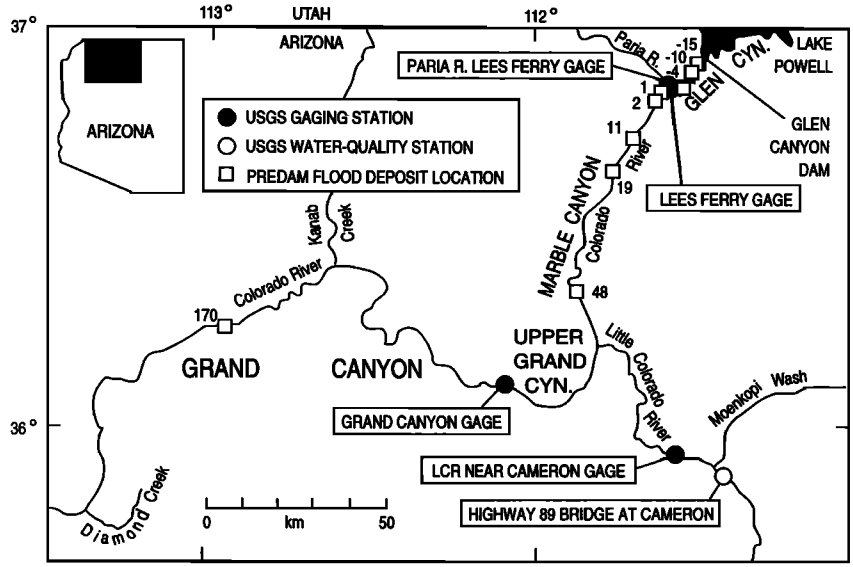


Figure 1. Map of the Grand Canyon region showing the locations where the data presented and analyzed in this paper were collected. Numbers next to the locations of predam flood deposits indicate the river miles of these locations.

of the bed [*Leopold and Maddock*, 1953; *Brooks*, 1958; *Howard and Dolan*, 1981; *Burkham*, 1986]. Furthermore, seasonal decreases in the predam upstream supply of sediment have been interpreted to cause coarsening of the suspended sediment during the annual snowmelt flood, resulting in inversely graded predam flood deposits [*Rubin et al.*, 1998].

Since March 1963, Glen Canyon Dam has regulated flows on the Colorado River and has greatly diminished the supply of sediment in lowermost Glen Canyon and in Marble and Grand Canyons. Growing public concern over perceived degradation of the riverine environment downstream from the dam culminated in the completion of the Glen Canyon Dam Environmental Impact Statement [*U.S. Department of the Interior*, 1995]. A major conclusion of this environmental impact statement was that the dam reduced the sand-transport capacity to a greater degree than it reduced the supply of sand, thus transforming a naturally net degradational system into one in which sand may accumulate over time. This conclusion was reached by applying concepts developed in the framework of classical alluvial channels with ample supplies of sediment and without a detailed investigation of the flow and sediment-transport processes that operated in the potentially supply-limited predam bedrock-canyon river.

The goals of this investigation are to determine the degree to which the predam Colorado River in Glen, Marble, and Grand Canyons was supply-limited with respect to fine sediment (i.e., sand and finer material) and to quantify the major downstream sediment-related impacts of Glen Canyon Dam. In this paper we pursue these goals by first determining the degree to which the predam Colorado River displayed evidence of the four effects of sediment supply limitation. Then, we construct and analyze a sediment budget to determine if the predam and early postdam river in Marble Canyon and upper Grand Canyon met the integral constraint of supply limitation, that is, to see if, and over what timescale, the river exported the fine sediment supplied to it.

The work we present in this paper draws heavily on both analyses of historical flow and sediment-transport data collected by the U.S. Geological Survey (USGS) on both the Colorado River and its major tributaries and also on fieldwork that we have conducted in the postdam river. Our study reach extends from Glen Canyon Dam to the Grand Canyon gage (Figure 1). For the purposes of this paper, Glen Canyon lies upstream from Lees Ferry, Marble Canyon extends from river mile 0 at Lees Ferry to river mile 61.5 at the mouth of the Little Colorado River, and upper Grand Canyon extends from the mouth of the Little Colorado River to the Grand Canyon gage at river mile 87.4. We present and analyze historical flow and sediment-transport data that were collected by the USGS at five sites (four stream gages and one water-quality station). These sites are the Colorado River at Lees Ferry, Arizona (station number 09380000), herein referred to as the "Lees Ferry gage"; the Colorado River near Grand Canyon, Arizona (station number 09402500), herein referred to as the "Grand Canyon gage"; the Paria River at Lees Ferry, Arizona (station number 09382000), herein referred to as the "Paria River Lees Ferry gage"; the Little Colorado River near Cameron, Arizona (station number 09402000), herein referred to as the "LCR near Cameron gage"; and the Little Colorado River at Cameron, Arizona (station number 09401200), herein referred to as the "highway 89 bridge at Cameron."

2. Definition of Sediment Supply Limitation

A complete definition of sediment supply limitation in a fluvial system requires: (1) precise specification of the grain sizes for which the system is supply-limited and (2) the timescale over which the system is supply-limited for these grain sizes. In this sense a reach of a river will be supply-limited with respect to a certain sediment grain size over a chosen timescale if, over that timescale, the river has the capacity to transport more of that size class of sediment than is supplied to it. According to this definition most rivers are expected to exhibit some degree of supply limitation. A second implication of this definition is that sediment supply limitation does not require

that a river be erosional; net deposition of coarser sizes may occur even if a river is supply-limited with respect to finer sizes.

3. Hypothesized Effects of Sediment Supply Limitation

In a reach that is supply-limited with respect to a specified size class of sediment over a given timescale, four coupled effects are hypothesized to result. First, within the timescale over which the reach is supply-limited, hysteresis in transport rates of the specified size class will result [e.g., *Nanson*, 1974; *Dunne and Leopold*, 1978; *Moog and Whiting*, 1998]. Following sediment-supplying events to the reach, transport rates of sediment in the supply-limited size class will initially increase independently of discharge, then subsequently decrease as that size class becomes depleted. As a result of the same process, transport rates of the supply-limited size class will be higher on the rising limb than on the receding limb of a flood.

The interplay between different size classes of sediment in a supply-limited reach leads to the second effect of sediment supply limitation. Sediment input to a supply-limited reach will travel downstream as an elongating "sediment wave," with the finest sizes (because of their lower settling velocities) traveling the fastest. This sediment wave will have a component in the bed, the bed load, and the suspended load. As the front of a sediment wave passes a given location, the sediment-transport rate will first increase as the grain size in the reach fines, then subsequently decrease as the grain size in the reach coarsens [*Topping et al.*, this issue]. Thus, associated with the hysteresis in sediment-transport rates described above, hysteresis will also exist in sediment grain size during a flood passing through a supply-limited reach. The grain size of sediment in transport on the rising limb will be finer than that on the receding limb of the flood. Furthermore, by virtue of the physical linkage between particle settling velocity and suspended-sediment-transport rate [e.g., *Rouse*, 1937; *Hunt*, 1969; *Smith*, 1977; *McLean*, 1992], in the same flow conditions the transport rate of finer sediment will be greater than that of coarser sediment. Therefore, following a discrete sediment-supplying event, the timescale over which a reach becomes supply-limited with respect to a finite amount of finer sediment is shorter than that over which it becomes supply-limited with respect to an equivalent amount of coarser sediment.

The third hypothesized effect of sediment supply limitation follows directly from the second effect. Because the grain size of sediment in suspension will coarsen over time during floods passing through a supply-limited reach, the sediment available for deposition on floodplains, on channel margins, or in eddies will coarsen through time. Thus deposits produced during floods passing through a supply-limited reach will coarsen upward [*Iseya*, 1989; *Rubin et al.*, 1998].

The fourth hypothesized effect of sediment supply limitation has to do with the temporal patterns of scour and fill of the bed during floods passing through a supply-limited reach [*Topping et al.*, this issue]. If the upstream supply of sediment decreases during a flood, a lag may develop or be modified between the time of the flood peak and the time of either maximum or minimum bed elevation. At a cross section where convergence occurs in the boundary shear stress field with increasing flow, the time of maximum bed elevation in a supply-limited case will occur prior to that in a non–supply-limited case. Thus, at this type of cross section, an observation of maximum bed elevation leading a flood peak, with scour beginning prior to the flood peak, indicates the presence of sediment supply limitation. At a cross section where divergence occurs in the boundary shear stress field with increasing flow, the time of minimum bed elevation in a supply-limited case will occur after that in a non–supply-limited case. However, because, at this second type of cross section, minimum bed elevation lags the flood peak in both the supply-limited and non–supply-limited cases, an observation of minimum bed elevation lagging a flood peak may suggest, but does not require, the presence of sediment supply limitation. Therefore, as with the previously described hysteresis in sediment-transport rate and grain size, hysteresis may also exist in bed elevation at a cross section during floods, and, depending on reach geometry, the presence of this hysteresis can be used to deduce the presence of sediment supply limitation.

4. Systematic Seasonal Changes in Sediment Concentration, Grain Size, and Bed Elevation: Evidence for Predam Annual Fine-Sediment Supply Limitation in Grand Canyon

4.1. Coupled Hysteresis in Suspended-Sediment Concentration, Grain Size, and Bed Elevation

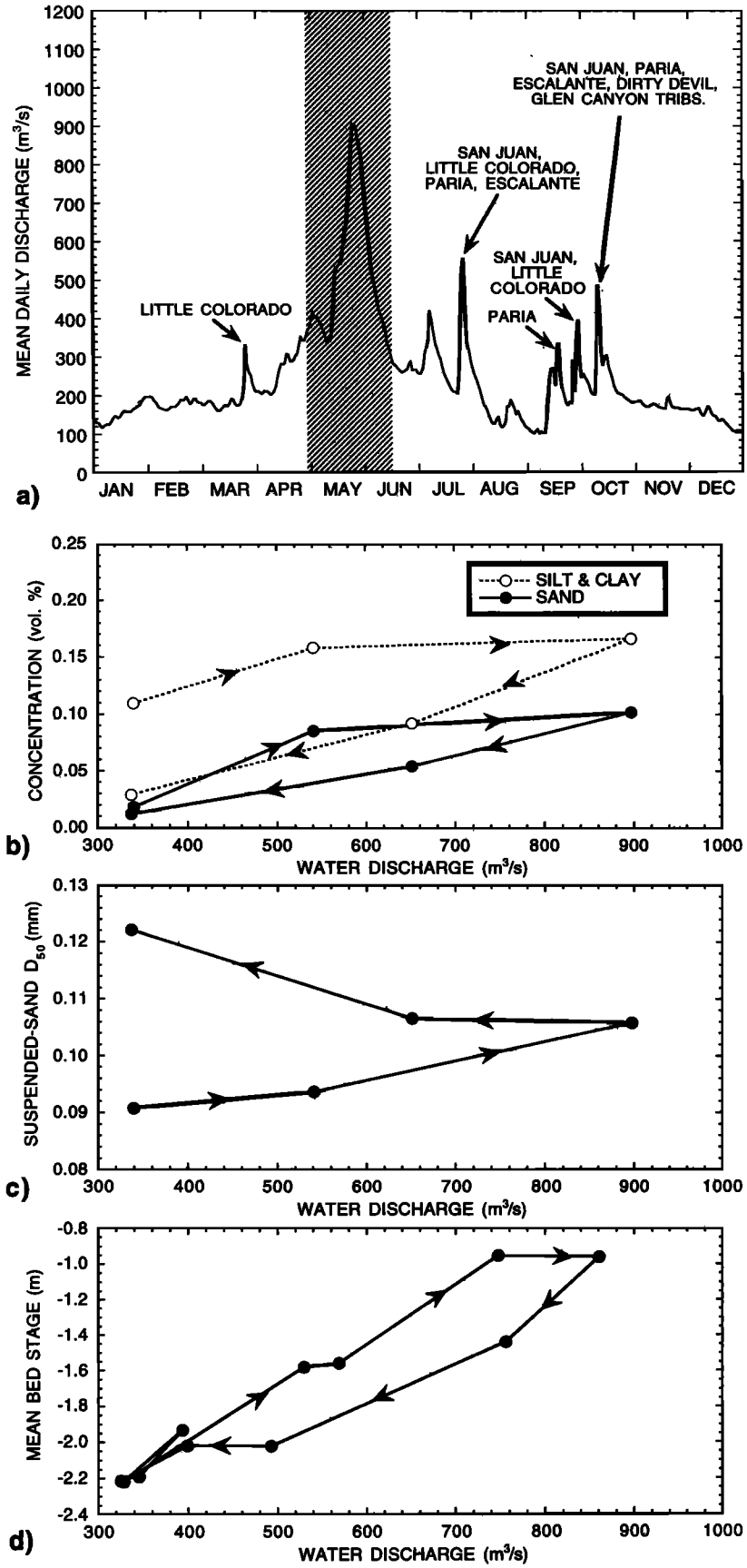
Calendar year 1954 provides a good example of the behavior of suspended-sediment concentration, suspended-sediment grain size, and bed elevation during an annual predam flood cycle. The peak discharge of the 1954 snowmelt flood was below average, and the duration was shorter than average, extending only from mid-April to mid-June (Figure 2a). Because of this shorter than normal duration, little overlap existed between the snowmelt flood and the onset of tributary sediment-supplying floods during the summer thunderstorm season. Thus 1954 provides a clear example of the response of the river to changes in the upstream supply of sediment during the annual snowmelt flood, without any of the complications due to resupply of sediment to the river during the subsequent summer thunderstorm season. As the upstream supply of sediment decreased during the 1954 snowmelt flood (Figure 2b), the suspended sand coarsened (Figure 2c) and the bed began to scour (Figure 2d). Also, note that in 1954 the maximum bed elevation led the flood peak by about a week.

4.2. Vertical Grain-Size Trends in Predam Flood Deposits in Marble and Grand Canyons

Sediment deposited in eddies in the Colorado River provides an accurate record of changes in suspended-sediment grain size during floods [*Rubin et al.*, 1998; *Topping et al.*, 1999, this issue]. To determine trends in grain size recorded in predam flood deposits, we sampled predam flood deposits vertically for grain size at six sites in Marble and Grand Canyons during 1997 and 1998 (Figure 1). As we found in deposits of the 1996 flood experiment [*Rubin et al.*, 1998; *Topping et al.*, 1999] and the 1997 test flow [*Topping et al.*, this issue], the predam flood deposits in the majority of Marble Canyon (i.e., below river mile 2) and Grand Canyon coarsened upward. This coarsening occurred both by a decrease in the percentage of silt and clay and also by coarsening of the sand (Figure 3). The deposit at river mile 1 (at the head of Marble Canyon) did not coarsen upward, however. In this deposit the silt and clay content increased, and the sand fined upward.

4.3. Discussion

All four of the hypothesized effects of sediment supply limitation occurred in the predam Colorado River in Grand Can-


MEAN DAILY DISCHARGE (m³/s)
LITTLE COLORADO
SAN JUAN, LITTLE COLORADO, PARIA, ESCALANTE
SAN JUAN, PARIA, ESCALANTE, DIRTY DEVIL, GLEN CANYON TRIBS.
SAN JUAN, LITTLE COLORADO
PARIA
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
a)
CONCENTRATION (vol. %)
SILT & CLAY
SAND
WATER DISCHARGE (m³/s)
b)
SUSPENDED-SAND D50 (mm)
WATER DISCHARGE (m³/s)
c)
MEAN BED STAGE (m)
WATER DISCHARGE (m³/s)
d)

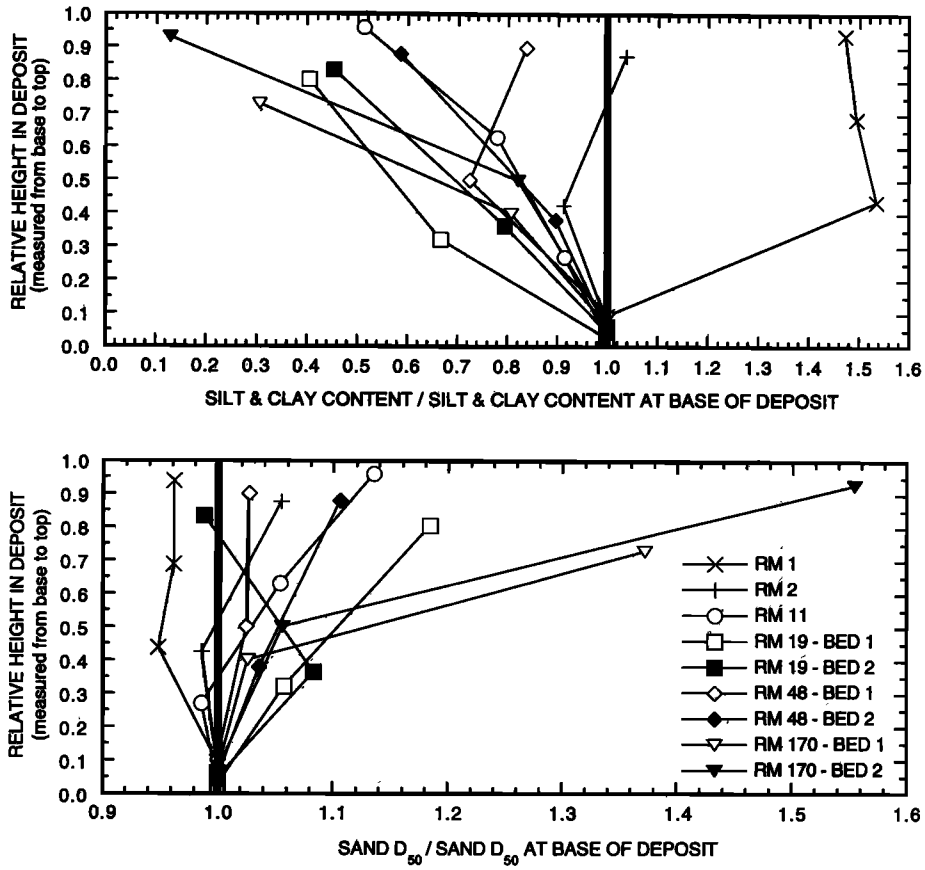


Figure 3. Vertical trends in the silt and clay content and the median size of sand in predam flood deposits in Marble and Grand Canyons. Both the silt and clay content and the median size of sand are normalized by the values measured near the base. The beds coarsened upward in probable response to depletion of the finer sediment during floods. "RM" stands for river mile.

yon. The style of coupled hysteresis in suspended-sediment concentration, suspended-sediment grain size, and bed elevation documented during the 1954 snowmelt flood suggests that the predam river was supply-limited with respect to fine sediment (i.e., sand and finer material). The fact that this behavior was observed during the annual flood suggests that the timescale over which this supply limitation occurred was a year or less. Furthermore, the observation that predam flood deposits coarsen upward in the majority of Marble and Grand Canyons, suggesting a depletion of fines during floods, lends further support to this supply-limited interpretation.

Figure 2. (Opposite) (a) The 1954 mean-daily discharge record from the Grand Canyon gage showing the seasonal separation between tributary sediment-input events and the annual snowmelt flood. Tributary rivers that contributed to the observed discharge peaks are indicated. Cross-hatched region indicates the period from April 28, 1954, through June 14, 1954, during which the data shown in Figures 2b–2d were collected. (b) Hysteresis in the concentration of suspended silt and clay and suspended sand; arrows indicate the sequence of measurements. Progressive depletion of the finer sediment caused the concentrations (for a given discharge) to be lower on the receding limb than on the rising limb. (c) Hysteresis in the median grain size of the suspended sand. The suspended sand was coarser (for a given discharge) on the receding limb than on the rising limb. (d) Hysteresis in mean bed elevation. Stage is relative to gage datum.

5. Evidence for Predam Differences in the Degree of Sediment Supply Limitation in Grand and Glen Canyons

The hydraulic geometry of the predam Colorado River in Marble and Grand Canyons was very different from that in Glen Canyon. Though the mean depths of the predam river in Glen, Marble, and Grand Canyons were comparable, the river was generally narrower (by about a factor of 1.5–2) and steeper (by a factor of 3–5) in Marble and Grand Canyons than it was in Glen Canyon. Because of this difference in hydraulic geometry, the reach-averaged boundary shear stress, and hence the transport capacity for a given supply of sediment, would probably have been lower in Glen Canyon. Predam USGS sediment records collected at the Lees Ferry and Grand Canyon gages indicate that most of the sediment that passed the Grand Canyon gage first passed through Glen Canyon. Therefore, though the predam river in Marble and Grand Canyons was probably annually supply-limited with respect to fine sediment by virtue of the difference in hydraulic geometry, the river in Glen Canyon may not have been. *Howard and Dolan* [1981] first suggested that because of the differences in hydraulic geometry, bed elevation in the predam river in Marble and

Grand Canyons was more sensitive to annual changes in the sediment supply than was bed elevation in the predam river in Glen Canyon. To determine the potential differences in the degree of sediment supply limitation in Marble and Grand Canyons versus Glen Canyon, we examined: (1) the differences in coupled hysteresis in suspended-sediment concentration, grain size, and bed elevation at the Grand Canyon and Lees Ferry gages and (2) the differences in vertical trends in grain size in predam flood deposits in Glen, Marble, and Grand Canyons.

5.1. Differences in Annual Hysteresis in Sediment Concentration and Grain Size

Because the groundwater and surface-water input to the Colorado River between the Lees Ferry and Grand Canyon gages is typically small, the downstream increase in flow between these gages is minimal. Indeed, the long-term average increase in discharge between the Lees Ferry and Grand Canyon gages based on data from water years 1923–1962 was only 13 m^3/s (i.e., an increase of only 3% over the mean-daily discharge at Lees Ferry during this period). Because the downstream increase in discharge is slight, suspended-sediment concentration as a function of discharge at the two gages can be compared without correcting for downstream changes in flow.

In the predam era the magnitude of annual hysteresis in suspended-silt and clay concentration was comparable at each gage (Figure 4a), but the magnitude of annual hysteresis in suspended-sand concentration was much greater at the Grand Canyon gage (Figure 4b). At the Grand Canyon gage, suspended-sand concentrations were much lower during the period from June 1 through July 20 (i.e., the last portion of the rising limb and most of the receding limb of the typical snowmelt flood) than those measured in similar flows during the rest of the year. This systematic annual variation in suspended-sand concentration at this site arose because the first portion of the snowmelt flood reduced the supply of the finer (i.e., 0.0625–0.25 mm) sand (Figures 4c and 4d). Thus the annual hysteresis in suspended-sand concentration at the Grand Canyon gage was coupled to an annual hysteresis in grain size, with the suspended sand sampled from June 1 through July 20 typically being coarser than that sampled during the rest of the year. In contrast, at the Lees Ferry gage, relatively little annual hysteresis in concentration or grain size existed for either the finer or the coarser sand (Figures 4b, 4c, and 4d).

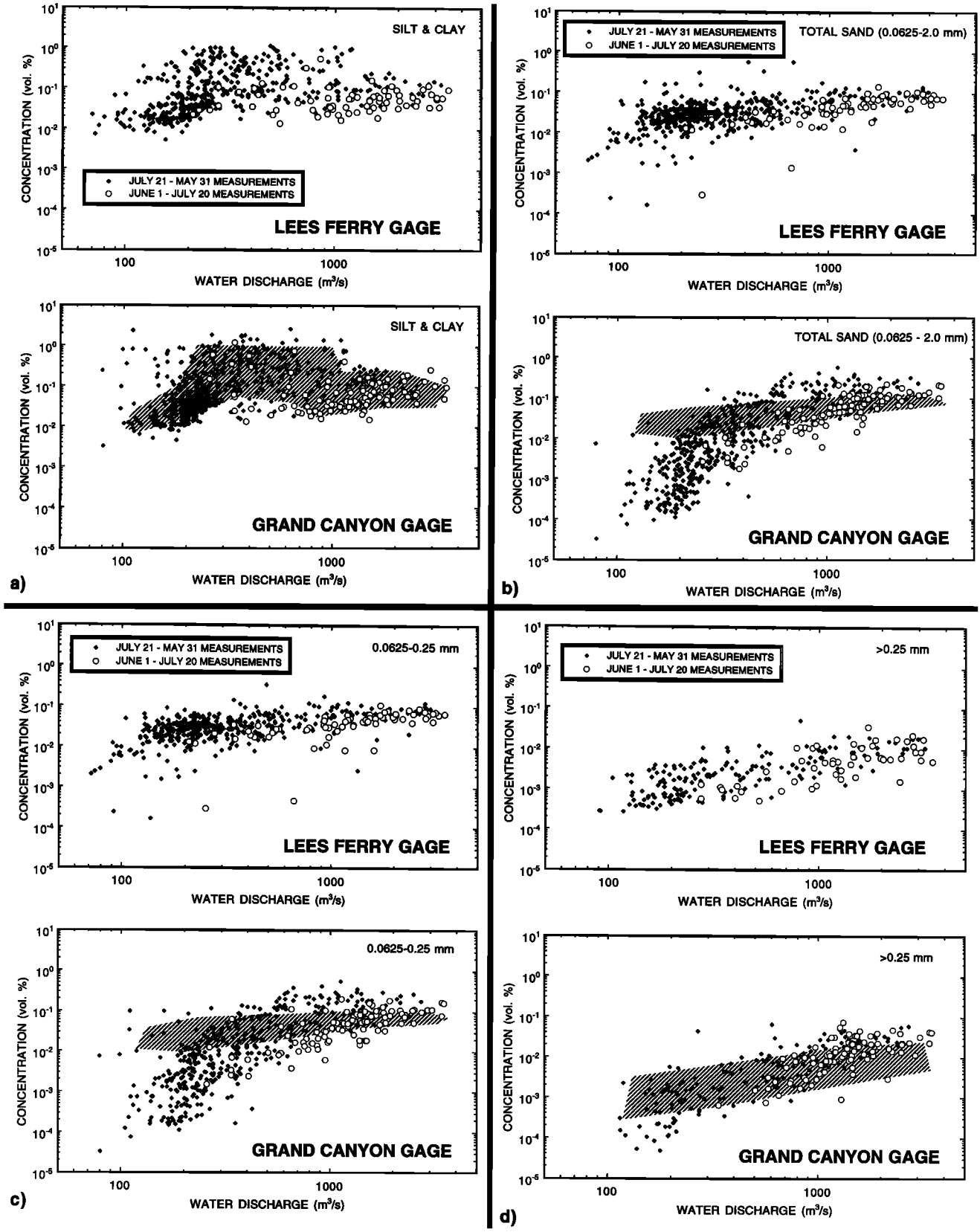
In addition to the difference between the magnitudes of the annual hysteresis in suspended-sand concentration a flow-dependent difference also existed between the sand-transport rates at the Grand Canyon and Lees Ferry gages. On average, in the predam river, more silt and clay were in suspension than sand, but flow-dependent differences in sand-transport rates were large enough to dominate the total fine-sediment (i.e., sand, silt, and clay) data [see *Howard and Dolan*, 1981, Figure 12]. Sand-transport rates were generally higher at the Lees Ferry gage than at the Grand Canyon gage during low flows, whereas the opposite was true during high flows depending on season. In flows below about 200–300 m^3/s, suspended-sand concentrations were substantially higher at the Lees Ferry gage than at the Grand Canyon gage (Figures 4b, 4c, and 4d). In contrast, in flows in excess of about 400–500 m^3/s the opposite was generally true but also depending on both grain size and season (Figures 4c and 4d). At these higher flows and occurring independently of season, the concentration of suspended coarser (i.e., >0.25 mm) sand was typically higher at the Grand Canyon gage than at the Lees Ferry gage. For finer sand, however, sand-transport rates at the two gages generally differed only during the initial portion of the annual snowmelt flood (i.e., when flows first exceeded about 400–500 m^3/s). During this initial period of higher flows, concentrations of suspended finer (0.0625–0.25 mm) sand were substantially higher at the Grand Canyon gage. Then, in similar high flows during the latter part of the snowmelt flood (i.e., after about June 1), concentrations of suspended finer sand at the Grand Canyon gage decreased to become comparable to those at the Lees Ferry gage.

5.2. Discussion of Differences in Annual Hysteresis in Sediment Concentration and Grain Size

The difference between the magnitudes of coupled annual hysteresis in suspended-sand concentration and grain size between the Grand Canyon and Lees Ferry gages suggests that the predam Colorado River in Grand Canyon was annually supply-limited with respect to sand to a far greater degree than it was in Glen Canyon. Though annual hysteresis existed in the concentration of silt and clay at both gages, it was of the same magnitude, suggesting that the degree of annual supply limitation with respect to silt and clay was similar in both Grand and Glen Canyons. Because substantial annual hysteresis in suspended-sand concentration existed in the finer (0.0625–0.25 mm) sand at the Grand Canyon gage, the river in Grand Canyon was probably supply-limited with respect to this size class of sand on an annual timescale. This represented an annual supply limitation with respect to 80–90% of the sizes of sand in transport (based on the data presented in Figure 4). Because little annual hysteresis existed in the concentration of coarser (>0.25 mm) sand at the Grand Canyon gage, the river in Grand Canyon was either not annually supply-limited with respect to this size class of sand, or it was supply limited with respect to this size class of sand on a timescale that was longer than either (1) the period between sediment-resupplying events to Marble Canyon and upper Grand Canyon or (2) the length of time required to transport sand coarser than 0.25 mm out of Marble Canyon and upper Grand Canyon.

The difference in sand-transport rates between the Grand

Figure 4. (Opposite) Predam sediment concentrations as a function of water discharge at the Lees Ferry and Grand Canyon gages shown at the same scale. Cross-hatched region overlaying the Grand Canyon gage data in Figure 4 indicates the region in concentration-discharge space occupied by the Lees Ferry data. Silt and clay concentrations were generally uniform at both gages, indicating no demonstrable storage of silt and clay in Marble Canyon and the upper Grand Canyon. At low flows, sand concentrations at the Lees Ferry gage were higher than at Grand Canyon gage, indicating sand accumulation in Marble Canyon and upper Grand Canyon. At high flows the stored sand was eroded from this reach, as reflected by the initially higher sand concentrations at the Grand Canyon gage. Sources of data are as follows: at the Grand Canyon gage, the 620 suspended-sediment samples collected (with modern sampling equipment) from June 6, 1944, through December 19, 1962, and analyzed for grain size, and at the Lees Ferry gage, the 504 suspended-sediment samples collected from July 21, 1949, through December 19, 1962, and analyzed for grain size. (a) Suspended-silt and clay concentrations at the two gages. (b) Suspended-sand concentrations at the two gages. (c) Concentrations of suspended finer (0.0625–0.25 mm) sand at the two gages. (d) Concentrations of suspended coarser (>0.25 mm) sand at the two gages.


SILT & CLAY
JULY 21 - MAY 31 MEASUREMENTS
JUNE 1 - JULY 20 MEASUREMENTS
LEES FERRY GAGE
GRAND CANYON GAGE
CONCENTRATION (vol. %)
WATER DISCHARGE (m³/s)
a)
TOTAL SAND (0.0625-2.0 mm)
TOTAL SAND (0.0625 - 2.0 mm)
b)
0.0625-0.25 mm
c)
>0.25 mm
d)

Canyon and Lees Ferry gages suggests that though the river in Grand Canyon may have been annually supply-limited with respect to finer (0.0625–0.25 mm) sand, it was not supply-limited with respect to this size class of sand in all seasons. Because the concentrations of both finer (0.0625–0.25 mm) and coarser (>0.25 mm) sand were lower at low flows in Grand Canyon than they were in Glen Canyon, sand did accumulate in Marble and Grand Canyons when flows were sufficiently low. However, the fact that hysteresis in sand concentration and grain size occurred even in years with small snowmelt floods, like 1954 (Figure 2), suggests that the seasonal sand-storage potential was relatively small in Marble Canyon and upper Grand Canyon.

As shown by (1) the higher concentrations of suspended coarser (>0.25 mm) sand during the entire snowmelt flood and (2) the higher concentrations of finer (0.0625–0.25 mm) sand during the initial portion of the snowmelt flood (when flows first exceeded 400–500 m^3/s), the river in Grand Canyon had the capacity to transport more sand than was supplied to it from Glen Canyon. Therefore, as required by conservation of mass, the sand stored in Marble Canyon and upper Grand Canyon would have been depleted at these higher flows until the concentration of suspended sand at the Grand Canyon gage decreased to a value equal to that upstream at the Lees Ferry gage. By virtue of their lower settling velocities the finer sizes of sand would have had higher transport rates. Thus the finer sizes of sand stored in Marble Canyon and upper Grand Canyon would have been depleted more quickly than the coarser sizes during these higher flows. This effect led to the observed decrease in the concentration of finer (0.0625–0.25 mm) sand at the Grand Canyon gage to match the lower upstream supply of this size class of sand at the Lees Ferry gage during the latter portion of the snowmelt flood. Furthermore, this effect led to the lack of any substantial decrease in the concentration of suspended coarser (>0.25 mm) sand at the Grand Canyon gage, even though in flows in excess of about 400–500 m^3/s the upstream supply of this size class of sand was less at the Lees Ferry gage.

5.3. Differences in Coupled Changes in Suspended-Sand Concentration, Suspended-Sand Grain Size, Bed Grain Size, and Bed Elevation

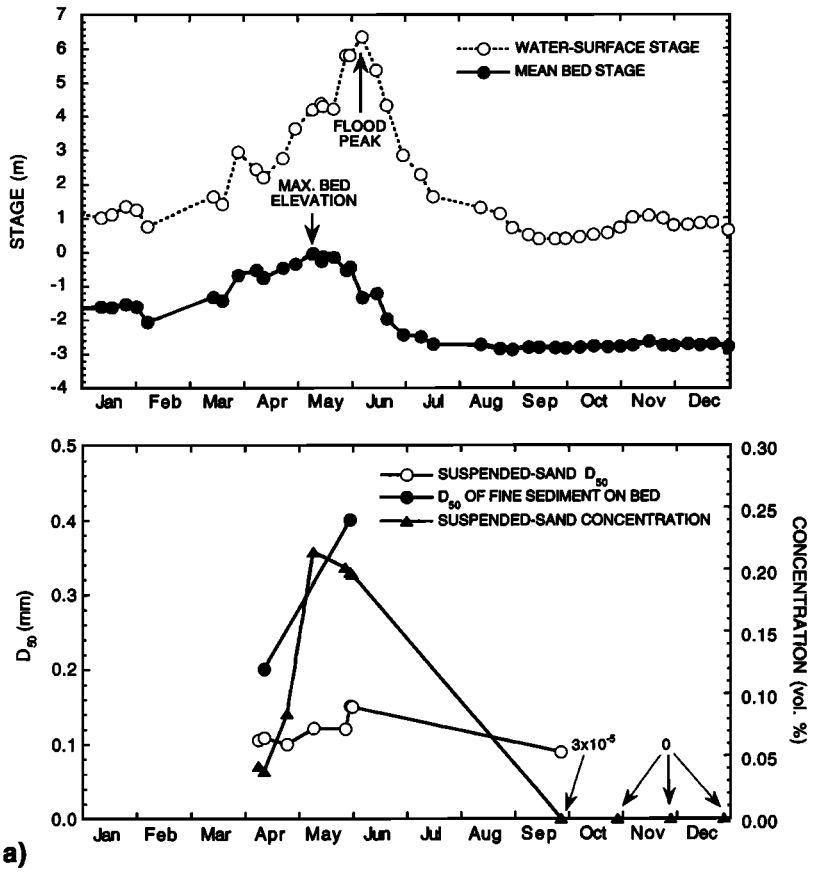
Calendar year 1956 was the only predam year in which suspended-sand concentration, suspended-sand grain size, and bed-sediment grain size were measured at both the Grand Canyon and Lees Ferry gages. Therefore comparison of data collected at these two gages during this year serves to further illustrate some of the predam sediment-related differences between Grand and Glen Canyons. During the 1956 snowmelt flood at the Grand Canyon gage, hysteresis existed in suspended-sand concentration and grain size, with the concentration of suspended sand decreasing and the suspended sand coarsening during the latter part of the rising limb of the flood (Figure 5a). In contrast, no significant hysteresis in either suspended-sand concentration or grain size existed at the Lees Ferry gage, and the suspended-sand grain size increased with concentration such that the maximum sand concentration and grain size occurred together at the peak of the flood (Figure 5b). During the initial part of the rising limb of the 1956 snowmelt flood, the bed at the Grand Canyon cableway aggraded, while the bed at the upper Lees Ferry cableway scoured (Figures 5a and 5b). Maximum bed elevation at the Grand Canyon cableway led the flood peak by about 4 weeks and occurred at about the same time as the maximum suspended-sand concentration. In contrast, at the upper Lees Ferry cableway, minimum bed elevation occurred at about the same time as the flood peak and the maximum suspended-sand concentration. During the rising limb of the 1956 snowmelt flood the fine sediment on the bed at the Grand Canyon cableway coarsened, whereas the fine sediment on the bed at the upper Lees Ferry cableway fined slightly (Figures 5a and 5b). At the Grand Canyon cableway, coarsening of the bed was associated with coarsening of the suspended sand (Figure 5a). This style of coupled bed and suspended-sand coarsening was similar to that observed by *Rubin et al.* [1998], *Topping et al.* [1999], and *Topping et al.* [this issue] in the postdam river.

To investigate the degree to which the observed systematic changes in bed elevation in 1956 reflected general changes in the upstream sediment supply during an average predam year in Grand and Glen Canyons, a new methodology was developed and applied to the predam periods of suspended-sand record at the Grand Canyon and Lees Ferry gages. The first goal of this analysis was to identify the degree to which a lag existed between the annual flood peak and either maximum or minimum bed elevation during an average year. The second goal of this analysis was to determine the degree to which sand-supply depletion was coupled to bed scour during floods.

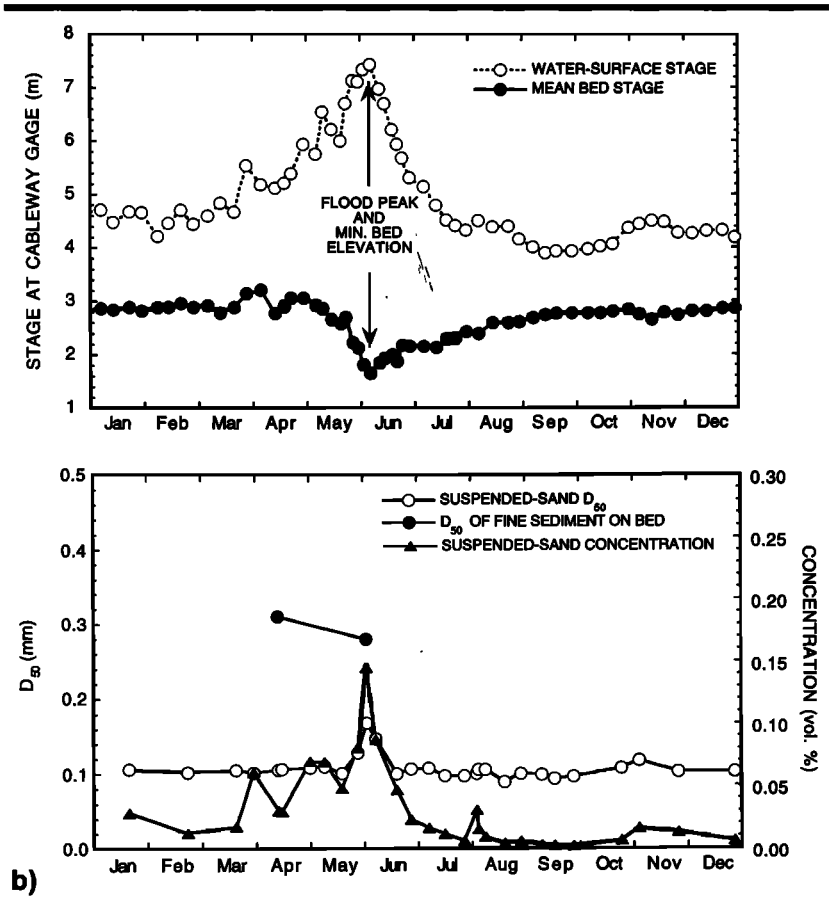
At both gages the mean relationship between bed elevation and the flow during the average predam year was determined for the periods of suspended-sand record. This was done by binning and averaging the measurements of water-surface stage, mean bed stage, and minimum bed stage [from *Burkham*, 1986] (Figures 6a and 6b). A bin size of 2 weeks was found to be optimum to ensure that enough data were included in each bin. Both mean and minimum bed stage were included in this analysis to determine if a change in bed elevation across the cross section was real and not an artifact of cross-section geometry. First, mean bed stage provides information on the change in bed elevation over the entire width of a cross section, whereas minimum bed stage provides information only on the magnitude of the deepest scour in the cross section. Second, a slight apparent increase in mean bed stage will occur with an increase in water-surface stage simply because of the trapezoidal cross-sectional shape of a river channel.

To quantify the seasonal style and importance of changes in the upstream sand supply, we developed a method based on

Figure 5. (Opposite) Water-surface stage, bed stage, grain size (in suspension and on the bed), and suspended-sand concentration at the Grand Canyon and upper Lees Ferry cableways during calendar year 1956. Greater hysteresis was present in all of these quantities at the Grand Canyon cableway, suggesting a greater depletion of the upstream supply of sand in Grand Canyon than in Glen Canyon. (a) Water-surface stage, mean bed stage, median size of the suspended sand, median size of the fine sediment (i.e., sand and finer material) on the bed, and suspended-sand concentration at the Grand Canyon cableway. Stage is that measured at the lower gage (measured relative to the same datum as at the upper gage). (b) Water-surface stage, mean bed stage, median size of the suspended sand, median size of the fine sediment on the bed, and suspended-sand concentration at the upper Lees Ferry cableway. Cableway stage is measured relative to a different datum than stage at the recording gage. Data in Figures 5a and 5b are from unpublished U.S. Geological Survey (USGS) discharge-measurement field notes.


WATER-SURFACE STAGE
MEAN BED STAGE
FLOOD PEAK
MAX. BED ELEVATION
STAGE (m)
SUSPENDED-SAND D_{50}
D_{50} OF FINE SEDIMENT ON BED
SUSPENDED-SAND CONCENTRATION
D_{50} (mm)
CONCENTRATION (vol. %)
$3x10^{-5}$
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

a)


WATER-SURFACE STAGE
MEAN BED STAGE
FLOOD PEAK AND MIN. BED ELEVATION
STAGE AT CABLEWAY GAGE (m)
SUSPENDED-SAND D_{50}
D_{50} OF FINE SEDIMENT ON BED
SUSPENDED-SAND CONCENTRATION
D_{50} (mm)
CONCENTRATION (vol. %)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

b)

the physical relationships that link changes in suspended-sand concentration to changes in suspended-sand grain size. These relationships are based on the suspended-sediment theory reviewed by *Topping et al.* [this issue] and hold true for all cases where suspended-load transport is the dominant transport mode of the sand on the bed (i.e., when the Rouse number of the median size of the sand on the bed is less than about 1).

The relationships that link changes in suspended-sand concentration and grain size are relatively straightforward when (1) the upstream supply of sand is in equilibrium with the flow conditions, (2) the upstream supply of sand becomes depleted while the flow is steady or increasing, and (3) the upstream supply of sand becomes enhanced while the flow is steady or decreasing. Given an upstream supply of sand that is in equilibrium with the flow conditions, sand in suspension will coarsen only when its concentration increases. In this case the coupled increase in suspended-sand concentration and grain size is caused by an increase in boundary shear stress associated with an increase in flow. At steady or increasing flows, given a decreasing upstream supply of sand, the grain size of the sand in suspension will either increase or remain constant if the concentration of sand decreases. At steady or decreasing flows, given an increasing upstream supply of sediment, the grain size of the sand in suspension will either fine or remain constant if the concentration of sand increases.

The relationships that link changes in suspended-sand concentration and grain size are more complicated in flows that are decreasing while the sediment supply is being depleted and in flows that are increasing while the sediment supply is being enhanced. This increase in complexity arises from the fact that under these conditions the rate at which the boundary shear stress changes can offset the influence of a change in the upstream supply of sand. For example, in decreasing flows, though the concentration of sand will always decrease when the upstream supply of sediment is depleted, the sand in suspension may actually fine if the boundary shear stress decreases quickly enough. Likewise, in increasing flows, though the concentration of sand will always increase when the upstream supply of sediment is enhanced, the sand in suspension may actually coarsen if the boundary shear stress increases quickly enough.

In summary, regardless of how the flow changes, (1) a decrease in suspended-sand concentration associated with either coarsening or no change in grain size always indicates sand depletion, (2) a decrease in suspended-sand concentration associated with fining is inconclusive, (3) an increase in sand concentration associated with either fining or no change in grain size always indicates an increase in the upstream supply of sand, and (4) an increase in suspended-sand concentration associated with coarsening is inconclusive. In this analysis these four types of sand-supply events are referred to as (1) sand-depletion events, (2) decreasing-concentration inconclusive events, (3) sand-enhancement events, and (4) increasing-concentration inconclusive events, respectively.

Determination of the relative seasonal importance of each of these four types of sand-supply events at the Grand Canyon and Lees Ferry gages was an eight-step process. First, the suspended-sand data from each gage were placed in the format of a time series. Second, these data were analyzed to determine how the measured concentration and grain size of the suspended sand changed from sample to sample (i.e., each pair of samples was assigned to one of the four defined types of sand-supply events). Third, so that this analysis would be consistent with the bed-elevation analysis in Figure 6a, only those samples that were collected within 2 weeks of each other were used. Fourth, the time of each sand-supply event was calculated as the midpoint in time between the two samples. Fifth, the data were then segregated into the same 2-week bins used in the bed-elevation analysis. Sixth, each sand-supply event was then weighted by the measured suspended-sand load at the time of each event. This weighting was applied because the degree to which the upstream supply of sand gets depleted or enhanced depends strongly on the sand-transport rate. For example, sand-depletion events occurring when the sand-transport rate is low represent a smaller decrease in the upstream supply of sediment than those occurring when the sand-transport rate is high. Seventh, for each of the four types of sand-supply events in each 2-week bin, the load-weighted data were summed to determine the load-weighted occurrence of each type of sand-supply event. Finally, before the data in either different bins or at the Grand Canyon and Lees Ferry gages could be compared, a correction had to be made to remove the dependence of the load-weighted occurrences on the different total number of sand-supply events in each bin. Therefore, eighth, the "normalized load-weighted occurrence" of each type of sand-supply event was determined by dividing the load-weighted occurrence of each type of event by the total number of the four types of sediment-supply events in each bin (Figures 6a and 6b).

5.4. Discussion of the Differences in Coupled Changes in Suspended-Sand Concentration, Suspended-Sand Grain Size, Bed Grain Size, and Bed Elevation in Grand and Glen Canyons

In the average predam year the bed at the Grand Canyon and upper Lees Ferry cableways responded very differently during the annual snowmelt flood. The bed at the Grand Canyon cableway would initially aggrade, while the bed at the upper Lees Ferry cableway would initially scour. Following the initial portion of the snowmelt flood (but still during the rising limb), the response of the bed at the Grand Canyon cableway would reverse, and the bed at both cableways would scour. During the receding limb of the flood the bed at the Grand Canyon cableway would typically remain stable, whereas the bed at the upper Lees Ferry cableway would aggrade. The systematic response of the bed at the Grand Canyon cableway during floods was first recognized by *Leopold and Maddock* [1953], who related it to systematic changes in the upstream sediment supply and mean velocity during a flood. This interpretation was essentially restated by *Burkham* [1986], who analyzed time series of bed scour and mean velocity at the Grand Canyon and upper Lees Ferry cableways. The opposing initial responses of the bed at the two sites during floods was first documented by *Colby* [1964], who attributed this difference not to the mechanism proposed by *Leopold and Maddock* [1953] but rather to the control of reach geometry on the pattern of scour and fill during a flood. *Colby* [1964] indicated that sediment concentrations were increasing at both the Grand Canyon and Lees Ferry gages during the rising limb of the snowmelt flood but that the response of the bed at the two sites was the opposite. *Colby* [1964] demonstrated through flume experiments that, given only a difference in reach geometry, one reach will scour and one will fill given the same upstream supply of sediment. Using a conceptual model of sediment redistribution during high flows, *Howard and Dolan* [1981], like *Colby* [1964], suggested that the initial response of the bed at the Grand Canyon cableway was controlled by reach geometry [*Howard and Dolan*, 1981, Figure 7] and that the initial scour

of the bed at the upper Lees Ferry cableway during snowmelt floods was also controlled by reach geometry.

Our analyses, in combination with those presented by *Topping et al.* [this issue], suggest that *Leopold and Maddock* [1953], *Colby* [1964], *Howard and Dolan* [1981], and *Burkham* [1986] were all partially correct and that both reach geometry and a reduction in the upstream sand supply played important roles in the responses of the bed at the Grand Canyon and upper Lees Ferry cableways. The response of the bed at both sites was initially controlled by a reach-geometry-driven redistribution of the boundary shear stress field (as the flow increased), but the response of the bed at the Grand Canyon cableway much more strongly reflected a seasonal depletion of the upstream supply of sand. The bed at the Grand Canyon cableway aggraded with the initial increase in water-surface stage during the snowmelt flood (from March 1 through May 10). Then, from about May 10 through July 20, the bed degraded back to its presnowmelt-flood elevation. Thus maximum bed elevation at the Grand Canyon cableway led the peak of the snowmelt flood by about 4 weeks (Figure 6a). This is the style of bed response predicted at this type of cross section by *Topping et al.* [this issue] for the case when the upstream supply of sand becomes depleted during a flood. While the bed was scouring at the Grand Canyon cableway, the suspended-sand data at the Grand Canyon gage were dominated by sand-depletion events (Figure 6a). In the average predam year the bed at the upper Lees Ferry cableway scoured with the increase in water-surface stage during the snowmelt flood and began to aggrade about 2 weeks after the peak of the snowmelt flood (Figure 6b). As shown by *Topping et al.* [this issue], this style of bed-topography response may be due to, but does not require, depletion of the upstream supply of sand. In any case the lag between the maximum or minimum bed elevation and the flood peak was much less at the upper Lees Ferry cableway than at the Grand Canyon cableway. This suggests that bed elevation changes at the upper Lees Ferry cableway were driven more by changes in the spatial distribution of boundary shear stress (caused by changes in discharge) than by depletion of the upstream supply of sediment. Furthermore, unlike at the Grand Canyon cableway, sand-depletion events were never dominant at the upper Lees Ferry cableway (Figure 6b). Thus the Colorado River in Glen Canyon showed the bed-topographic effects of sediment supply limitation to a far lesser degree than it did in Grand Canyon.

5.5. Long-Term Trends in Bed Stage at the Grand Canyon and Upper Lees Ferry Cableways

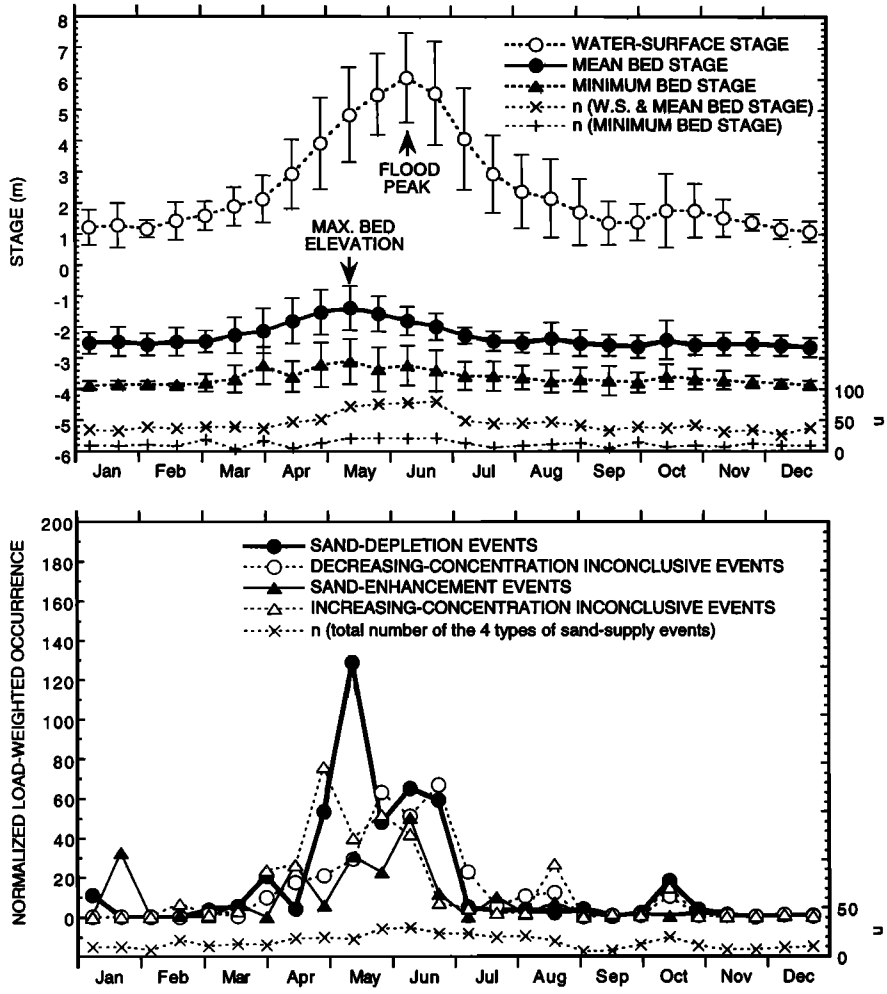
If a river is annually supply-limited with respect to fine sediment, then over multiyear timescales the amount of fine sediment present in the channel should either decrease or be zero. However, for a decrease in the amount of fine sediment in a cross section over multiyear timescales to be attributable to sediment supply limitation, this decrease must occur in the absence of changes in the local hydraulics that might cause changes in the local patterns of scour and fill. *Burkham* [1986] indicated that the channel bed at the upper Lees Ferry cableway was scouring over multiyear timescales prior to the closure of Glen Canyon Dam in 1963 and suggested that this scour was due to a decrease in the upstream supply of sediment. To determine whether multiyear changes in cross-section geometry were related to changes in either the sediment supply or the local hydraulics, F-test trend analyses were conducted on the measurements of mean bed stage (Figures 7a and 7b). Because the channel width and stage-discharge relationship were both stable (Figures 7c and 7d) at the Grand Canyon cableway, the 1922–1962 bed-stage data at this site could be analyzed as a single time series (Figure 7a). However, because of three major changes in channel geometry (two related to changes at the mouth of the Paria River and one caused by a large rockslide (Figures 7c and 7d)) in the Lees Ferry reach that could have influenced the response of the bed at the upper cableway, the 1921–1962 bed-stage data at this site had to be analyzed in four segments (Figure 7b).

5.6. Discussion of the Long-Term Trends in Bed Stage at the Grand Canyon and Upper Lees Ferry Cableways

At both the Grand Canyon and upper Lees Ferry cableways, trends in bed stage during the predam era were slightly, but significantly, negative (Figures 7a and 7b). Though these trends are consistent with the interpretation that both Grand and Glen Canyons were, to some degree, supply-limited with respect to fine sediment, other factors (e.g., changes in flow and externally forced changes in channel geometry) may have affected the response of the bed at these sites. However, because the bed at both sites (sites at which bed elevation responded in opposing manners during the annual flood) scoured over multiyear timescales, these other factors can probably be ruled out (though they are still discussed below). Therefore the long-term scour at both sites was probably due to the transport capacity of the river in both canyons exceeding the long-term upstream supply of sediment. In other words, the river in both canyons was probably supply-limited over multiyear timescales with respect to some fraction of the sizes of sediment in transport.

Because at the Grand Canyon cableway, no major change occurred from 1922 through 1962 in either the channel width (because the channel margins are bedrock) or in the stage-discharge relationship (Figures 7c and 7d), the entire predam period could be analyzed as a single time series. From November 12, 1922, through December 31, 1962, the bed at the Grand Canyon cableway scoured at a rate of 1.6 cm/yr; this trend is significant at less than the 1.0×10^{-16} level. Thus, given the approximate 90-m width of the channel, about 1.4 m^2 more sediment was eroded from this cross section than was supplied to it each year. Because the channel width and stage-discharge relationship at the Grand Canyon cableway were effectively constant, this long-term erosion of sediment can be interpreted to be either due to a long-term depletion in the upstream sediment supply or due to a long-term change in either the discharge of water or the water-surface stage. Analysis of the USGS discharge records from the Grand Canyon gage indicates that from 1922 through 1962 the mean-daily discharge of water decreased by about 25%, corresponding to a decrease in water-surface stage of about 15%. Therefore, though sediment supply limitation may have caused the 1922–1962 decrease in bed elevation, because the bed at the Grand Canyon cableway scours slightly with decreasing water-surface stage [*Topping et al.*, this issue], the 1922–1962 decrease in water-surface stage cannot be ruled out as a contributing factor.

At Lees Ferry, interpretation of long-term trends in bed stage are complicated by three externally forced changes in channel geometry that may have affected the response of the bed at the upper cableway. First, during the first week of April 1923, as flows first increased above 500 m^3/s during the annual snowmelt flood, a large downward shift in the stage-discharge relationship occurred (Figure 7d). This was likely the result of



a)

Figure 6. Relationships between water-surface stage, bed stage, and changes in the upstream sand supply during the average predam year at the Grand Canyon and upper Lees Ferry cableways. Depletion of the upstream supply of sand played a greater role in the response of the bed topography at the Grand Canyon cableway. (a) Water-surface stage, mean bed stage, and minimum bed stage in 2-week bins during the average predam year and the load-weighted normalized occurrence (in 2-week bins) of the four types of sand-supply events at the Grand Canyon cableway. Analysis is conducted on all the 1944–1962 discharge measurements and on the suspended-sand data presented in Figure 4; stage error bars are 1 standard deviation. (b) Water-surface stage, mean bed stage, and minimum bed stage in 2-week bins during the average predam year and the load-weighted normalized occurrence (in 2-week bins) of the four types of sand-supply events at the Lees Ferry gage. Analysis is conducted on all the 1949–1962 discharge measurements made at the upper Lees Ferry cableway and on the suspended-sand data presented in Figure 4; stage error bars are 1 standard deviation. The lower Lees Ferry cableway was not included in this analysis because the channel at that location was almost twice as wide as at the upper cableway, and relatively few discharge measurements were made there. The cofferdam at the Glen Canyon Dam site (23 km upstream from the upper cableway) was completed on February 11, 1959 [*Martin*, 1989], and immediately began to trap some of the upstream supply of sediment [*Pemberton*, 1976]. Though the bed at the upper cableway began to scour in 1959 in probable response to this partial trapping of the upstream sediment supply, the magnitude of this scour was much smaller than the magnitude of the natural seasonal scour and fill at the upper cableway. Thus inclusion of the period 1959–1962 did not greatly affect this analysis, as indicated by the slight difference between the values of mean bed stage for 1949–1962 and 1949–1958. The number of minimum bed-stage measurements in Figures 6a and 6b is less than the number of water-stage and mean bed-stage measurements because *Burkham* [1986] analyzed a subset of the USGS discharge measurements.

a rearrangement of the gravel bars at the mouth of the Paria River that form the hydraulic control for the Lees Ferry gage. Second, a large Paria River flood caused backwater in the Colorado River at the Lees Ferry gage on August 2, 1929, and rearranged the hydraulic control for the gage again, shifting the stage-discharge relationship back to its pre-April 1923 state (Figure 7d). Third, a large rock slide on December 19, 1944, fell on the right end of the upper cableway (unpublished USGS

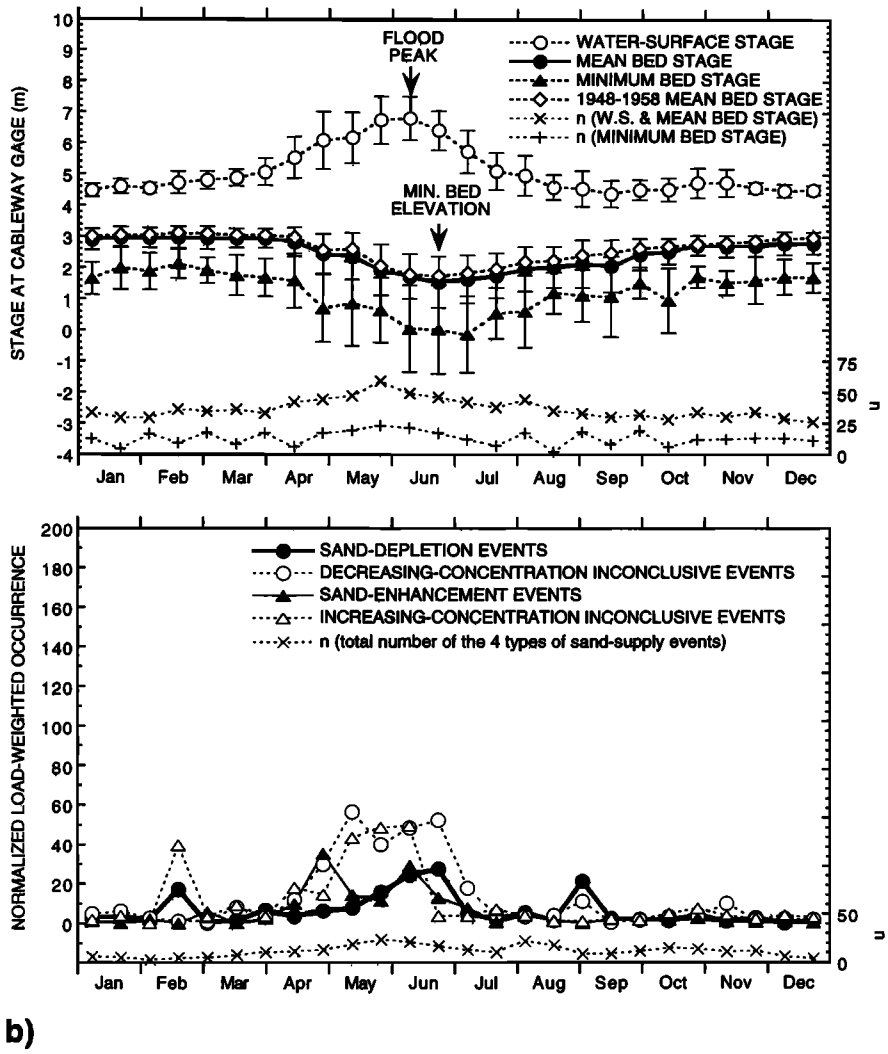


Figure 6. (continued)

Lees Ferry gage annual technical file, 1945) and caused approximately 10 m of channel narrowing (Figure 7c). Because of these externally forced changes in geometry, the bed-stage data from the upper cableway were analyzed in four segments: (1) from August 3, 1921, through April 8, 1923, (2) from April 10, 1923, through July 31, 1929, (3) from August 2, 1929, through December 7, 1944, and (4) from January 10, 1945, through February 7, 1959. To ensure that only natural long-term trends were detected in this analysis, the period after completion of the cofferdam at the Glen Canyon Dam site on February 11, 1959 [*Martin*, 1989], was not included. Though the effect of the cofferdam was probably small at the upper cableway during 1959–1962, by trapping some of the upstream supply of sediment, the cofferdam may have slightly enhanced the scour at the upper cableway (Figure 6b) [see *Pemberton*, 1976].

From August 2, 1929, through February 7, 1959, and as observed at the Grand Canyon cableway, the trend in bed stage at the upper Lees Ferry cableway was slightly, but significantly, negative (Figure 7b). Trends in mean bed stage from August 3, 1921, through April 8, 1923, and from April 10, 1923, through July 31, 1929, are not significant at either the 5% or 10% level, however. From August 2, 1929, through December 7, 1944, the bed at the upper cableway scoured at a rate of 2.5 cm/yr; this trend is significant at the 1.6×10^{-5} level. From January 10, 1945, through February 7, 1959, the bed scoured at a rate of 3.0 cm/yr; this trend is significant at the 3.9×10^{-4} level. Thus, given the approximate 120-m width of the channel at the upper cableway, about 3.0 m^2 more sediment was eroded from this cross section than was supplied to it each year during 1929–1944, and about 3.6 m^2 more sediment was eroded from this cross section than was supplied to it each year during 1945–1958. From August 2, 1929, through February 7, 1959, the 15-min discharge of water at the Lees Ferry gage increased by only 10%, and the 15-min water-surface stage increased by only 3% (L. E. Vierra and D. J. Topping, unpublished data, 1999). Thus long-term changes in either discharge or stage can be ruled out as the cause of the 1929–1958 erosion. Furthermore, because the August 2, 1929, to February 7, 1959, stage-discharge relationship was effectively constant (Figure 7d), the 1929–1958 decrease in the amount of sediment at the upper cableway suggests that Glen Canyon, like Grand Canyon, was supply-limited with respect to fine sediment. However, the previous analyses (shown in Figures 4, 5, and 6) suggest that the degree of sediment supply limitation in Glen Canyon was much less than in Grand Canyon.

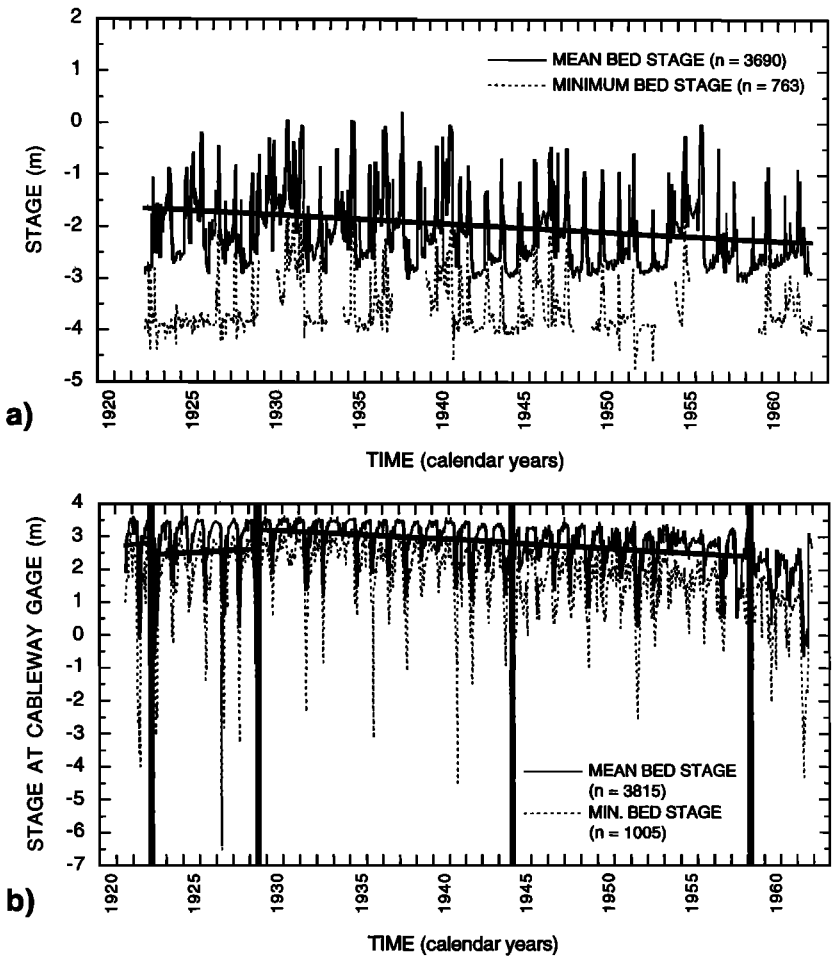
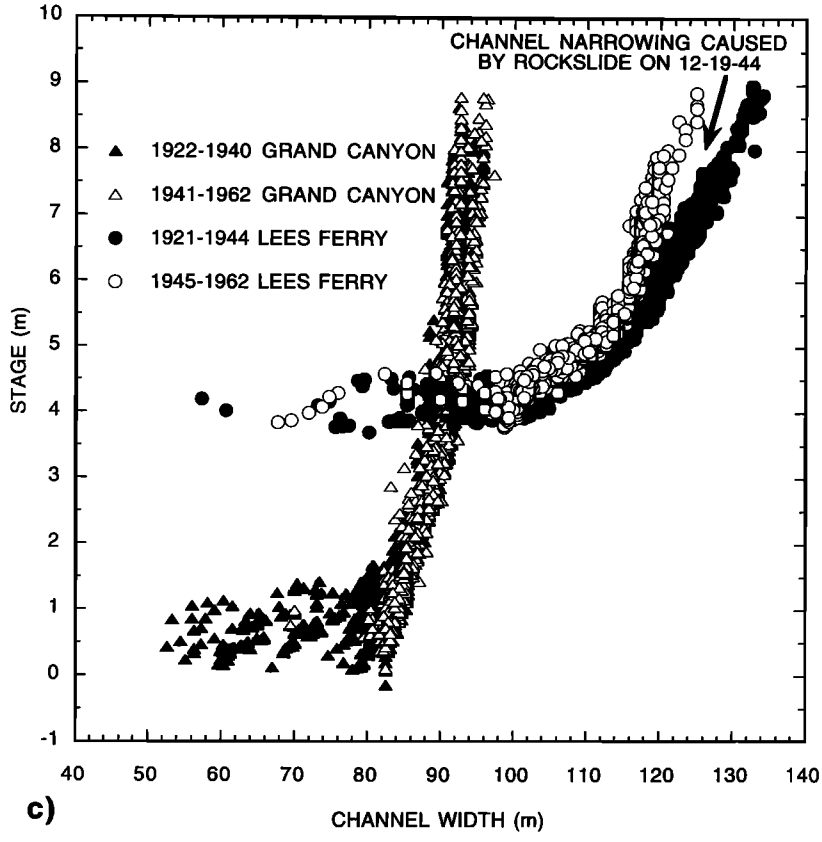


Figure 7. (a) Mean and minimum bed stage as a function of time at the Grand Canyon cableway. Values of mean bed stage are from the 3690 USGS discharge measurements made from 1922 through 1962; values of minimum bed stage are from the 766 USGS discharge measurements analyzed by *Burkham* [1986]. Stage is that measured at the lower gage (relative to the same datum as at the upper gage). The linear regression used in the F-test trend analysis of mean bed stage is shown. (b) Mean and minimum bed stage as a function of time at the upper Lees Ferry cableway. Values of mean bed stage are from the 3815 USGS discharge measurements made from 1921 through 1962; values of minimum bed stage are from the 1005 USGS discharge measurements analyzed by *Burkham* [1986]. Stage is that measured at cableway gage (relative to a different datum than at the recording gage). Bold vertical lines indicate where the time series of mean bed stage was subdivided into the four segments for the F-test trend analyses, see text for justification of this subdivision; linear regressions used in the F-test trend analysis of the data in each segment are shown. (c) Width as a function of stage at the Grand Canyon and upper Lees Ferry cableways. Note the channel narrowing caused by the December 19, 1944, rockslide at the Lees Ferry cableway. For comparison, data from the Grand Canyon cableway are also subdivided into two portions to illustrate the stability of the channel at that site. Stage at the Grand Canyon cableway is that measured at the lower gage; stage at the Lees Ferry cableway is that measured at the cableway gage. The 1922–1940 Grand Canyon data are from the 2406 USGS discharge measurements made from November 12, 1922, through December 30, 1940; 1941–1962 Grand Canyon data are from the 1284 USGS discharge measurements made from January 5, 1941, through December 31, 1962. The 1921–1944 Lees Ferry data are from the 2592 USGS discharge measurements made at the upper cableway from August 3, 1921, through December 7, 1944; 1945–1962 Lees Ferry data are the 1223 USGS discharge measurements made at the upper cableway from January 10, 1945, through December 30, 1962. (d) Discharge of water as a function of stage at the Grand Canyon and Lees Ferry gages. Data from the Grand Canyon gage are subdivided as in Figure 7c to illustrate the stability of the stage-discharge relationship from 1922 through 1962. Stage at the Grand Canyon gage is that measured at the lower gage. Data from the Lees Ferry gage are subdivided into the three periods with approximately stable stage-discharge relationships: August 3, 1921, through April 8, 1923, April 10, 1923, through July 31, 1929, and from August 2, 1929, through February 7, 1959. Unlike in Figures 7b and 7c, stage at the Lees Ferry gage is that measured at the recording gage. At Lees Ferry the August 3, 1921, through April 8, 1923, data are from the 237 discharge measurements made at the upper cableway during this period; April 10, 1923, through July 31, 1929, data are from the 464 discharge measurements made at the upper cableway and the 41 discharge measurements made at the lower cableway during this period; August 2, 1929, through February 7, 1959, data are from the 2896 discharge measurements made at the upper cableway and the 286 discharge measurements made at the lower cableway during this period.



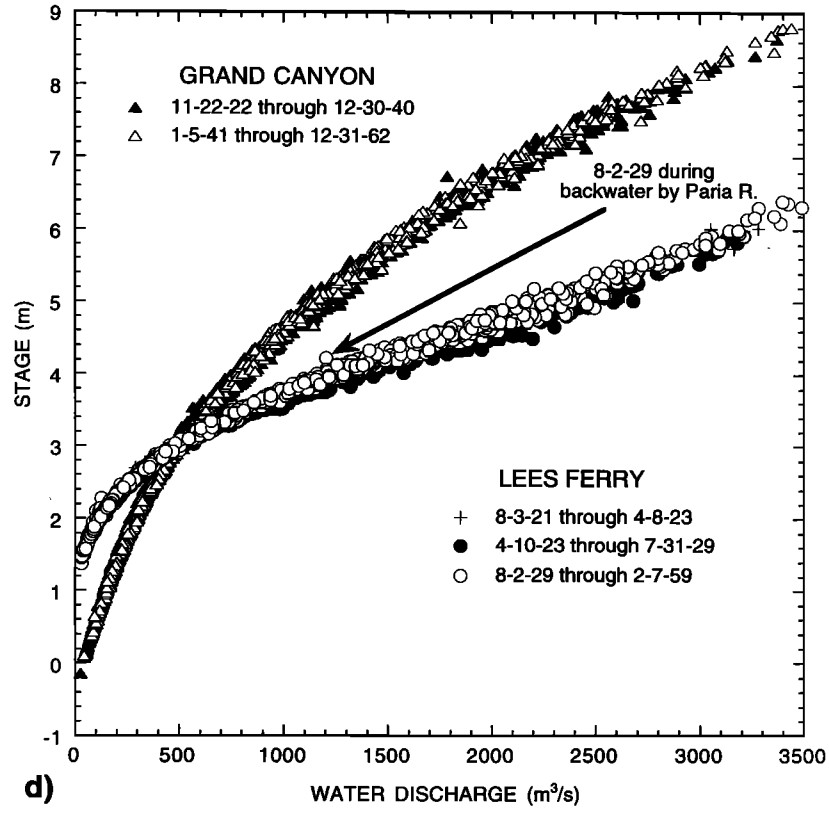


Figure 7. (continued)

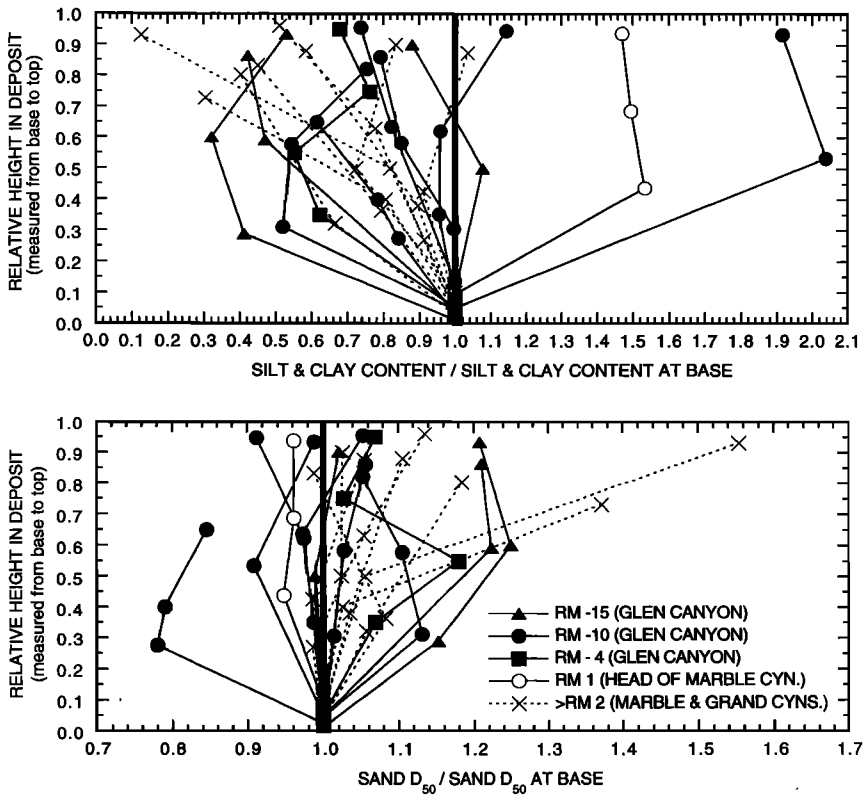


Figure 8. Vertical trends in the silt and clay content and the median size of sand in predam flood deposits in Glen Canyon, at the head of Marble Canyon, and in Marble (downstream from river mile 2) and Grand Canyons. Both the silt and clay content and the median size of sand are normalized by the values measured near the base of each deposit. In Glen Canyon and at the head of Marble Canyon the beds did not consistently coarsen upward with respect to sand, as they did in Marble and Grand Canyons. Thus the upstream supply of sand probably did not get as depleted during floods in Glen Canyon as it did downstream in Marble and Grand Canyons.

5.7. Differences in Vertical Grain-Size Trends in Predam Flood Deposits in Marble and Grand Canyons and Glen Canyons

As suggested by the above series of analyses, predam Glen, Marble, and Grand Canyons were all annually supply-limited with respect to silt and clay, whereas predam Marble and Grand Canyons were annually supply-limited with respect to sand to a greater degree than was predam Glen Canyon. If these interpretations are correct, then some difference should exist between the vertical trends in grain size preserved in predam flood deposits in Marble and Grand Canyons and those preserved in predam flood deposits in Glen Canyon. Though most of Glen Canyon is today inaccessible beneath the waters of Lake Powell, some predam flood deposits are preserved in the 25-km-long reach between Glen Canyon Dam and Lees Ferry. To compare the vertical trends in grain size preserved in predam flood deposits in Glen Canyon with those preserved in predam deposits in Marble and Grand Canyons, we sampled a total of 10 predam flood deposits vertically for grain size at three sites in Glen Canyon in 1998 and 1999 (Figures 1 and 8).

5.8. Discussion of the Differences Between the Vertical Grain-Size Trends in Predam Flood Deposits in Marble and Grand Canyons and Glen Canyon

As in Marble and Grand Canyons, the content of silt and clay generally decreases upward in the predam flood deposits in Glen Canyon, with the silt and clay content at the top being less than that at the base in about 80% of the sampled deposits. However, in contrast to Marble and Grand Canyons, less generality exists in the vertical trends in sand grain size in the predam flood deposits in Glen Canyon. In Glen Canyon the sand was actually finer at the top than at the base in about 30% of the deposits (as was the case in the predam deposit at the head of Marble Canyon). Therefore the sedimentologic record preserved in the predam flood deposits lends further support to the interpretation that in the predam era, the majority of Marble Canyon and all of Grand Canyon were annually supply-limited with respect to fine sediment to a greater degree than was Glen Canyon. Thus a predam transition to increased annual fine-sediment supply limitation may have occurred near the head of Marble Canyon.

6. Support for Annual Sediment Supply Limitation From Late Predam and Early Postdam Sediment Budgets

In addition to displaying the four above-described and documented effects associated with sediment supply limitation, the integral constraint on whether a reach is annually supply-limited with respect to fine sediment (i.e., sand and finer material) is that the reach must export all of the fine sediment supplied to it each year. The above analyses provide evidence that is necessary, but not sufficient, to conclude that the pre-

dam river in Marble and Grand Canyons was annually supply-limited with respect to fine sediment. Therefore, to test whether the predam Colorado River between the Lees Ferry and Grand Canyon gages met the integral constraint of annual supply limitation with respect to fine sediment, we constructed a sediment budget for the 141-km-long reach of the Colorado River in Marble Canyon and upper Grand Canyon.

6.1. Annual Sediment Budget

Fine sediment is supplied to the Colorado River in Marble Canyon and upper Grand Canyon from (1) the Colorado River in Glen Canyon (this ceased to be a major source after closure of the dam), (2) the Paria River (which enters the Colorado River at river mile 0.9 at the head of Marble Canyon), (3) the Little Colorado River (which enters the Colorado River at river mile 61.5 at the lower end of Marble Canyon), and (4) the smaller ungaged tributaries between river mile 0 and 87.4. During the predam era, large quantities of fine sediment were supplied to the Colorado River in Marble Canyon and upper Grand Canyon during tributary floods that typically occurred in both July–October and January–April, whereas the largest quantities of fine sediment were exported during the annual snowmelt flood. Thus neither calendar years (January–December) nor water years (October–September) were the best time period to use in computing annual sediment budgets because the season of largest sediment export fell between the two seasons of greatest tributary sediment supply. Therefore we constructed a sediment budget for years beginning on July 1 of the preceding calendar year and ending on June 30 of the current calendar year, a year herein defined as a "sediment year." For example, by this definition, sediment year 1957 was the year between July 1, 1956, and June 30, 1957.

Constructing a sediment budget for Marble Canyon and the upper Grand Canyon was a relatively straightforward process because of the high spatial density and long duration of sediment-transport data collected by the USGS. For over 2 decades, daily suspended-sediment concentrations were measured at two stations on the main stem in this reach and at stations on the two major tributary suppliers of sediment, that is, the Paria and Little Colorado Rivers. On the main stem Colorado River these data were collected at the Lees Ferry and Grand Canyon gages (Figure 1). At the Lees Ferry gage, suspended-sediment concentrations were measured with modern USGS sampling equipment from October 1, 1947, through August 13, 1965. After August 13, 1965, suspended-sediment concentrations were measured only occasionally at this site. At the Grand Canyon gage, suspended-sediment concentrations were measured with modern USGS sampling equipment from June 1, 1944, through November 28, 1944, from April 25, 1945, through April 27, 1945, and from May 13, 1945, through September 30, 1972. Suspended-sediment data collected at the Grand Canyon gage prior to June 1, 1944, from November 29, 1944, through April 24, 1945, and from April 28, 1945, through May 12, 1945, were not used in this analysis because the suspended-sediment sampler used during these periods has been shown to oversample suspended sand by as much as a factor of 2–2.5 depending on the method of sampler deployment [*Federal Inter-Agency River Basin Committee*, 1957; *Topping et al.*, 1996]. On the Paria River, suspended-sediment concentrations were measured at the Paria River Lees Ferry gage from October 1, 1947, through September 30, 1976 (Figure 1). On the Little Colorado River, suspended-sediment concentrations were measured from October 1, 1947, through September 30, 1970, at the highway 89 bridge at Cameron, Arizona (Figure 1).

In this sediment budget the monthly fine-sediment supply was set equal to the combined measured monthly loads of the Colorado River at Lees Ferry, the Paria River, the Little Colorado River, and an estimation of the monthly loads of the ungaged tributaries (described in Appendix A). The monthly fine-sediment export was set equal to the measured monthly load of the Colorado River at the Grand Canyon gage. During periods of missing record, most notably between the measurements made after August 1965 at the Colorado River Lees Ferry gage, daily sediment loads were estimated by interpolation. Longer periods of missing record at the Grand Canyon gage prevented sediment budgets from being constructed from June 2, 1956, through August 31, 1956, and from August 1, 1958, through March 31, 1959.

Prior to constructing and interpreting any sediment budget, it is essential that the sources and magnitudes of measurement error be understood and quantified so that appropriate uncertainties can be assigned. As justified in Appendix B, the following uncertainties were assigned to the measured monthly and annual sediment loads: (1) 5% for the Colorado River at the Lees Ferry and Grand Canyon gages and (2) 20% for the Paria and Little Colorado Rivers. As justified in Appendix A, an uncertainty of a factor of 3 was assigned to the estimated monthly and annual sediment loads of the ungaged tributaries. These uncertainties in the measured and estimated loads are not unreasonably high and, if anything, may be too low.

The annual supplies of fine sediment (from each of the four sources) to the reach between the Lees Ferry and Grand Canyon gages and the annual export of fine sediment from this reach are shown in Figure 9a. Prior to closure of the dam, the major supplier of fine sediment to this reach was the Colorado River above the Lees Ferry gage (i.e., the Colorado River in Glen Canyon). During the predam years with complete sediment-transport data at the Lees Ferry gage (sediment years 1949–1962), the mean annual supply of sediment from the Colorado River in Glen Canyon was 57 ± 3 million t (t indicates metric ton) (of which approximately 40% was sand). During the predam years with complete sediment-transport data at the Grand Canyon gage (i.e., sediment years 1948–1955, 1958, and 1960–1962), the mean-annual export of fine sediment from this reach was 83 ± 4 million t (of which approximately 35% was sand). Because the first few years after closure of Glen Canyon Dam in March 1963 were not representative of the fluctuating flows that typify most of the postdam era [*U.S. Department of the Interior*, 1995], these years were not used to determine mean-annual postdam loads of the Colorado River. Dam releases during these years consisted of quasi-steady low flows through much of 1963 and 1964 and sustained high flows during April–June 1965 (Figure 9b). In the initial period of daily fluctuating flows following the high dam releases of 1965 (i.e., sediment years 1966–1970), the mean-annual supply of sediment from the Colorado River in Glen Canyon was only 0.24 ± 0.01 million t. This represented a decrease of 99.5–99.6% in the mean-annual predam supply of fine sediment from this source. Following the high flows in 1965 (i.e., sediment years 1966–1972), the mean-annual export of fine sediment past the Grand Canyon gage was 14 ± 1 million t. This represented a decrease of 81–85% in the mean-annual predam export of fine sediment.

The other major predam suppliers of fine sediment, and the only major suppliers of sediment to the reach between the Lees

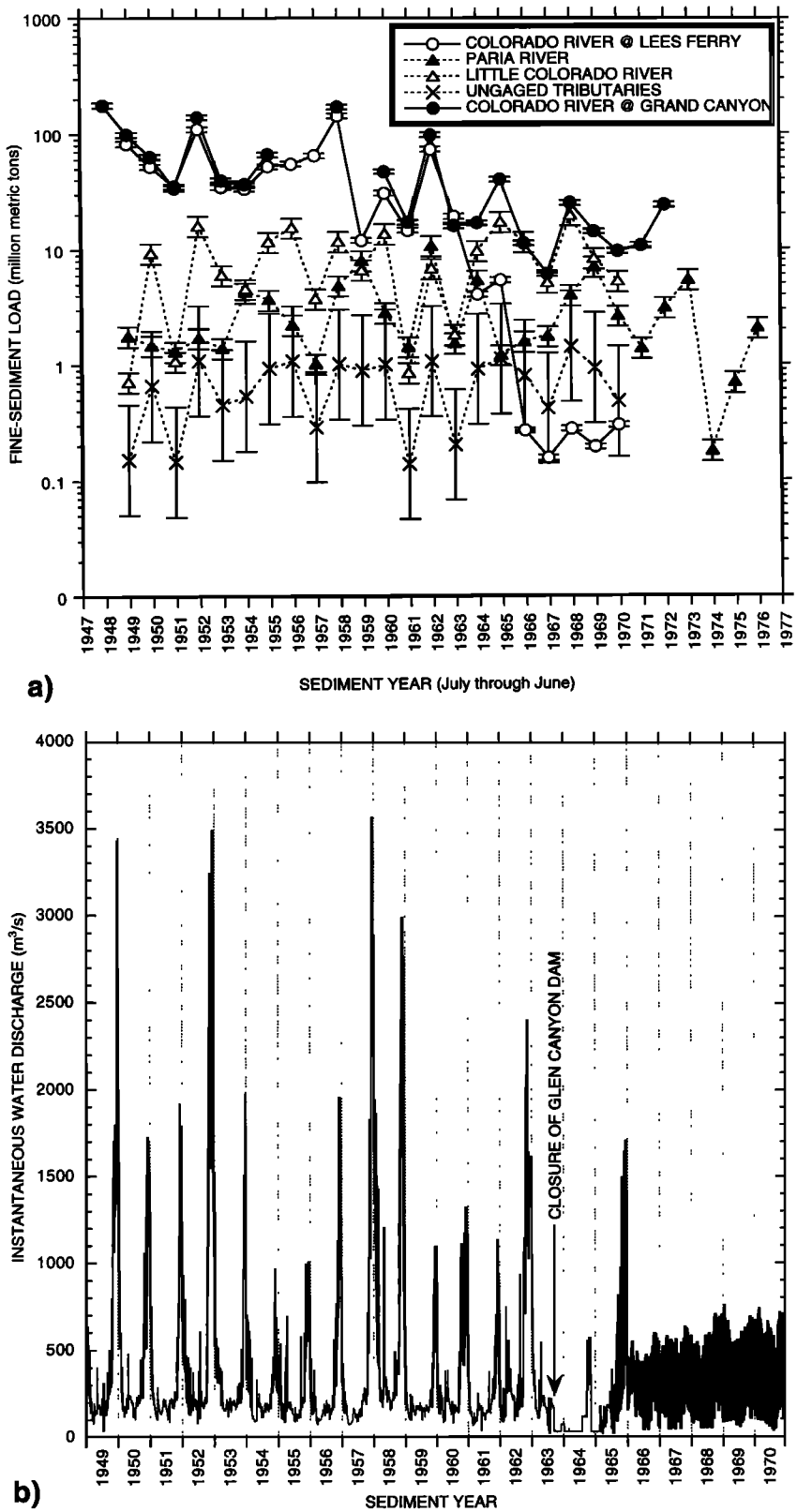


Figure 9. (a) Annual fine-sediment (i.e., sand and finer material) loads of the Colorado River in Glen Canyon (as measured at the Lees Ferry gage), the Paria River, the Little Colorado River, the ungaged tributaries, and the Colorado River at the Grand Canyon gage. Error bars indicate the uncertainties in the loads (see text). (b) Instantaneous water discharge of the Colorado River at Lees Ferry during sediment years 1949–1970. This time series was constructed using unpublished raw USGS stage and discharge data. (c) Annual fine-sediment supply to and export from Marble Canyon and upper Grand Canyon. In all but a few years, the supply and export of fine sediment in both the predam and postdam periods were equal within the uncertainties in the sediment budget.

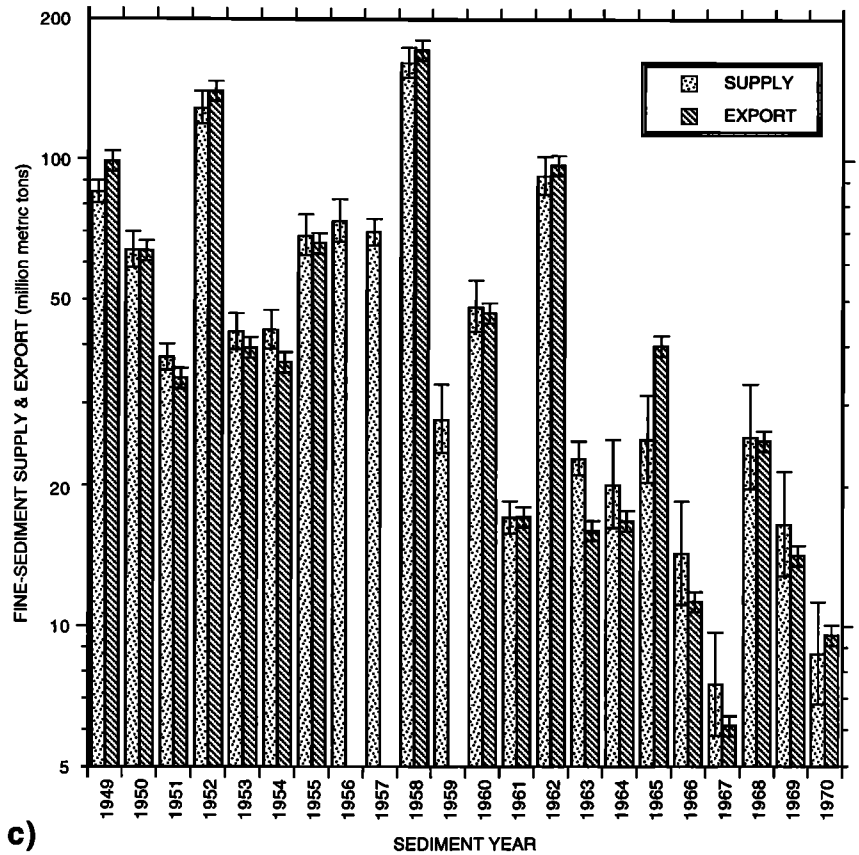


Figure 9. (continued)

Ferry and Grand Canyon gages in the postdam era, are the Paria and Little Colorado Rivers. During their respective periods of sediment record the mean-annual supplies of fine sediment were 3.0 ± 0.6 million t from the Paria River (of which about 50% was sand) and 8.6 ± 1.7 million t from the Little Colorado River (of which about 30–40% was sand). During the period of sediment years 1949–1970 the mean-annual supply of fine sediment from the ungaged tributaries between Lees Ferry and the Grand Canyon gage was estimated at 0.72 ± (a factor of 3) million t [after *Griffiths et al.*, 1998].

Because the periods of record at each of the four USGS sediment stations were different, a reasonable sediment budget for Marble Canyon and upper Grand Canyon could only be constructed for sediment years 1949–1955, 1958, and 1960–1970 (Figure 9c). This period included 11 years from the predam era and the first 7 years of the postdam era. During both the predam and postdam periods in this sediment budget the mean-annual fine-sediment supply generally equaled the mean-annual export to within the measurement error (Figure 9c and Table 1). As discussed in Appendix B and shown in the analysis in Table 1, the uncertainties in the sediment loads would have to be much lower than is reasonable to result in the prediction of substantial multiyear storage of fine sediment in either the predam or postdam periods. Given the uncertainties in the sediment budget, the only years in which the fine-sediment supply can be shown to have exceeded the export were sediment years 1954 and 1963, and the only years in which the export can be shown to have exceeded the supply were sediment years 1949 and 1965.

6.2. Magnitude and Duration of Seasonal Sediment Storage

Our analysis of the predam differences in sand-transport rates between the Lees Ferry and Grand Canyon gages (Figure 4b) suggests that sand accumulated in Marble Canyon and upper Grand Canyon during low flows and was eroded from Marble Canyon and upper Grand Canyon during high flows. Therefore, to determine the mean seasonal patterns of fine-sediment accumulation, storage, and erosion both under natural conditions and under normal dam operations, we averaged, differenced, and integrated the monthly sediment-load data for the 11 predam years with complete data and the 5 postdam years with fluctuating flows. This approach is justified because the annual fine-sediment supply to and export from Marble Canyon and upper Grand Canyon during these periods were equal to within the uncertainties in the sediment budget, with the exception of only 2 of the 11 predam years. The mean supplies (Colorado River at Lees Ferry, Paria River, Little Colorado River, and ungaged tributaries) and export (Colorado River at Grand Canyon) of fine sediment each month during the average predam and postdam years are shown in Figures 10a and 10b. The amount of fine sediment in storage after each month during the average predam and postdam year are shown in Figures 10c and 10d.

Substantial differences exist between the magnitude and duration of seasonal fine-sediment storage in the average predam and postdam years (Figures 10c and 10d). During the average predam year the most rapid accumulation of fine sediment in Marble Canyon and upper Grand Canyon occurred from July

Table 1. Maximum Demonstrable Annual Change in Fine-Sediment Mass in Marble Canyon and Upper Grand Canyons as a Function of Uncertainty in the Sediment Loads of the Colorado River, Paria and Little Colorado Rivers, and Ungaged Tributaries

Sediment Year	Uncertainties Assigned to Sediment Loads,* %											
	2†, 5†	2†, 10†	2†, 20	2†, 30	5, 5†	5, 10†	5, 20‡	5, 30	10, 5†	10, 10†	10, 20	10, 30
1949	−9.9	−9.8	−9.5	−9.3	−4.4	−4.3	−4.1	−3.8	0	0	0	0
1950	0	0	0	0	0	0	0	0	0	0	0	0
1951	2.1	1.9	1.7	1.5	0	0	0	0	0	0	0	0
1952	−3.3	−2.4	−0.6	0	0	0	0	0	0	0	0	0
1953	0.9	0.6	0	0	0	0	0	0	0	0	0	0
1954	4.1	3.7	2.8	1.9	2.0	1.5	0.7	0	0	0	0	0
1955	0	0	0	0	0	0	0	0	0	0	0	0
1958	−1.4	−0.6	0	0	0	0	0	0	0	0	0	0
1960	0	0	0	0	0	0	0	0	0	0	0	0
1961	0	0	0	0	0	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0	0	0
1963	5.8	5.7	5.3	5.0	4.8	4.6	4.3	3.9	3.0	2.8	2.5	2.2
1964	1.4	0.7	0	0	0.8	0.1	0	0	0	0	0	0
1965	−10.8	−9.8	−8.0	−6.1	−9.4	−8.5	−6.6	−4.7	−7.1	−6.2	−4.3	−2.5
1966	1.6	0.9	0	0	1.3	0.6	0	0	0.7	0	0	0
1967	0.6	0.3	0	0	0.5	0.1	0	0	0.1	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0.7	0	0	0	0.3	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0	0	0	0	0	0

Values are in million metric tons; positive values indicate net annual storage of sediment; negative values indicate net annual erosion of sediment; and zero values indicate that the magnitude of net annual storage or erosion of sediment is less than the magnitude of the uncertainty in the sediment budget.

*The first number indicates the uncertainty assigned to the measured sediment loads of the Colorado River at the Lees Ferry and Grand Canyon gages. The second number indicates the uncertainty assigned to the measured sediment loads of the Paria and Little Colorado Rivers. In each case an uncertainty of a factor of 3 was assigned to the estimated sediment loads of the ungaged tributaries (see Appendix A).

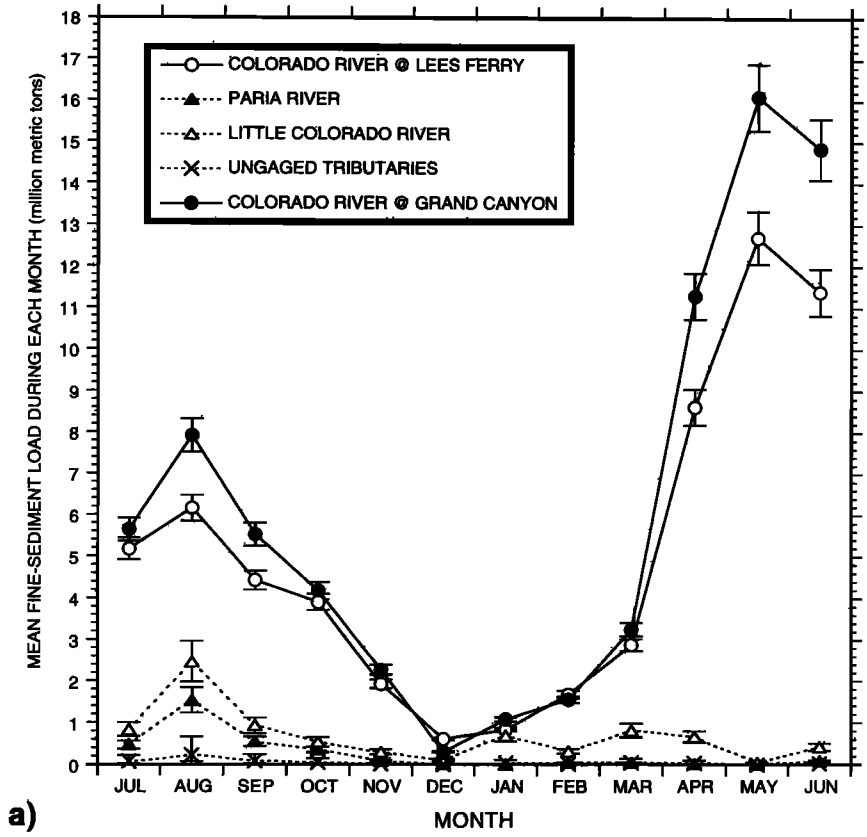
†These uncertainties are thought to be unreasonably low based on the discussion in Appendix B.

‡These are uncertainties used in this paper.

through August, and, given the assigned uncertainties, at least 1 million t of fine sediment were retained in storage from September through March. Then, from April through June this stored sediment was probably eroded and may have been exhausted by the end of April. As shown in section 5.1, relatively little difference in predam silt and clay concentration existed between the Lees Ferry and Grand Canyon gages (Figure 4a), whereas large flow-dependent differences in sand concentration existed between the two gages (Figure 4b). These differences were greatest for the 0.0625–0.25 mm sand (Figures 4c and 4d); thus the fine sediment seasonally stored in Marble Canyon and upper Grand Canyon was probably largely composed of 0.0625–0.25 mm sand. To place these minimal magnitudes of seasonal sand storage in perspective, the 1949–1976 mean-annual sand load of the Paria River was approximately 1.76 million t, of which half was finer than 0.125 mm and 90% was finer than 0.25 mm [*Topping*, 1997]. In contrast to the predam case, given the same set of uncertainties, sand cannot be demonstrated to accumulate for more than 1 month or be retained in storage for more than 2 months in Marble Canyon and upper Grand Canyon during the average postdam year (Figure 10d).

The hydrology of the predam Colorado River during the seasons of sand accumulation and storage (July–March) and sand erosion (April–June) is that expected, given the flow-dependent differences in the transport rates of finer (0.0625–0.25-mm) sand at the Lees Ferry and Grand Canyon gages (Figure 4c). As shown in Figure 4c, (1) finer sand should have accumulated in Marble Canyon and upper Grand Canyon when the flows were lower than about 200–300 m^3/s, (2) finer sand should have been conveyed through Marble Canyon and upper Grand Canyon when flows exceeded 200–300 m^3/s, and (3) finer sand should have been either eroded from or conveyed through Marble Canyon and upper Grand Canyon when flows exceeded 400–500 m^3/s. Indeed, during the season of sand accumulation and storage (July–March), flows exceeded

Figure 10. (Opposite) (a) Mean supplies and export of fine sediment each month (with uncertainties) during the average predam year. These values were calculated from the data collected during sediment years 1949–1955, 1958, and 1960–1962 (i.e., the predam years with complete sediment data). (b) Mean supplies and export of fine sediment each month (with uncertainties) during the average postdam year with fluctuating flows. These values were calculated from the data collected during sediment years 1966–1970. Note that the cumulative monthly loads of the Paria and Little Colorado River are highly correlated with the monthly export of fine sediment past the Grand Canyon gage, suggesting minimal accumulation of fine sediment in the postdam river. (c) Amount of fine sediment in storage after each month (with uncertainties) during the average predam year. These values were determined by differencing and integrating the data in Figure 10a. In the average predam year, fine sediment accumulated in Marble Canyon and the upper Grand Canyon during 9 months of the year and then was eroded. This seasonally stored and eroded fine sediment was probably largely 0.0625–0.25 mm sand (see text). (d) Amount of fine sediment in storage after each month (with uncertainties) during the average postdam year with fluctuating flows. These values were determined by differencing and integrating the data in Figure 10b. In the average postdam year, fine-sediment storage in Marble Canyon and the upper Grand Canyon cannot be demonstrated for more than 2 months. As in Figure 10c, this stored and eroded fine sediment was probably largely sand.


COLORADO RIVER @ LEES FERRY
PARIA RIVER
LITTLE COLORADO RIVER
UNGAGED TRIBUTARIES
COLORADO RIVER @ GRAND CANYON
MEAN FINE-SEDIMENT LOAD DURING EACH MONTH (million metric tons)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
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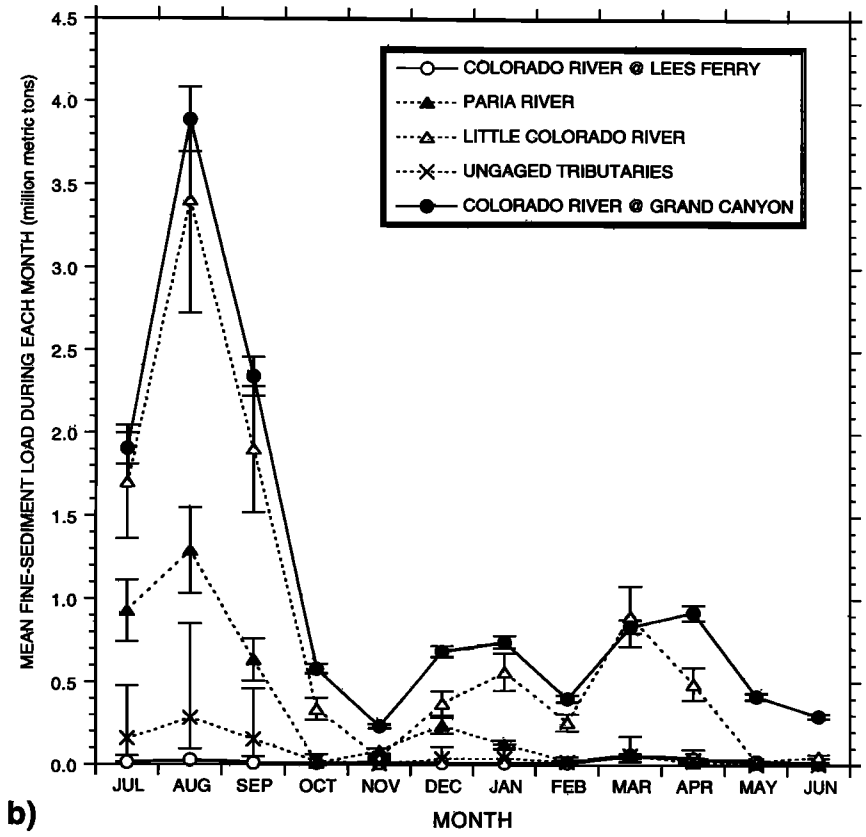
a)


COLORADO RIVER @ LEES FERRY
PARIA RIVER
LITTLE COLORADO RIVER
UNGAGED TRIBUTARIES
COLORADO RIVER @ GRAND CANYON
MEAN FINE-SEDIMENT LOAD DURING EACH MONTH (million metric tons)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
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JUL
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b)

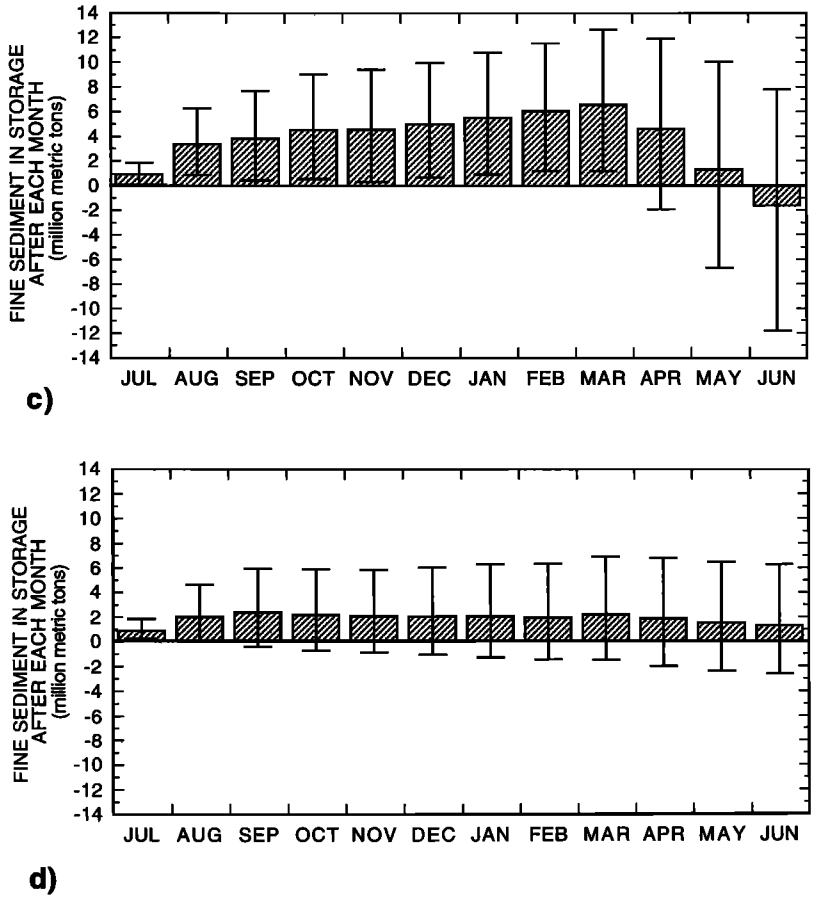

Figure 10. (continued)

the approximate threshold between sand accumulation and conveyance (i.e., 250 m^3/s) only 27.0% of the time and exceeded the approximate threshold between sand conveyance and erosion (i.e., 450 m^3/s) only 8.8% of the time. During the season of sand erosion (April–June), flows exceeded the approximate threshold between sand accumulation and conveyance 90.4% of the time and exceeded the approximate threshold between sand conveyance and erosion 69.1% of the time (Figure 11).

When compared to that in the predam era, the hydrology of the postdam Colorado River during sediment years 1966–1970 was closer to that during the predam season of sand erosion (April–June) than it was to the hydrology during the predam season of sand accumulation and storage (July–March). Furthermore, given that the hydrology of the Colorado River during sediment years 1966–1970 was similar to that during the rest of the postdam era (sediment years 1966–1998), interpretations of the magnitude and duration of sand storage based on this limited period of sediment data should be valid for the entire postdam era (Figure 11). Indeed, flows were slightly higher during sediment years 1966–1998 than they were during sediment years 1966–1970, suggesting that the data from sediment years 1966–1970 provide an upper bound on the magnitude and duration of seasonal sand accumulation and storage. During sediment years 1966–1970, flows exceeded the approximate predam threshold between sand accumulation and conveyance 68.1% of the time; during sediment years 1966–1998, flows exceeded the approximate predam threshold between sand conveyance and erosion 73.6% of the time (Figure 11).

6.3. Discussion of the Annual and Seasonal Sediment Budgets

Analysis of the annual sediment budget does not invalidate the hypothesis that in both the predam and postdam era the Colorado River in Marble Canyon and upper Grand Canyon was an annually supply-limited system with respect to fine sediment (i.e., sand and finer material). During the 19 years of complete sediment data the magnitudes of the annual fine-sediment supply and export are equal to within the uncertainties in the sediment budget in all but four years. The fine-sediment export can be shown to have exceeded the supply in only sediment years 1949 and 1965. Sediment year 1949 was a year in which a large snowmelt flood occurred (Figure 9b), and sediment year 1965 was a year with abnormally high dam releases (Figure 9b). The high flows in 1965 scoured the reach immediately downstream of the dam [*Pemberton*, 1976; *Williams and Wolman*, 1984; *Burkham*, 1986] and, as suggested by this sediment budget, scoured sediment from much of Marble and Grand Canyons. The fine-sediment supply can be shown to have exceeded the export in only sediment years 1954 and 1963 (Table 1). Sediment year 1954 was the predam year in the period of sediment record with the lowest flows (Figure 9b), and sediment year 1963 was the year in which the dam was closed and in which the naturally erosive snowmelt flood was

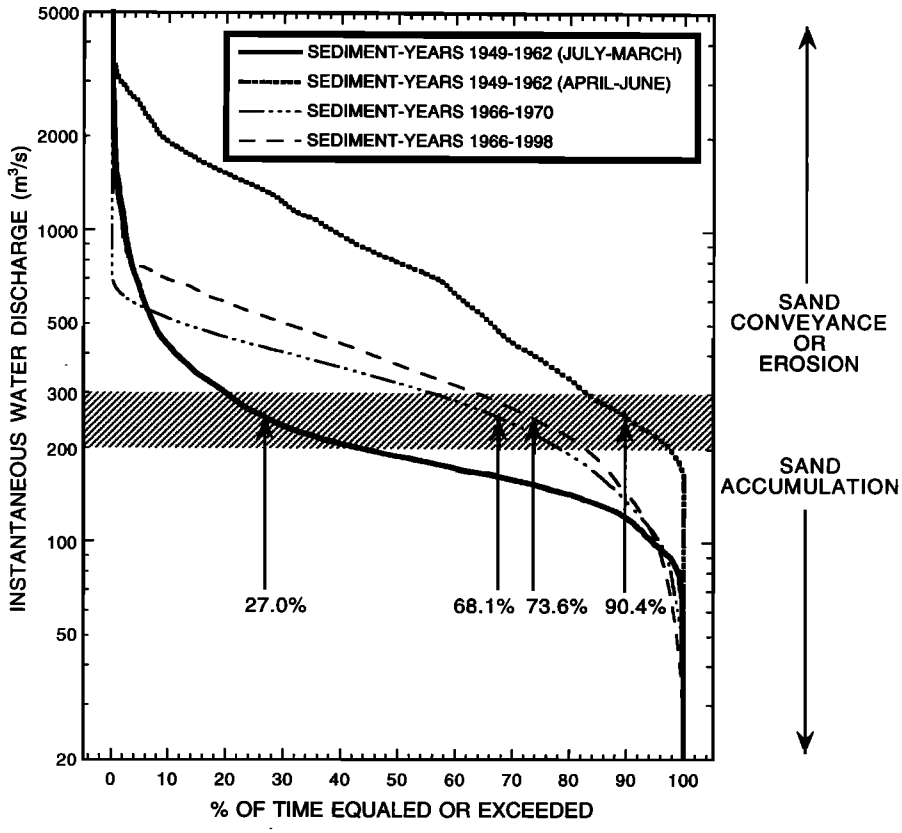

Figure 11. Flow-duration curves constructed from the instantaneous discharge record of the Colorado River at the Lees Ferry gage for the predam season of sand accumulation and storage (July–March), the predam season of sand erosion (April–June), sediment years 1966–1970, and sediment years 1966–1998. The cross-hatched region indicates the predam 200–300 m^3/s transition from sand accumulation to sand conveyance or erosion; also shown are the percentages of time at which flows of 250 m^3/s were equaled or exceeded in each period. The predam curves were constructed from data from sediment years 1949–1955, 1958, and 1960–1962. Because the raw stage and discharge data from October 1977 to September 1979 and October 1980 to September 1981 could not be found, the curve for sediment years 1966–1998 was constructed exclusive of these periods of missing data.

replaced by steady 30 m^3/s flows (Figure 9b). Closure of the dam in 1963 occurred in March; thus the dam was closed after the predam season of sand accumulation and storage (July–March), when storage of sand in Marble Canyon and the upper Grand Canyon was probably at an annual maximum.

In addition to greatly diminishing the sediment supply, Glen Canyon dam has transformed a reach in which accumulation or storage of sand dominated over most of a year to a reach in which conveyance or erosion of sand dominates over most of a year. In the average predam year, newly input sand was retained in storage in Marble Canyon and upper Grand Canyon for 9 months (given the assigned uncertainties). In contrast, in the average postdam year, newly input sand may be retained in storage for only 2 months.

Our interpretation of the postdam sediment budget agrees more closely with the early interpretation made by *Laursen et al.* [1976] than with three of the more recent interpretations. *Laursen et al.* [1976] concluded that under normal power plant releases, the capacity of the river to transport fine sediment exceeded the supply. In contrast, *Howard and Dolan* [1981], *Andrews* [1990, 1991], and *U.S. Department of the Interior* [1995] all predicted multiyear fine-sediment accumulation in Marble Canyon and upper Grand Canyon during normal power plant fluctuating flows. Our analyses do not preclude long-term fine-sediment accumulation under normal power plant flows in the postdam river but rather suggest that one cannot conclude this, given the uncertainties in the sediment budget. *Howard and Dolan* [1981] predicted that fine sediment should accumulate at a system-wide average rate of about 1 m per decade under normal power plant flows. They based their conclusion on (1) a high annual sediment yield for the ungaged tributaries of 780 t/km^2 and, more importantly, (2) the assumption that the uncertainties in the measured sediment loads were zero. *Andrews* [1990, 1991] based his conclusions on an estimated annual sediment export past the Grand Canyon gage of 9–11 million t, not on the measured mean-annual 1966–1972 export of 14 million t. The *U.S. Department of the Interior* [1995] based their conclusion on the assumption of stable relationships between the discharge of water and the sand-transport rate (i.e., stable sand rating curves). *Topping et al.* [this issue] have shown that because the grain size of sand on the bed of the Colorado River changes substantially over time, relationships between the discharge of water and sand-transport rate change significantly over time. During and immediately following a tributary flood, the sand on the bed of the Colorado River fines as the sand supply becomes enhanced. This causes the sand-transport rates in the Colorado River to increase independently of the discharge of water.

Then, in the weeks or months after the tributary flood the sand on the bed of the Colorado River is winnowed as the sand supply becomes depleted. This causes the sand-transport rates in the river to decrease independently of the discharge of water [*Topping et al.*, this issue]. Because the approach used by *U.S. Department of Interior* [1995] was calibrated to a relatively depleted bed-sediment condition, they probably underpredicted sand export and overpredicted sand accumulation in Marble Canyon and upper Grand Canyon [*Topping et al.*, 1999].

Further support for our interpretation of the postdam sediment budget comes from both predam and postdam measurements of sand-volume change in Marble Canyon and upper Grand Canyon. Geomorphic observations made in the postdam Colorado River do not generally support the system-wide accumulation of fine sediment predicted by *Howard and Dolan* [1981], *Andrews* [1990, 1991], and *U.S. Department of the Interior* [1995]. Except for during periods of local aggradation (fill) and subsequent degradation (scour) following large tributary sediment inputs, the recent geomorphic studies conducted in Marble Canyon and upper Grand Canyon have documented either no substantial net change in total sand volume over multiyear timescales or continued erosion of sand from this reach over multiyear timescales [*Webb*, 1996; *Graf et al.*, 1995, 1997; *Anima et al.*, 1998; *Grams and Schmidt*, 1998; *Hazel et al.*, 1999]. Storage of a fraction of the sand input during large floods on the Little Colorado River (in January–February 1993) has been observed to persist for as long as 3 years in the postdam Colorado River [*Graf et al.*, 1995, 1997; *Konieczki et al.*, 1997]. However, the magnitude of this measured longer-term storage was less than about 10% of the volume of the sand input during these extreme events [after *Graf et al.*, 1995, 1997; *Wiele et al.*, 1996; *Konieczki et al.*, 1997; *Rote et al.*, 1997]. Local increases in high-elevation sand volume after high main stem flows have been documented by *Beus et al.* [1985], *Schmidt and Graf* [1990], *Andrews et al.* [1999], *Hazel et al.* [1999], *Schmidt* [1999], and *Schmidt et al.* [1999], but these increases reflect mainly redistribution of sand in a reach and not net gains in sand volume. In the postdam river, only *Melis et al.* [1995], in their investigation of sediment accumulation in a pool upstream from a recently aggraded debris fan, documented a potentially substantial long-term increase in the volume of local sand storage.

The sole example used by *Howard and Dolan* [1981] to support of their prediction of net system-wide accumulation of fine sediment under normal power plant flows was an increase in bed elevation at the Grand Canyon cableway. Like the example studied by *Melis et al.* [1995], the bed at the Grand Canyon cableway aggraded by about 2 m in response to the December 1966 flood/debris flow on Bright Angel Creek [*Cooley et al.*, 1977; *Burkham*, 1986]. This event caused the rapid downstream from the cableway to aggrade and caused a major change in the stage-discharge relationship at the Grand Canyon gage [*Cooley et al.*, 1977; *Burkham*, 1986]. During a high dam release of 2800 m^3/s in 1983, the rapid was partially reworked, and the bed at the cableway scoured to its former elevation [*Burkham*, 1986]. Data reported by *Topping et al.* [this issue] show that though the bed at the Grand Canyon cableway temporarily aggraded during the 1996 flood experiment, the bed both the day before and 3 weeks after the 1996 flood experiment was at this lower pre-1966 elevation. These observations suggest that the 1967–1983 higher bed elevation at the Grand Canyon cableway was not indicative of system-wide aggradation (as interpreted by *Howard and Dolan* [1981]) but instead reflected a local change in conditions at the rapid immediately downstream from the cableway.

7. Conclusions

The predam Colorado River in Marble and Grand Canyons was an annually supply-limited system with respect to fine sediment (i.e., sand and finer material). The predam river in Grand Canyon exhibited four effects of sediment supply limitation: (1) seasonal hysteresis in sediment concentration, (2) seasonal hysteresis in sediment grain size associated with the hysteresis in sediment concentration, (3) production of inversely graded flood deposits, and (4) development or modification of a lag between the time of a flood peak and the time of either maximum or minimum (depending on reach geometry) bed elevation. Though the predam Colorado River in Glen Canyon also displayed some evidence of supply limitation, none of these effects occurred in Glen Canyon to the degree that they occurred downstream in Marble and Grand Canyons. Thus a predam increase in the degree of sediment supply limitation probably occurred at the change in hydraulic geometry near the head of Marble Canyon (where the river steepens and narrows).

Sediment budgets provide further evidence that the predam river in Marble Canyon and upper Grand Canyon was annually supply-limited with respect to fine sediment and suggest that the postdam river in this reach is also annually supply-limited with respect to fine sediment. Given reasonable uncertainties in the annual sediment loads (5% on the main stem Colorado River, 20% on the Paria and Little Colorado Rivers, and a factor of 3 on the ungaged tributaries), the annual supply of fine sediment to Marble Canyon and upper Grand Canyon can be shown to exceed the export in only 1 of the 11 predam years with complete data and in none of the first 7 years of the postdam era. The sole year in which substantial sediment was probably stored for more than 1 year was sediment year 1963. During this year, Glen Canyon Dam was closed in March, when storage of sand in Marble Canyon and upper Grand Canyon was probably at an annual maximum, and the naturally erosive annual snowmelt flood was replaced by sustained low flows.

Though the predam river in Marble Canyon and upper Grand Canyon was annually supply-limited with respect to fine sediment, it was not supply-limited during all seasons. During the average predam year, 0.0625–0.25 mm sand accumulated in this reach from July through March, with the storage of sand being relatively high from September through March. Then, during the higher flows of the annual snowmelt flood (April–June) this stored sand was eroded. During the average postdam year with fluctuating flows, however, no season of sand accumulation and storage is evident. Given the uncertainties in the sediment budget, storage of newly input sand can be documented in Marble Canyon and upper Grand Canyon for only 2 months (July through August). Indeed, because the flows in the postdam river are more similar to predam flows during periods of sand erosion than they are to predam flows during periods of sand accumulation and storage, substantial long-term accumulation of sand in the postdam system is unlikely. Thus the sediment-related impacts of the dam have not been only on the volume of the annual fine-sediment supply but, perhaps most significantly, also on the seasonal pattern of sand storage and erosion. Glen Canyon Dam has converted a system

in which sand would generally accumulate over 9 months and erode during 3 months of a year to one in which substantial storage of newly input sand cannot be demonstrated for more than 2 months per year.

Appendix A: Estimation of Ungaged Tributary Sediment Input

We estimated the monthly sediment loads of the ungaged tributaries by a two-step process. First, a long-term supply rate of 7.2 million t per decade for the ungaged tributaries between the Lees Ferry and Grand Canyon gages was estimated for the period of sediment-data overlap in the Paria and Little Colorado Rivers (i.e., sediment years 1949–1970). This value is equivalent to an annual fine-sediment yield of 220 t/km^2 (t indicates metric ton) and was determined by *Griffiths et al.* [1998] using the method of *Renard* [1972]. On the basis of USGS sediment-transport data and a 20% uncertainty, the annual sediment yields for the Paria and Little Colorado River basins are respectively 780 ± 160 and 130 ± 26 t/km^2. Because the geology in the ungaged tributary basins is more similar to that in the Little Colorado River basin than that in the Paria River basin and because the fine-sediment yield of the Paria River basin is known to be amongst the highest on the Colorado Plateau, the fine-sediment yield of 220 t/km^2 computed by *Griffiths et al.* [1998] is appropriate. After determination of the long-term supply rate, because the hydrology of the ungaged tributaries is somewhat similar to that of the Paria and Little Colorado Rivers, the fine-sediment load of the ungaged tributaries each month within sediment years 1949–1970 was set as proportional to the combined monthly fine-sediment load of the Paria and Little Colorado Rivers.

On the basis of the comparison of predictions of fine-sediment yield by the *Renard* [1972] method and field data from the Little Colorado River basin [*Griffiths et al.*, 1998], the uncertainty associated with the estimate of the fine-sediment loads in the ungaged tributaries was determined to be approximately a factor of 3. Though this approach may seem primitive, the sediment budget is not extremely sensitive to the uncertainty in the estimated fine-sediment input from the ungaged tributaries because the mean-annual input from this source (i.e., 0.72 ± (a factor of 3) million t/yr) is comparable to the mean-annual uncertainty associated with the measured fine-sediment inputs. For example, given a 5% uncertainty in the load of the Colorado River at Lees Ferry and a 20% uncertainty in the loads of the Paria and Little Colorado Rivers, the mean-annual uncertainty associated with the measured inputs is 5.3 million t/yr during the predam era and 2.3 million t/yr during the postdam era.

Appendix B: Sources of Sediment-Load Measurement Error

There are six major sources of measurement error inherent in the daily sediment loads used to construct the sediment budget for Marble Canyon and upper Grand Canyon. The first and most easily quantifiable source of error in daily sediment loads arises from the computation of the discharge of water. This error is greatest in rivers with poorly defined stage-discharge rating curves, like the hydrologically flashy Paria River. For the main stem Colorado River the rating curves and shifts in ratings were well defined; thus the discharge errors reported by the USGS were only 2% (unpublished USGS annual technical files from the Lees Ferry and Grand Canyon gages, 1948–1970). For the Little Colorado River the discharge errors reported by the USGS were typically 5% (unpublished USGS annual technical files from the LCR near Cameron gage, 1948–1970), though the discharge errors exceeded this during higher flows. However, for the Paria River, because of a general lack of discharge measurements at higher flows, the errors were much larger and greatly exceeded 10% during periods of high flow. During the period for which a sediment budget can be constructed (October 1947 through September 1970), 50% of all discharge measurements on the Paria River were made at flows less than 0.45 m^3/s, 97% of all discharge measurements were made at flows less than 15 m^3/s, and the highest discharge measurement was made at a flow of 76 m^3/s [after *Topping*, 1997]. During October 1947 to September 1970, 13 floods had peaks higher than the highest discharge measurement made during this period [*Topping*, 1997]. Because of these problems, the discharge errors reported by the USGS for the Paria River were typically 5% at flows less than 14 m^3/s and were greater than 8% at higher flows (unpublished USGS annual technical files from the Paria River Lees Ferry gage, 1948–1970). Prior to the first use of the modern slope-area method for estimating the peak discharge during a flood (method described by *Dalrymple and Benson* [1967]) in September 1963, errors in Paria River peak flood discharges sometimes exceeded 50% [*Topping*, 1997].

The five major sources of error related to determining sediment concentration are much harder to quantify and are typically larger than those associated with computing the discharge of water. The first of these is best termed a "sediment-station location error." This error has to do with whether a suspended-sediment measurement station is in a good location to measure sediment loads. In the Grand Canyon region this source of error was significant (but hard to quantify) only on the Little Colorado River (LCR), where discharges and suspended-sediment concentrations were measured at different locations. On this river, discharges (and ultimately sediment loads) were computed at the LCR near Cameron gage, but suspended-sediment concentrations were measured upstream at the highway 89 bridge at Cameron, Arizona (Figure 1). Importantly, a major sediment supplier to the LCR, that is, Moenkopi Wash, enters the LCR downstream from the suspended-sediment measurement station and upstream from the gage. The limited number of USGS suspended-sediment measurements made on Moenkopi Wash indicate that in similar flows, sediment concentrations in this stream are typically a factor of 5 or more higher than in the LCR. Indeed, in some years, more of the sediment supplied to the Colorado River by the LCR is from Moenkopi Wash than from the LCR above Moenkopi Wash [e.g., *Graf et al.*, 1996, Figure 25]. Memoranda circulated between the USGS and the Bureau of Reclamation (the agency who provided funding for the sediment-load measurements on the LCR) in 1949 indicate that the USGS was aware of this problem but because of funding limitations could not add a daily sediment station on Moenkopi Wash (unpublished USGS permanent technical file from the LCR at Cameron water-quality station (located at the highway 89 bridge at Cameron)). Therefore, during October 1947 through September 1970, the USGS attempted to account for the sediment inputs from Moenkopi Wash either by (1) subtracting the discharge from Moenkopi Wash and using the concentrations as measured at the LCR at Cameron, Arizona, water-quality station or (2) increasing the measured concen-

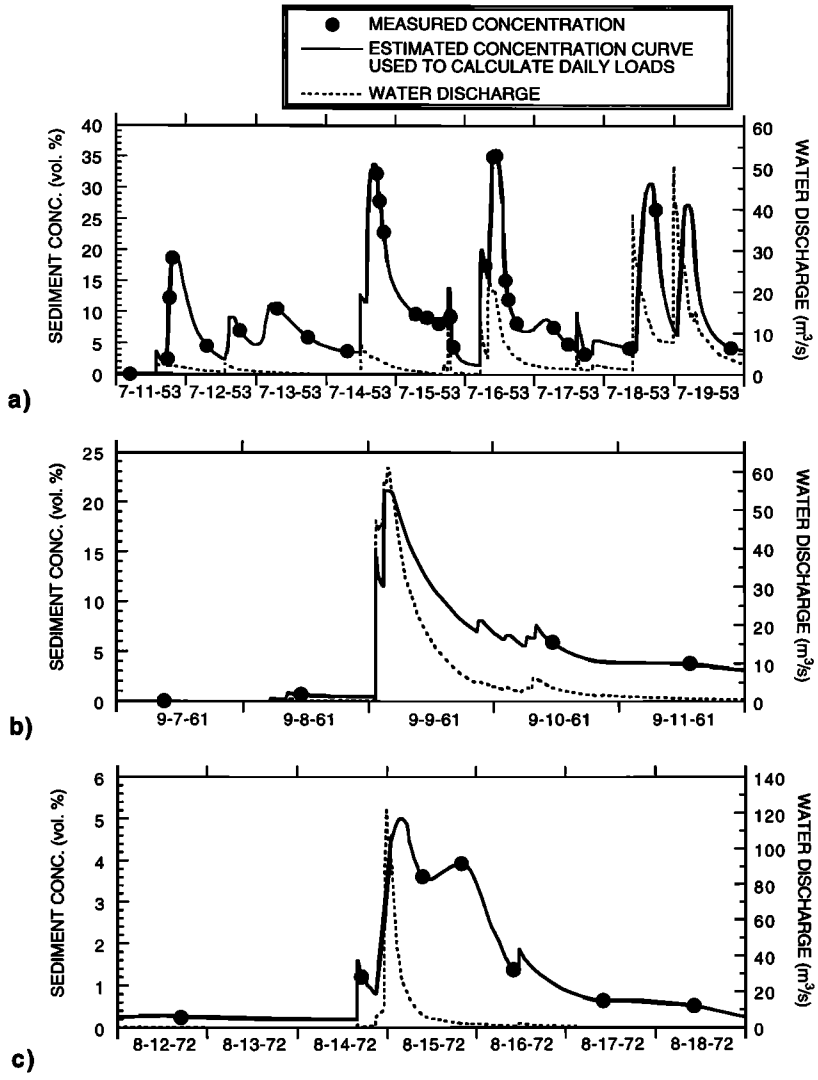

Figure 12. Paria River measured suspended-sediment concentrations, the curves constructed by the USGS to estimate sediment concentrations between the times of the measurements, and the instantaneous discharge of water. Measured and estimated concentrations in Figure 12 are from unpublished USGS sediment notes from the Paria River at Lees Ferry gage; the discharge of water was computed by *Topping* [1997] using unpublished raw USGS stage and discharge data from this gage. (a) An example of an unusually well measured period of tributary sediment loads in 1953. Note that in some cases, the time of the peak concentration was assumed to occur at the same time as the flood peak, and, in other cases (especially on July 18 and 19), it was assumed to lag the flood peak. (b) An example of a typically sparsely measured period of tributary loads in 1961. Note that (1) the concentrations during the entire flood on September 9 were estimated and not measured and (2) the peak concentration was assumed to be quite high and to occur at the same time as the flood peak. (c) Another example of a sparsely measured period of tributary sediment loads (but one in which a different interpretation was used to estimate concentrations) in 1972. In this case, like in Figure 12b, no measurements of sediment concentration were made during the flood on August 14–15. However, in this case, the peak concentration was assumed to be much lower than in Figure 12b (even though the peak discharge of this flood was much larger than that during the September 1961 flood) and was assumed to lag the flood peak.

trations at the LCR at Cameron, Arizona, water-quality station. Unpublished internal USGS memoranda dated December 26, 1950, and November 3, 1952, suggest that the error associated with the LCR sediment loads ranged from slightly less than 25% to as much as 50% (memoranda on file in unpublished USGS annual sediment technical files from the LCR at Cameron, water-quality station, 1949, 1951). In the memorandum dated November 3, 1952, the Regional Chemist C. S. Howard stated that "... the Geological Survey was getting records at the Cameron Bridge because that was where the Bureau of Reclamation wanted them but that we in the Survey knew they were not good records." In this same memorandum he argued that the sediment records from the LCR at Cameron should not be published and stated that he could not agree "... that the figures may have some definite value to others." Thus this "sediment-station location" source of error is extremely difficult to quantify.

The second source of error related to determining sediment

concentration arises from how well the spatial distribution of suspended sediment in a cross section is characterized. An example of this type of error comes from 1957 at the Lees Ferry gage, when only inadequate sampling equipment was available at the gage. During 1957, a D-43 suspended-sediment sampler was the only type of suspended-sediment sampler available for use at the Lees Ferry gage (unpublished USGS Lees Ferry gage annual technical file, 1958). Because a D-43 sampler could only sample to a depth of 4.5 m [*Guy and Norman*, 1970], the lower portion of the Colorado River at Lees Ferry could not be sampled properly during higher flows. Thus the measured sediment load at the Lees Ferry gage during the higher portions of the 1957 snowmelt flood was too low. The USGS corrected this problem during 1958, when the D-43 was replaced by a P-46 sampler, a sampler designed for deeper, higher-velocity flows (unpublished USGS Lees Ferry gage annual technical file, 1958).

The third source of error related to determining sediment concentration arises from how well changes in sediment concentration over time are characterized during periods of rapidly varying flow. During these periods, sediment loads in the intervals between measured concentrations were estimated by first drawing a curve between the measured concentrations and then multiplying the estimated concentrations along this curve by the discharge during these intervals (see *Porterfield* [1972] for a detailed description of this procedure). Because typically only 1 or 2, and sometimes no, samples were collected during large flood events on the Paria and Little Colorado Rivers, this source of error may easily have been as high as 100% during individual floods on these rivers (Figure 12). This source of error also became significant on the main stem Colorado River at the Grand Canyon gage during the postdam era when only one sample was collected each day under daily fluctuating flows. Therefore this source of error is probably the largest source of error in the sediment budget for Marble Canyon and upper Grand Canyon.

The fourth and fifth sources of error related to determining sediment concentration arise from changes in personnel and laboratory analyses. Because of the complexity of measuring sediment loads in a river, significant errors or changes in the magnitude of error can be introduced into sediment-load data when there is a change in the personnel making the measurements [e.g., *Allen and Petersen*, 1981]. Allen and Petersen found that a difference in sediment load of 30% was possible when the load was calculated using samples collected by personnel with different levels of experience. Also, a significant error or change in the magnitude of error can be introduced when there is a change in the personnel making the computations. For example, in computing loads, one person might assume that the maximum sediment concentration occurs at the same time as the flood peak, and another might assume that it occurs at a different time (Figure 12). The other place where errors can be introduced into sediment-load data is in the laboratory where the samples are processed, but this is typically the smallest of all of the sources of error.

As indicated by the above summary of the sources of measurement error, uncertainties in the calculated sediment load on any individual day can be quite large but are difficult to quantify. On the main stem Colorado River they were probably as large as 10–30%, and on the Paria and Little Colorado Rivers, they could easily have been as high as 50–100%. Because the uncertainty in the mean of a time series is typically much smaller than the uncertainties associated with the individual measurements (when the various sources of error are uncorrelated), the uncertainties associated with sediment loads over monthly or annual timescales were probably smaller. However, because the error associated with measurements of sediment concentration are all much larger than the error associated with the computation of the discharge of water, the uncertainties in the sediment loads still had to be much larger than those associated with the computation of the discharge of water.

Therefore, perhaps the best way to estimate the minimal probable uncertainty in monthly or annual sediment loads is to multiply the uncertainty in the discharge of water by about a factor of 2. This approach yields minimal uncertainties in the monthly or annual sediment loads in the Colorado, Paria, and Little Colorado Rivers of about 5%, 20%, and 10%, respectively. However, because of the different locations at which sediment concentrations and the discharge of water were measured, the errors thought by USGS personnel to exist in the Little Colorado River sediment records ranged from slightly less than 25% to as much as 50%. Thus a reasonable minimal uncertainty in the monthly or annual sediment loads in the Little Colorado River is also 20%. Therefore, in this paper, uncertainties of 5% are assigned to the measured sediment loads of the Colorado River, and uncertainties of 20% are assigned to the measured sediment loads of the Paria and Little Colorado Rivers.

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D. M. Rubin, U.S. Geological Survey, 345 Middlefield Road, MS 999, Menlo Park, CA 94025. (drubin@usgs.gov)

D. J. Topping, U.S. Geological Survey, National Center, MS 430, 12201 Sunrise Valley Drive, Reston, VA 20192. (dtopping@usgs.gov)

L. E. Vierra Jr., Department of Civil and Environmental Engineering, University of Colorado, Boulder, CO 80309. (Leslie.Vierra@Colorado.EDU)

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