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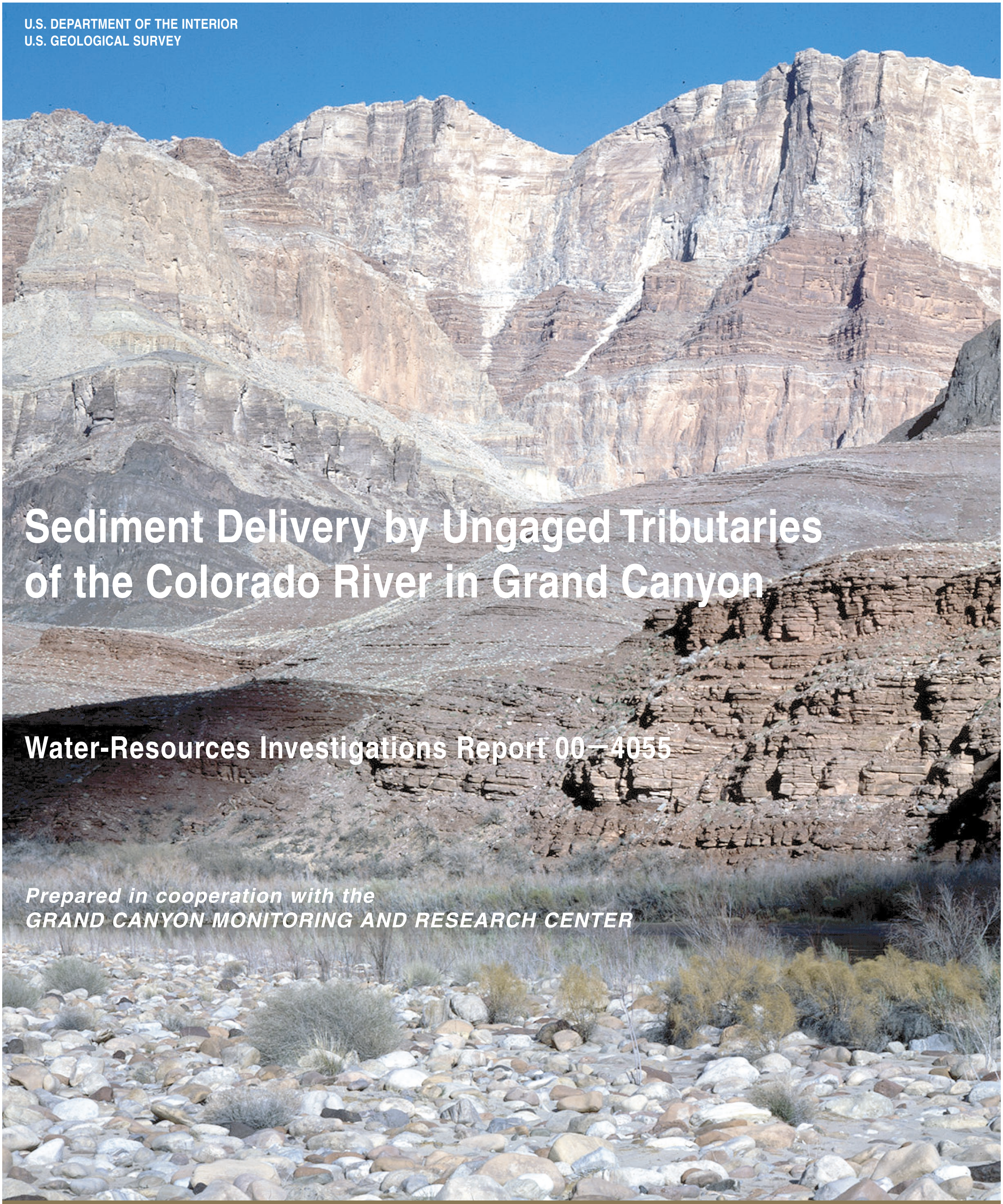

Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon

Water-Resources Investigations Report 00–4055

Prepared in cooperation with the
GRAND CANYON MONITORING AND RESEARCH CENTER

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Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon, Arizona

By Robert H. Webb, Peter G. Griffiths, Theodore S. Melis, and Daniel R. Hartley

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Tucson, Arizona
2000

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

For readers who prefer to use inch-pound units, conversion factors for the terms in this report are listed below:

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.2818	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second(m^3/s)	35.31	cubic foot per second (ft^3/s)
gram (g)	0.03527	ounce avoirdupois (oz avdp)
kilogram (kg)	2.205	pound avoirdupois (lb avdp)
megagram (Mg)	1.102	tons, short (2,000 pounds)

Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon, Arizona

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Abstract

Sediment input to the Colorado River in Grand Canyon, Arizona, is a valuable resource required to sustain both terrestrial and aquatic ecosystems. A total of 768 ungaged tributaries deliver sediment to the river between Glen Canyon Dam and the Grand Wash Cliffs (river miles -15 to 276). The 32 tributaries between the dam and Lee's Ferry produce only streamflow floods, whereas 736 tributaries in Grand Canyon produce streamflow floods and debris flows. We used three techniques to estimate annual streamflow sediment yield from ungaged tributaries to the Colorado River. For the Glen Canyon and Marble Canyon reaches (river miles -15 to 61.5), respectively, these techniques indicate that $0.065 \cdot 10^6$ and $0.610 \cdot 10^6$ Mg/yr ($0.68 \cdot 10^6$ Mg/yr of total sediment) enters the river. This amount is 20 percent of the sediment yield of the Paria River, the only gaged tributary in this reach and a major sediment contributor to the Colorado River. The amount of sand delivered ranges from $0.10 \cdot 10^6$ to $0.51 \cdot 10^6$ Mg/yr, depending on the sand content of streamflow sediment. Sand delivered in Glen Canyon is notably coarser (D_{50} = 0.24 mm) than sand in other reaches (D_{50} = 0.15 mm). A relation is given for possible variation of this sediment delivery with climate.

Debris flows transport poorly-sorted sediment onto debris fans in the Colorado River. In the pre-dam era, debris fans were completely reworked during Colorado River floods, liberating all fine-grained sediment to the river; in the post-dam river on average only 25 percent of debris-fan volume is reworked, leading to storage of sand in the matrix of debris fans. We develop a sediment-yield model for debris flows that uses a logistic-regression model of debris-flow frequency in Grand Canyon, a regression model of debris-flow volumes, particle-size distributions of intact debris-flow deposits, and debris-fan reworking. On average, debris flows deliver between $0.14 \cdot 10^6$ and $0.30 \cdot 10^6$ Mg/yr of sediment to debris fans throughout Grand Canyon. Together, streamflow and debris flow deliver nearly $2.8 \cdot 10^6$ Mg/yr of sediment to the Colorado River from ungaged tributaries. In the post-dam era of minimal debris-fan reworking, the combined sand delivery rate in Glen and Marble Canyons averages $0.32 \cdot 10^6$ Mg/yr, which is 20 percent of the sand delivery of the Paria River and double the $0.17 \cdot 10^6$ Mg/yr of sand estimated for this reach in the 1995 environmental impact statement for operation of Glen Canyon Dam.

INTRODUCTION

Because of the presence and operation of Glen Canyon Dam on the Colorado River, sediment supply and transport in Grand Canyon is an important management issue (U.S. Department of the Interior, 1995; Schmidt and others, 1998). Glen Canyon Dam blocks the prodigious input of fine-grained sediment that used to enter Grand Canyon, replenish beaches, and provide substrate for the riverine ecosystem. With the closure of the dam in 1963, sources of fine-grained sediment in Grand Canyon have been limited to major tributaries, such as the Paria and Little Colorado Rivers and Kanab and Havasu Creeks (Andrews, 1991), and numerous small tributaries. The major tributaries have gaging records from which flow and sediment transport have been estimated (U.S. Department of the Interior, 1995).

With the exception of Bright Angel Creek (fig. 1), the small tributaries below the dam are ungaged. Previous estimates of sediment yield from these tributaries range from zero to the yield from a major gaged tributary with a drainage area equivalent to the total drainage area of all ungaged tributaries. A combination of fluvial and hillslope processes occurs in small tributaries in Grand Canyon, making estimates of sediment yield complicated. Sediment-yield estimates must consider the contributions of streamflow, which occur annually in most tributaries, as well as debris flow (Webb and others, 1989). In addition to their importance as sources of fine-grained sediment, the small tributaries create and maintain debris fans and rapids on the Colorado River (Powell, 1895; Hamblin and Rigby, 1968; Dolan and others, 1974; Howard and Dolan, 1981; Kieffer, 1985). These tributaries transmit large boulders in debris flows (Cooley and others, 1977; Webb and others, 1989), and reworking of debris fans creates a pool-rapid configuration that stores fine-grained sediment along the Colorado River (Howard and Dolan, 1981; Schmidt and Graf, 1990; Schmidt and Rubin, 1995; Webb, 1996).

Debris flows occur in 736 tributaries of the Colorado River in Grand Canyon between Lee's Ferry and Diamond Creek, Arizona. By supplying boulders that exceed the competence of regulated discharges in the river, debris flows also directly control the navigability of the Colorado River, affecting the more than 20,000 whitewater enthusiasts who use the Colorado River for recreation each year (Stevens, 1990). Understanding the sediment contribution of debris flows over long and short periods of time is important to future adaptive management of the riparian ecosystems and recreational resources of Grand Canyon. Debris flows periodically contribute relatively large volumes of sediment to the river. The hundreds of debris fans that have accumulated along the Colorado River directly control the formation and stability of most sand bars (Schmidt, 1990; Schmidt and Graf, 1990; Schmidt and Rubin, 1995). Therefore, a better understanding of debris flows and the amount of sediment yield from ungaged tributaries is useful to understand trends in the highly regulated sediment budget of Grand Canyon.

Development of a sediment budget for the Colorado River through Grand Canyon requires an estimate of long-term sediment yields for both coarse and fine particles from hundreds of ungaged tributaries. Estimating these sediment yields depends on estimates of debris-flow frequency and magnitude for as many tributaries as possible. Because the river removes only the finer particles from debris-flow deposits, sediment-yield estimates also require knowledge of the particle-size distributions of those debris flows that reach the river. Increased knowledge of debris flow and mainstem processes in Grand Canyon will contribute to future efforts to operate Glen Canyon Dam in ways that minimize downstream impacts. This report presents the total sediment yield and sand delivery rates for the ungaged tributaries, which previously have been unknown or assumed parts of the sediment budget for the Colorado River.

Purpose and Scope

The purpose of this report is to estimate the total sediment yield and sand delivery from ungaged tributaries in each of six reaches between Glen Canyon Dam and upper Lake Mead reservoir at the Grand Wash Cliffs (fig. 1). This includes the entire drainage area between Glen Canyon Dam and upper Lake Mead reservoir except for the four largest tributaries. These estimates are based on an evaluation of both the debris-flow and streamflow components of sediment yield by multiple techniques. As a secondary objective, we evaluate the potential influence of climatic variability on sediment input in the light of historical climatic fluctuations. This study was funded in cooperation with the Bureau of Reclamation, as part of the Glen Canyon Environmental Studies Program, and the Grand Canyon Monitoring and Research Center.

Acknowledgments

The authors thank many individuals who helped with the field and office work that led to this report. These individuals have been cited in other publications, including Melis and others (1994),

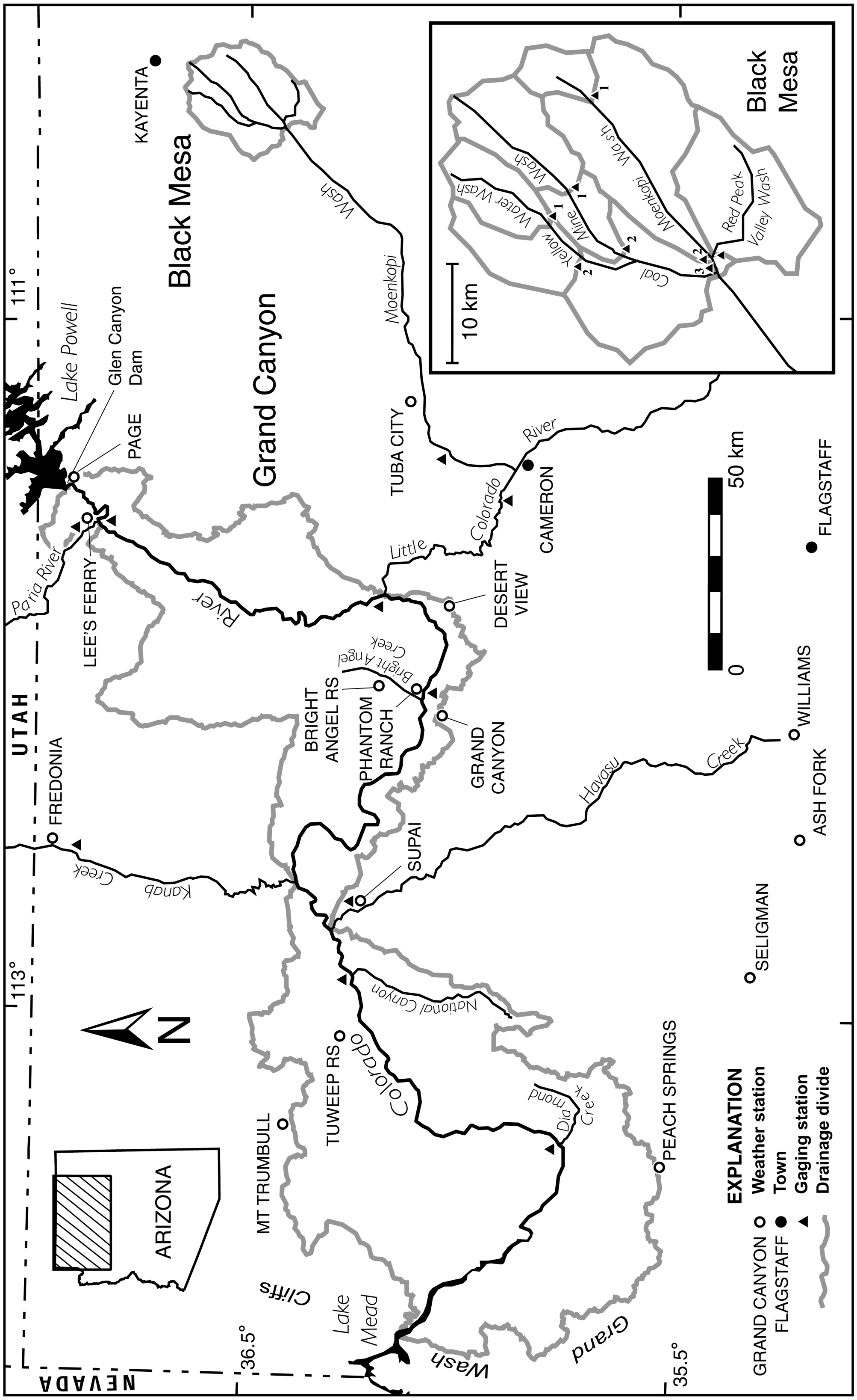

Figure 1. The Colorado River between Lake Powell and Mead reservoirs.

Webb (1996), and Webb and others (1999b), and their names will not be repeated here. The authors thank Bill Dietrich and Alan Howard for sharing ideas that led to some of the techniques used in this report. We also thank Grand Canyon Monitoring and Research Center and David Topping for laboratory analysis of streamflow sediment, and Waite Osterkamp, Richard Hereford, David Topping, and Jon Major for their reviews of the manuscript. We particularly thank Dave Wegner for his support of this project over the span of a decade.

Units and Place Names

In this report, we use metric units for all measures except river mile, which is used to describe the location of tributaries in Grand Canyon (Stevens, 1990), certain reference river discharges (*e.g.*, 10,000 ft^3/s), and in equations that were originally developed for use in English units. Use of river mile has considerable historical precedent and provides a reproducible method of describing the location of tributaries with respect to the Colorado River. The locations of tributaries are described using river miles downstream from Lee's Ferry and a descriptor of "L" for confluences on river-left and "R" for river-right. The left and right sides of the Colorado River are determined as one faces downstream.

We typically refer to "Grand Canyon" in broad reference to the Colorado River watershed between Glen Canyon Dam and the Grand Wash Cliffs, including Glen, Marble, and Grand Canyon proper. "Marble Canyon" is the canyon reach of the Colorado River between Lee's Ferry and the confluence with the Little Colorado River (river miles 0 to 61.5; fig. 1); we refer to Marble Canyon only for specific tributaries in that reach. For our purposes, "Glen Canyon" is the canyon reach of the Colorado River between Glen Canyon Dam (mile -15) and Lee's Ferry (mile 0). Following Reilly (1999), we use an apostrophe in "Lee's Ferry," despite the official Board of Geographic spelling of "Lees Ferry."

For sediment particle sizes, we use the standard unit ϕ, defined as

$$D = 2^{-\phi}, \qquad (1)$$

where D = the diameter, in millimeters, of the intermediate axis, also known as the b-axis (Folk, 1974).

PREVIOUS STUDIES

Definitions of Flow Types That Occur in Grand Canyon Tributaries

Debris flows are an important sediment-transport process in a variety of geomorphic settings throughout the world. Costa (1984) described debris flows as water-based slurries of poorly sorted material ranging in size from clay to boulders. Debris flows occur in arid, semi-arid, tropical, and montane environments. In these settings, they are typically called mudflows, debris slides, and debris torrents, to name a few of the more common terms (Blackwelder, 1928; Sharp and Nobles, 1953; Johnson and Rodine, 1984; Pierson, 1984; Pierson and Costa, 1987). Debris flows can have devastating effects on populated areas (Pierson and others, 1990), but damage can also be significant even in sparsely populated areas (Glancy and Harmsen, 1975; Wohl and Pearthree, 1991).

Debris flows are slurries of clay- to boulder-sized sediment with volumetric water concentration ranges from about 10 to 30 percent (Pierson and Costa, 1987; Major and Pierson, 1992). A variety of classifications has been proposed for distin-guishing debris flows, "hyperconcentrated flows," and streamflow (Beverage and Culbertson, 1964); recent work has focused on rheological properties (Pierson and Costa, 1987) and the interactions of fluid and solid forces (Iverson, 1997). Debris flows are characterized by cohesive properties that are probably related to clay content, sand content, grain-particle interactions, and the ability to transport large boulders (Rodine and Johnson, 1976; Johnson and Rodine, 1984; Costa, 1984). Source lithologies strongly affect particle-size distributions and, therefore, flow rheology in debris flows. These lithologies vary greatly within and between individual drainages in Grand Canyon. Most debris-flow deposits have few or no sedimentary structures, very poor sorting, and massive appearance. In low-gradient channels, debris flows typically are depositional. In steep channels, all of these types of floods can cause erosion, particularly debris flows (Pierson, 1980).

In addition to debris flows, streamflow and "hyperconcentrated flow" occur in Grand Canyon. Streamflow typically has a sediment concentration by weight of less than 40 percent (Pierson and Costa, 1987). Hyperconcentrated flow, as originally defined by Beverage and Culbertson (1964) and modified by Pierson and Costa (1987), contains 40 to 70 percent sediment by weight. Hyperconcentrated-flow deposits are differentiated from those of streamflow and debris flow by sedimentological criteria based on differences in particle-size distribution, sedimentary structures such as slight laminar bedding, and an overall coarse-sand, upward-coarsening texture commonly containing erratic cobbles and boulders (Pierson and Costa, 1987). Hyperconcentrated flow has been associated with recessional flow following debris flows in Grand Canyon (Webb and others, 1989).

Magnitude and Frequency of Debris Flows

Before 1990, three studies addressed the magnitude and frequency of debris flows in Grand Canyon. Cooley and others (1977) examined debris flows that occurred in 1966 in several tributaries of the Colorado River, including Lava Canyon and Crystal Creek (river miles 65.5-R and 98.2-R). They estimated the magnitude of the debris flow in Dragon Creek, a tributary of Crystal Creek (river mile 98.2-R), and inferred some frequency information from damage to archaeological sites. In an examination of aerial photography, Howard and Dolan (1981) reported that 25 percent of all debris fans in Grand Canyon had been affected by tributary floods between 1965 and 1973. In addition, Webb and others (1989) reported magnitude and frequency information for three tributaries of the Colorado River.

Many researchers have described the rapids that dominate the river corridor of Grand Canyon (Leopold, 1969; Cooley and others, 1977; Graf, 1979; Howard and Dolan, 1981; Webb and others, 1988, 1989; Melis and others, 1994). The infrequent and episodic nature of debris flows in Grand Canyon's tributaries results in catastrophic modifications to alluvial debris fans and associated rapids over very short time periods, in most cases minutes to hours (Webb and others, 1988, 1989). Similarly, debris flows are capable of altering sand bars, commonly termed "beaches," through burial and (or) erosion when they issue from tributaries into the river channel. Debris flows also influence the net volume of fine sediment stored in the river channel by forming low-velocity sediment traps, commonly referred to as eddy-complexes, upstream and downstream of debris fans. Eddies effectively trap fine sediment entering the river channel from tributaries (Schmidt and Graf, 1990).

Howard and Dolan (1981) attributed aggradation on debris fans between 1965 and 1973 to tributary flooding, but only generally referred to debris flow as a sediment-transport process. Other researchers have more-fully documented the role of debris flow in the creation and maintenance of debris fans and rapids in Grand Canyon (Cooley and others, 1977; Webb, 1996; Webb and others, 1988, 1989; Melis and others, 1994). On the Green River, Graf (1979) studied the effects of regulated releases from Flaming Gorge Reservoir on downstream rapids. He reported a significant increase in the stability of rapids, and predicted a trend of continuing aggradation at those sites because of reduced mean-annual discharges in the river.

Before flow regulation began in 1963, the Colorado River in Grand Canyon was known for the high inter-annual variability of its flooding. Periodic, large floods on the river worked together with tributary rockfalls and debris flows in forming one of the world's most spectacular erosional features. The reduction of the size of the annual flood on the Colorado River since 1963 now limits the river's competence to extensively erode newly-deposited debris that continues to accumulate on debris fans. Howard and Dolan (1981) report that this decrease in the size of flood flows represented a four-fold decrease in the sediment-transport potential of the river. Tributaries downstream from Glen Canyon Dam remain unregulated, and their continuing debris flows remain an effective agent of change to the river corridor (Howard and Dolan, 1981; Webb, 1987). As a result, the "quasi-equilibrium" (Langbein and Leopold, 1964) that likely existed between the river and its tributaries in the pre-dam era have been perturbed in favor of the tributaries since 1963. Anticipated changes of locally-increased flow gradients and navigational hazards in rapids are only the most obvious consequences of continuing debris flows. Other consequences include burial and erosion of existing sand bars, increased sand storage in eddies and pools, and overall aggradation of the channel.

TRIBUTARIES AND REACHES OF THE COLORADO RIVER IN GRAND CANYON

Definition of Geomorphically Significant Tributaries

Our definition of "geomorphically significant tributaries" includes numerous small drainages that have potential to produce debris flows that alter the river channel or yield significant amounts of streamflow-transported sediment (appendix 1). The criteria for designating drainages were determined from analysis of 44 U.S. Geological Survey 7.5-minute topographic maps of the river corridor and 126 maps of the Grand Canyon region. Included were all tributaries between Glen Canyon Dam and the Grand Wash Cliffs (fig. 1) that: 1) have drainage areas larger than 0.01 km^2, 2) have mapped perennial or ephemeral streams, 3) clearly terminate at the Colorado River in a single channel, and (or) 4) contribute to formation of obvious debris fans and (or) rapids. We excluded the Paria and Little Colorado Rivers and Kanab and Havasu Creeks because their sediment yields are relatively well known. Drainage areas that could not be designated significant using the criteria outlined above were designated as "extra areas", rather than tributaries. This type of drainage area consists of steep slopes with no identifiable channel on topographic maps and contributes sediment primarily by streamflow, though it may occasionally yield small debris flows.

Drainage areas of geomorphically significant tributaries and extra areas were digitized from hand-drawn outlines on 7.5-minute topographic maps. Numerical routines that define drainage areas from digital elevation models (Jensen and Domingue, 1988) performed inadequately in the steep terrain of Grand Canyon and were not used. Place names were derived from well-known river guides (Stevens, 1990), gazetteers (Brian, 1992), and topographic maps. Exceptions were made where Board of Geographic Names spellings are not consistent with the person being commemorated. For example, "Deubendorf Rapid," the official name, is incorrectly named for Seymour Dubendorff (Webb, 1996), and therefore we refer to this rapid as Dubendorff Rapid (appendix 1).

Designation of Reaches of the Colorado River

Researchers long have recognized differences in the characteristics of the river corridor through Grand Canyon (Howard and Dolan, 1981). Previous studies have divided the Colorado River between Lee's Ferry and Diamond Creek into eleven reaches on the basis of topographic characteristics and bedrock type (Howard and Dolan, 1981), as well as on the basis of individual formations at river level and channel gradient (Schmidt and Graf, 1990). Using an approach modified after Howard and Dolan (1981), Melis modified Schmidt and Graf's reaches by including data on debris-fan morphology and spacing. By this approach, Melis (1997) re-defined the eleven reaches of Schmidt and Graf (1990) into six major reaches with two subdivisions of Reach 4 (table 1). For this paper, we add a reach 0 (Glen Canyon) and extend reach 6 of Melis (1997) to the Grand Wash Cliffs at the downstream end of Grand Canyon (table 1).

This designation of geomorphic reaches differs significantly from the reaches required for a sediment mass balance between gaging stations on the Colorado River and tributaries with sediment-yield data. At various times, sediment data have been collected at gaging stations on the mainstem Colorado River and its tributaries (Garrett and others, 1993; Rote and others, 1997). The mainstem gaging stations are the Colorado River at Lee's Ferry (station 09380000, mile 0.0), the Colorado River above the Little Colorado River (09383100, mile 61.5), the Colorado River near Grand Canyon

Table 1. Geomorphic and sediment-yield reaches of the Colorado River in Grand Canyon (modified from Melis, 1997).

Reach number	Reach name	RIVER MILE Starting	RIVER MILE Ending	Average Channel Width* (m)
	Geomorphic Reaches			
0	Glen Canyon	-15	0	137 (34)
1	Upper Wide I	0	8	108 (5)
2	Upper Narrow I	8	38	83 (2)
3	Upper Wide II	38	77	133 (2)
4	Middle Narrow II	77	170	69 (1)
4a	IIA†	87	100	84 (3)
4b	IIB†	117	128	93 (3)
5	Lower Wide III	170	213	126 (2)
6	Lower Narrow III	213	276	103 (5)§
	Sediment-Yield Reaches			
A	Glen Canyon Dam - Paria River	-15.5	0.9	
B	Paria - Little Colorado River	0.9	61.5	
C	Little Colorado - Bright Angel Creek	61.5	87.8	
D	Bright Angel - Kanab Creek	87.8	143.5	
E	Kanab - Havasu Creek	143.5	156.8	
F	Havasu - Diamond Creek	156.8	225.8	
G	Diamond - Grand Wash	225.8	276.0	

* Width measured at approximately 8,000 ft^3/s; standard deviation given in parentheses.
† Subreaches that widen over relatively short distances.
§ Based on measurements down to Diamond Creek; the river is impounded by Lake Mead reservoir below river mile 240.

(09402500, mile 87.3), the Colorado River above National Canyon (09404120, mile 166.0), and the Colorado River above Diamond Creek (09404200, mile 225.2); the primary tributary gaging stations are Paria River at Lee's Ferry (09382000), the Little Colorado River near Cameron (09402000), Kanab Creek near Fredonia (09403780), and Havasu Creek near Supai, Arizona (09404115). Several other gaging stations on these tributaries have short gaging records (Rote and others, 1997). A small amount of sediment data has been collected for Bright Angel Creek at Phantom Ranch. For this report, we use seven sediment-yield reaches that correspond to river segments between tributaries with gaging records or other estimates of sediment input (table 1).

Drainage Areas of Ungaged Tributaries

We designated 768 geomorphically significant tributaries between Glen Canyon Dam and the Grand Wash Cliffs, updating the results of Melis and others (1994; appendix 1). The total drainage area of these tributaries is 12,362 km^2 (table 2); most of these tributaries range from 1-5 km^2 in area (fig. 2a), and Reaches E and F have the largest area of ungaged tributaries (fig. 2b). When 461 extra areas that have an area of 514 km^2 are included, the total area of ungaged tributaries yielding sediment by streamflow is 12,876 km^2. Of the 768 tributaries, 736 in Grand Canyon produce streamflow floods and debris flows, whereas 32 tributaries between Glen Canyon Dam and Lee's Ferry (miles -15 to mile 0) produce only streamflow. Thus, the area of ungaged tributaries contributing debris flows in Grand Canyon is 12,072 km^2.

CLIMATIC VARIABILITY IN THE GRAND CANYON REGION

Geomorphic and sediment-transport processes in Grand Canyon are related to climatic variability (Graf and others, 1991; Hereford and Webb, 1992),

Table 2. Drainage areas of ungaged tributaries of the Colorado River between Glen Canyon Dam and Upper Lake Mead reservoir, Arizona.

Sediment-yield reach	River miles	Tributary drainage area (km^2)	Extra drainage area (km^2)	Total drainage area (km^2)
A	-15.5 to 0.9	291	31	321
B	0.9 to 61.5	2,833	120	2,953
C	61.5 to 87.8	458	36	494
D	87.8 to 143.5	1,540	100	1,640
E	143.5 to 156.8	234	42	276
F	156.8 to 225.8	3,820	138	3,958
G	225.8 to 276.0	3,187	48	3,236
	TOTAL	12,363	515	12,878

albeit in a complex manner (Webb and others, 1999b). Several studies have analyzed various aspects of rainfall variability in the Grand Canyon region (Hereford and Webb, 1992; Hereford and others, 1993; Melis and others, 1994, 1996; Webb and others, 1999b). To update these analyses, and to add more data, we used 14 weather stations from around Grand Canyon (fig. 1, table 3). Few of these weather stations are between the North and South Rims. Stations in the Grand Canyon region have mean annual precipitation that ranges from 148 to 655 mm; the average of the 14 stations is 316 mm. About 37 percent of precipitation in the Grand Canyon region occurs in winter (November-March) and 35 percent occurs in summer (July-September).

Seasonal precipitation by water year was standardized following an established technique (Hereford and Webb, 1992) to examine the effects of antecedent soil moisture on debris-flow initiation. For each weather station (table 3), we calculated the standardized seasonal precipitation, P_s, by

$$P_s = \frac{\Sigma\{\Sigma[(x_{ij} - u_i)/\sigma_i]/k\}}{n}, \qquad (2)$$

where $x_{i,j}$ = monthly precipitation for weather station i in month j (mm); μ_i = the mean and σ_i = the standard deviation of monthly precipitation for weather station i (mm); k = the number of months in the season; and n = the number of weather stations with data.

Annual and seasonal precipitation in the Grand Canyon region has varied considerably in the 20th century (figs. 3, 4). In the period from 1980 through 1998, 15 years had above-average annual

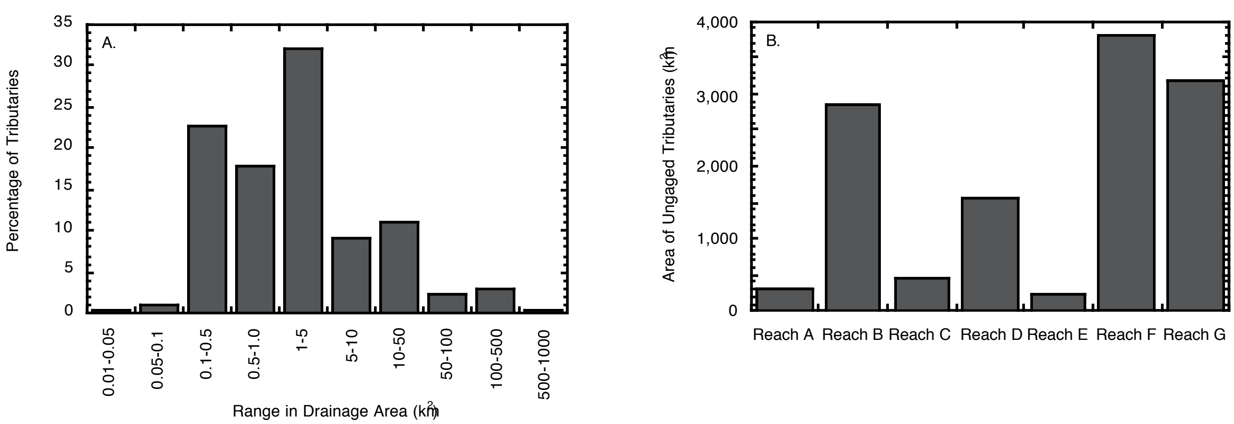

Figure 2. Drainage areas of ungaged Grand Canyon tributaries. A. Histogram of drainage areas. B. Comparison of total ungaged drainage area by sediment-yield reach.

Table 3. Characteristics of weather stations in the Grand Canyon region.

Station name*	Elevation (m)	Record length	Mean annual precipitation (mm)	Summer precipitation (%)	Winter precipitation (%)
Ash Fork**	1,581	4/09-12/98	366	39	39
Bright Angel RS**	2,726	7/48-12/98	655	23	44
Desert View	2,271	9/60-7/95†	347	31	37
Grand Canyon**	2,204	10/04-12/98	403	34	36
Lees Ferry	978	4/16-12/98	148	40	38
Mount Trumbull	1,818	10/20-12/78§	299	41	29
Page	1,315	11/57-12/98	169	28	41
Peach Springs	1,613	7/48-12/98	285	37	31
Phantom Ranch**	834	8/66-12/98	238	31	39
Seligman**	1,618	12/04-12/98	293	42	40
Supai	987	6/56-02/78§	212	40	32
Tuba City	1,550	1/00-12/98	164	37	38
Tuweep RS**	1,551	7/48-12/86#	288	35	39
Williams**	2,080	10/00-12/98	551	36	36

*All stations are in Arizona (fig. 1).
†Daily data from September 1, 1960, to July 1, 1975, have been lost at this station, which is not part of the NOAA network. Monthly data is available from September 1960 to about August 1995 from the National Park Service.
§Station discontinued.
#In 1986, Tuweep Ranger Station was discontinued as a cooperative observer station, which records rainfall in 0.25 mm accuracy and reports increments of daily rainfall. A tipping-bucket recording rain gage, which records rainfall in 2.54 mm increments and reports hourly as well as daily rainfall (*e.g*., U.S. Department of Commerce, 1966), remains in operation. Between 1995 and 1998 the station record is mostly missing.
** Daily precipitation and storm frequency was analyzed for this station.

precipitation (fig. 3), which is unique in the last century. On a decadal basis (fig. 5), the above-average precipitation of the 1980s and 1990s is comparable only to that of the 1900s. Annual precipitation from 1940 through 1979 was below average on a decadal basis, as shown by other regional studies (Hereford and Webb, 1992; Webb and Betancourt, 1992), indicating that annual precipitation in the southwestern United States is nonstationary.

Seasonal precipitation also shows considerable interannual and interdecadal variability. Summer (July-September) and winter (November-March) precipitation (fig. 4) has not responded in the same way in each year. With notable exceptions, particularly 1983 and 1984, summer precipitation generally has been above-average when winter precipitation was below average. From 1984 through 1998, summer precipitation was above average in 6 years (40 percent), whereas winter precipitation was above average in 10 years (67 percent). Despite this, the 1980s and 1990s both had above-average seasonal precipitation because of exceptional years (*e.g*., 1997 for summer, 1993 for winter). For summer precipitation, the decade of the 1930s was similar to the 1980s and 1990s, but the above-average winter precipitation in the last two decades is comparable only to that of the 1900s (fig. 5).

STREAMFLOW SEDIMENT YIELD

We used three methods to estimate streamflow sediment yield from the ungaged tributaries to Grand Canyon: (1) a regression equation relating drainage area to sediment yield for all relevant sediment-yield data from northern Arizona, (2) an empirical relation developed by Renard (1972), and (3) a new procedure that combines regional flood-frequency analysis with sediment-rating curves. All three methods are compared against regional data to determine their appropriateness for estimating sediment yield to Grand Canyon.

Given the limited amount of sediment data and variety of model types, we found it necessary to mix

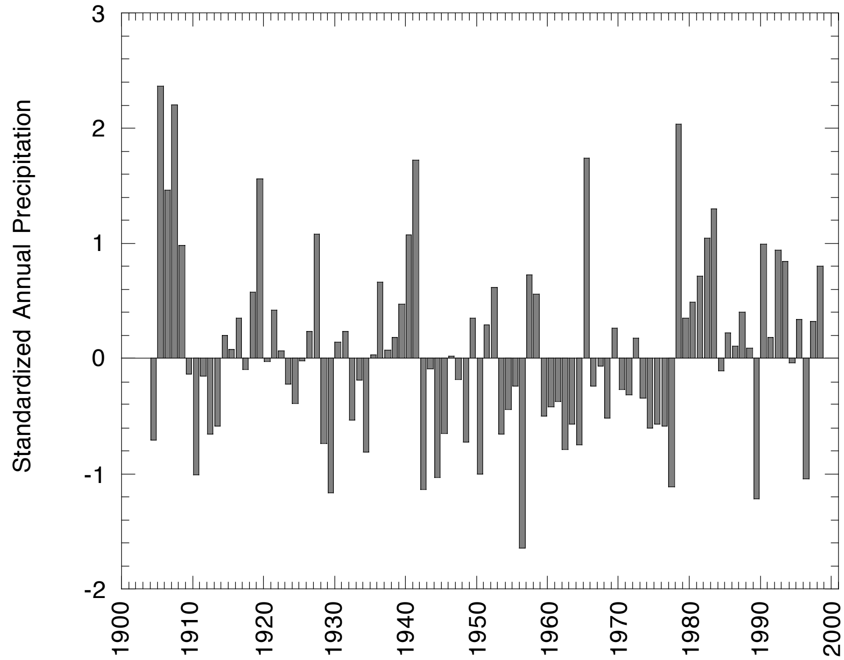

Figure 3. Standardized annual precipitation for the Grand Canyon region from 1904 through 1998 based on data from 14 weather stations (table 3).

and match estimates of suspended load and total load. We assume that in most of the drainages concerned, the difference between the two loads, bed load, is quite small, and certainly well within the range of our final estimates. A plot of regional data of mixed type (fig. 6; suspended load from gaging stations and total load from reservoirs) supports this view.

Regional Sediment-Yield Data

Other than at gaging stations on the Colorado River and its major tributaries, few sediment-transport data have been collected in Grand Canyon (Garrett and others, 1993; Rote and others, 1997). Therefore, streamflow-sediment yield must be estimated empirically. To develop a regression equation of sediment yield versus drainage area and to determine which other sediment-yield estimation techniques might be appropriate, we assembled sediment-yield data for the region.

Sediment loads at gaging stations on the pre-dam Colorado River, its major tributaries, and small drainages suggest a regional sediment yield of 105-820 Mg $km^{-2}yr^{-1}$ (table 4). These yields assume minimal long-term change in storage (Graf, 1987). The sediment yield of the Paria River is 820 Mg $km^{-2}yr^{-1}$, which is high for the Grand Canyon region. The sediment yield of 134 Mg $km^{-2}yr^{-1}$ for the Little Colorado River, measured at a gaging station upstream from most of the typical bedrock units exposed in Grand Canyon, is possibly low. Given some similarities in Mesozoic bedrock lithology, the sediment yield of 155 Mg $km^{-2}yr^{-1}$ for Moenkopi Wash near Tuba City (table 4) may be appropriate for estimating sediment yield in upper Marble Canyon (upstream from mile 17), but the record length for this station is only 3 years. Andrews' (1991) estimate (table 5), based on the difference in gaged sediment load in the Colorado River between Lee's Ferry and river mile 87 (Grand Canyon gage), is considerably higher at 2,130 Mg $km^{-2}yr^{-1}$. Andrews (1991) assumed that the additional yield is sand eroded from the bed of the Colorado River.

On the basis of a range in drainage area most comparable with that of Grand Canyon tributaries (fig. 2a), the most appropriate data are sedimentation data from small reservoirs in northeastern Arizona (Fort Defiance region of the Navajo Indian Reservation; Hains and others, 1952)

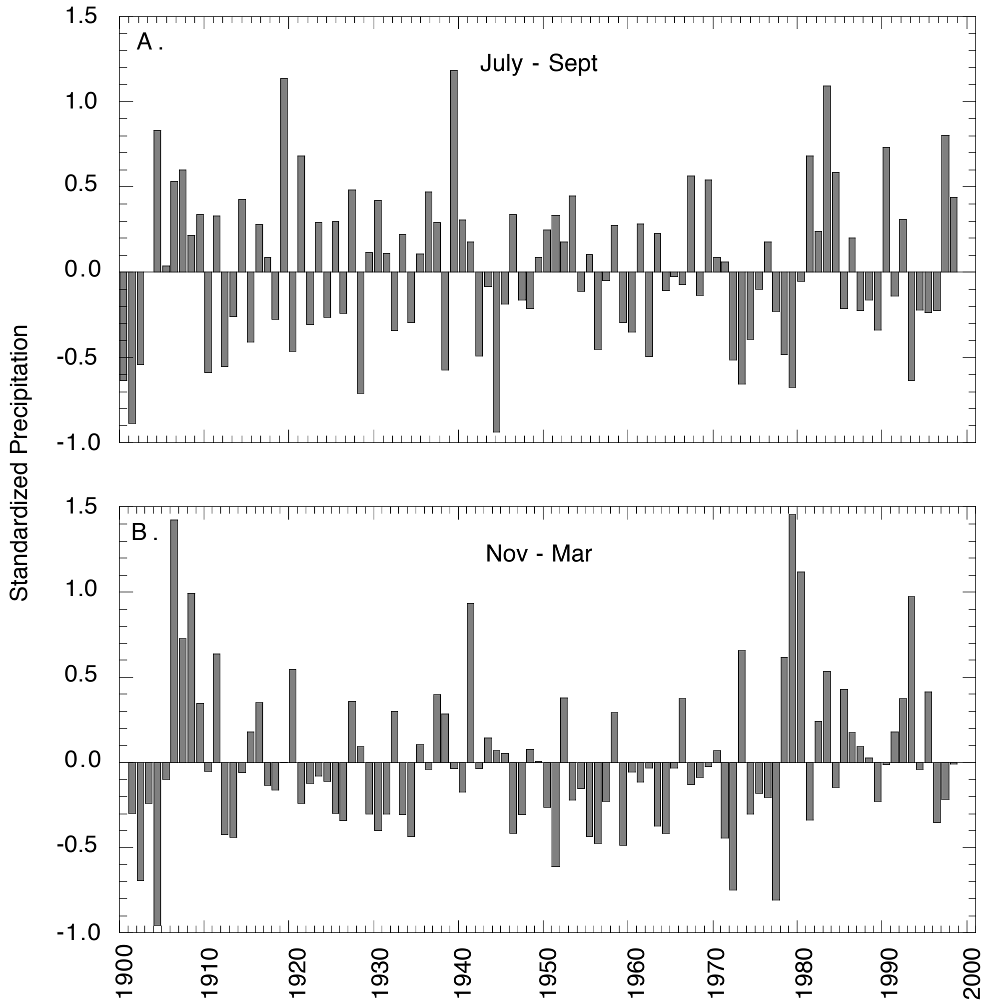

Figure 4. Standardized seasonal precipitation for the Grand Canyon region from 1904 through 1998 based on data from 14 weather stations (table 3). A. Summer (July through September). B. Winter (November through March).

and data from gaging stations on small drainages. Data are available for sediment yield per year per unit area for 25 reservoirs (fig. 6). In addition to the reservoir sedimentation data, we assembled sediment yield data from 12 gaging stations on small watersheds in the region (table 4). Data from eight of these watersheds are previously unpublished and come from gaging stations operated by Peabody Coal Company on Black Mesa (D.R. Hartley, unpublished data, 1999). The data were combined despite the fact that some stations have data predominantly from the period 1948-1979 and others from Black Mesa were collected in the 1980s and 1990s in a period of higher rainfall (figs. 3-5). In addition, the Hains and others (1952) data represent total sediment load whereas suspended load was measured at the gaging stations.

We combined the reservoir sedimentation data with the annual sediment yields from gaging stations in the region, excluding the mainstem Colorado River (table 4). Fitting a power function to these data (fig. 6), we obtained

$$Q_s = 193 \cdot A^{1.04}, R^2 = 0.86, \qquad (3)$$

where Q_s = sediment yield (Mg/yr), A = drainage area (km^2), and n = 37. We used equation (3), termed the data regression equation, to estimate sediment yields from all 768 tributaries, summed by geomorphic reach (table 6).

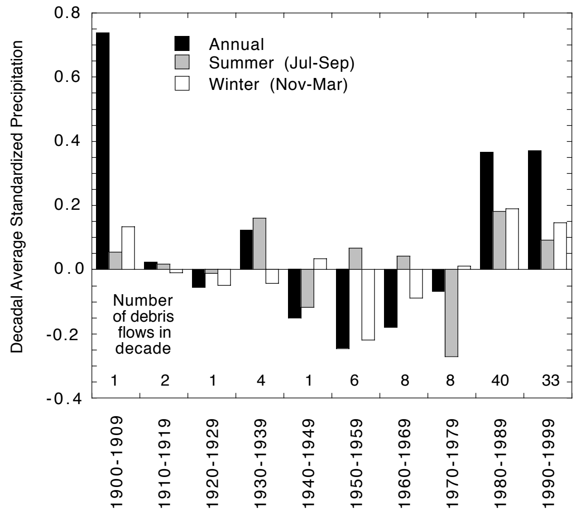

Figure 5. Standardized average decadal precipitation for the Grand Canyon region from 1900 through 1998 and the number of documented debris flows in each decade.

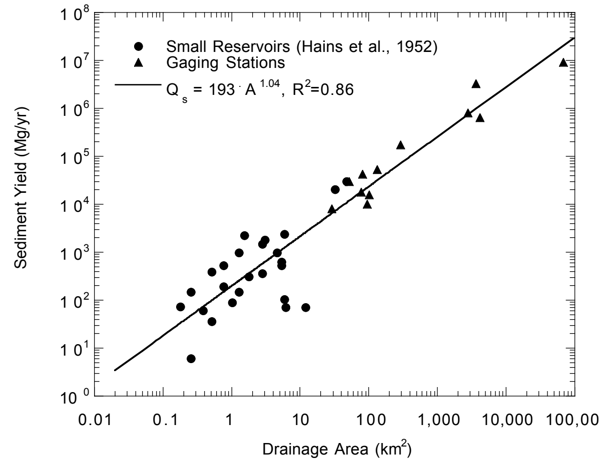

Figure 6. Sediment-yield data from small reservoirs (Hains and others, 1952) and gaging stations on the Colorado Plateau. Regional sediment-yield data is well correlated using the data regression equation of Q_S = 193 · $A^{1.04}$, with R^2 = 0.86, where Q_S = streamflow sediment yield in Mg/yr and A = drainage area in km^2.

Empirical Sediment-Yield Relations

Previous estimates of streamflow sediment yield from Grand Canyon tributaries have been based solely on empirical approaches (Laursen and others, 1976; Howard and Dolan, 1981; Randle and Pemberton, 1987). Estimates derived from the various approaches vary through two orders of magnitude (table 5). Laursen and others (1976) assumed that the ungaged tributaries contributed insignificant amounts of sediment when compared with the Paria and Little Colorado Rivers. Howard and Dolan (1981) assumed that ungaged tributaries yielded as much sediment per unit area as the gaged tributaries and estimated a sediment yield of 780 Mg km^{-2}yr^{-1} (table 6). Randle and Pemberton (1987) based their estimate of 731 Mg km^{-2}yr^{-1} on a relation of sediment yield to drainage area derived from reservoir sedimentation surveys of the western United States and adjusted with data from the Paria and Little Colorado Rivers, and Kanab and Havasu Creeks.

We compared several empirical relations for estimating streamflow sediment yield (table 5). These relations calculate total sediment yield only, with no discrimination of the particular particle sizes that may be transported. An implicit assumption in these approaches is that the percent of exposed bedrock in the drainage basin is not a factor in sediment yield. Most of the equations are in the form of power functions (table 5). Strand (1975) based his method on reservoir surveys throughout the western United States. Renard (1972) and Renard and Laursen (1975) used both reservoir sediment data and a stochastic runoff model calibrated to southwestern watersheds to calibrate their methods. Dendy and Bolton (1976) related both drainage area and mean annual runoff to sediment yield. Flaxman (1972) developed a more complicated empirical approach that relates sediment yield to mean annual climate (a proxy for vegetation), watershed slope, and soil characteristics.

Sediment yields calculated from the empirical sediment-yield equations range from 43 to 4,110 Mg km^{-2}yr^{-1} (table 5). Most of the empirically-based estimates are significantly larger than measurements at gaging stations (table 4). Of these equations, Renard's (1972) method best approximates the data from gaging stations and reservoir surveys (fig. 6). The Renard (1972) equation, converted to SI units and assuming a sediment density of 1.2 Mg/m^3, is

$$Q_s = 351 \cdot A^{0.88}, \qquad (4)$$

where Q_s = streamflow sediment yield (Mg/yr) and A = drainage area (km^2). Flaxman's (1972) approach produced the lowest sediment yield (43 Mg km^{-2}yr^{-1}; table 5), although results from his relation vary widely with small changes in the

Table 4. Measured sediment loads at gaging stations on Black Mesa, tributaries of the Colorado River, and for the Colorado River at Lee's Ferry and Grand Canyon, Arizona.

Gaging station name	Years of data (Water years)	Drainage area (km^2)	Sediment load (10^6 Mg/yr)	Sediment yield[#] ($Mg\ km^{-2}yr^{-1}$)
*Moenkopi Wash #1	1985-1997	29.2	0.0081	277
*Yellow Water Wash #1	1985-1997	52.2	0.030	575
*Coal Mine Wash #1	1985-1997	77.1	0.018	233
*Red Peak Valley Wash	1986-1997	80.9	0.042	519
*Coal Mine Wash #2	1987-1997	94.3	0.0099	105
*Yellow Water Wash #2	1985-1997	100	0.015	150
*Moenkopi Wash #2	1986-1997	131	0.052	396
*Coal Mine Wash #3	1986-1997	293	0.172	587
†Kanab Creek near Fredonia	1968-1973	2,810	0.809	288
†Paria River at Lees Ferry	1949-1976	3,650	3.0	820
†Moenkopi Wash near Tuba City	1977-1979	4,219	0.65	155
†Little Colorado River near Cameron	1957-1970	68,600	9.2	130
†Colorado River at Lee's Ferry	1948-1962	290,000	65	220
†Colorado River near Grand Canyon	1948-1962	366,000	84	230

*Sediment data are unpublished values from Peabody Coal Company.
†Sediment data are annual means for the water years shown from the USGS ADAPS database. These values differ slightly from Andrews (1991), who used different years of record.
#Sediment-yield calculation assumes no change in storage along the Colorado River.
na, not applicable

independent variables (fig. 7). The Flaxman (1972) equation overpredicts sediment yields for drainage areas < 10 km^2 and underpredicts substantially for larger drainages in comparison to the data regression equation and the Renard (1972) equation (fig. 7)

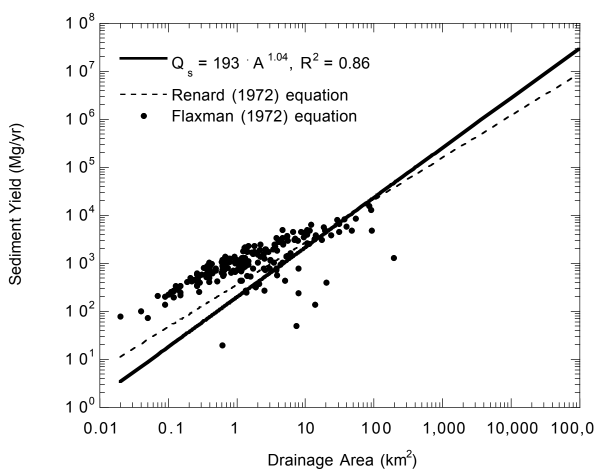

Figure 7. Estimates of streamflow sediment yield from the empirical equations of Renard (1972) and Flaxman (1972) and the data regression equation.

The data regression equation and the Renard (1972) equation produce similar sediment yields when ungaged tributaries in Grand Canyon are grouped by sediment-yield reach (table 6). Using these equations (eqs. 3 and 4), we estimate that ungaged tributaries in Grand Canyon bring $2.65 \cdot 10^6$ Mg/yr of sediment to the Colorado River by streamflow (table 6). Reach A, from Glen Canyon Dam to Lee's Ferry, receives an estimated sediment input of 64,800 to 76,400 Mg/yr, and Reach B (Marble Canyon, from Lee's Ferry to the Little Colorado River), receives about 600,000 Mg/yr (table 6). This combined annual sediment input by streamflow from reaches A and B is 20 percent of the annual sediment load delivered by the Paria River (table 4). Most of the sediment input by ungaged tributaries is in western Grand Canyon (Reaches F and G; table 6).

We rejected other sediment-yield approaches, such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978; Peterson and Swan, 1979), the CREAMS and WEPP models of the Agricultural Research Service (Knisel, 1980; Gilley and others, 1988), and the procedure

Table 5. Estimates of sediment contribution by streamflow from 219 ungaged tributaries of the Colorado River between Lee's Ferry and the Grand Canyon gage (river mile 87), Arizona.

Source	Original equation*	Units	Area (km^2)	Q_{s1} (10^6 Mg/yr)	Q_{s2}	Sediment yield ($Mg\ yr^{-1}\ km^{-2}$)
†Flaxman (1972)	$\log(Y + 100) = 6.21301 - 2.19113 \log(X_1 + 100) + 0.06034 \log(X_2 + 100) - 0.01644 \log(X_3 + 100) + 0.04250 \log(X_4 + 100)$	ac-ft/mi^2/yr	3,282	na	0.14	42.6
Renard (1972)	$0.001846\ A^{-0.1187}$	ac-ft/ac/yr	3,282	0.67	0.44	204
Soil Conservation Service (1975)	PSIAC method	ac-ft/mi^2/yr	3,282	nd	13.5	4,110
Strand (1975)	$1130\ A^{0.77}$	m^3/yr	3,282	1.62	0.69	494
§Dendy and Bolton (1976)	$1280\ Q^{0.46}(1.43 - 0.26 \log A)$	tons/mi^2/yr	3,282	0.81	0.39	247
#Howard and Dolan (1981)	$780\ A$	Mg/km^2/yr	3,282	2.56	2.56	780
#Randle and Pemberton (1987)	$1750\ A^{-0.24}$	m^3/km^2/yr	3,282	2.4	2.7**	731
Graf (1987)	$1200\ A^{1.0}$	m^3/yr	3,282	3.9	3.9	1,190
#Andrews (1991)	gaging data (1941-1957)	tons/yr	3,748	na	8	2,130

* A = drainage area in the units given; Q_{s1} = sum of sediment yields calculated for each individual tributary (used for sediment yield); Q_{s2} = sediment yield calculated for entire drainage area of 3,282 km^2 (Melis et al., 1994). Sediment density is estimated as1,200 kg/m^3.

† Y = sediment yield in ac-ft/mi^2/yr; X_1 = mean annual precipitation (inches) / mean annual temperature (°F), estimated as 0.19; X_2 = watershed slope, estimated as percent gradient of main channel; X_3 = percent of particles > 1 mm in diameter in the first 2 inches of soil, estimated as 60%; X_4 = soil pH factor, assumed to be 0 (pH of 7).

§ Q = annual runoff in inches assumed to be $0.4501\ A^{-0.1449}$ (A in mi^2).

\# Derived from daily suspended sediment loads.

** Sum of calculations by Randle and Pemberton (1987) for ungaged drainage area from Lees Ferry to the Little Colorado River (A = 3,095 km^2) and from the Little Colorado River to Grand Canyon (A = 466 km^2).

na, not applicable with given equation/method

nd, no data available

Table 6. Estimated annual streamflow sediment yield from ungaged tributaries of the Colorado River in Grand Canyon.

		DATA REGRESSION EQUATION			RENARD (1972) EQUATION		
Sediment yield reach	River miles	Tributary sediment* yield (Mg/yr)	Extra-area sediment* yield (Mg/yr)	Total sediment* yield (Mg/yr)	Tributary sediment† yield (Mg/yr)	Extra-area sediment† yield (Mg/yr)	Total sediment† yield (Mg/yr)
A	-15.5 to 0.9	58,300	6,490	64,800	67,100	9,330	76,400
B	0.9 to 61.5	585,000	25,300	610,000	556,000	36,800	593,000
C	61.5 to 87.8	90,700	7,010	97,700	115,000	12,000	127,000
D	87.8 to 143.5	311,000	20,300	332,000	343,000	32,000	375,000
E	143.5 to 156.8	47,300	9,650	57,000	52,200	11,500	63,700
F	156.8 to 225.8	792,000	29,300	821,000	737,000	41,900	779,000
G	225.8 to 276.0	661,000	8,400	669,000	614,000	18,900	633,000
	TOTAL	2,550,000	106,000	2,650,000	2,480,000	162,000	2,650,000

* Sediment yield is calculated using a regression equation developed during this study.
† Sediment yield is calculated using the Renard (1972) equation converted to metric units and using a sediment density of 1.2 Mg/m^3.

outlined by the PSIAC (Pacific Southwest Inter-Agency Committee, 1968). The USLE was developed strictly for low-slope agricultural land and is not appropriate for the steep terrain of Grand Canyon. Likewise, the CREAMs and WEPP models were developed for relatively low-slope agricultural and rangeland and require considerable watershed data for proper application. The PSIAC method involves rating a watershed on the basis of nine factors related to erosion (surface geology, soil, climate, runoff, topography, land use, upland erosion, and channel erosion/sediment transport) to produce an estimate of sediment yield. This method can be applied to large areas using pre-calculated PSIAC sediment-yield ratings mapped by the Soil Conservation Service (SCS, 1975; Hedlund and Curtis, 1984). It produces a high estimate of 4,110 Mg $km^{-2}yr^{-1}$ (table 5) and was rejected as a viable method for estimating sediment yield in Grand Canyon.

The Flood-Frequency, Rating-Curve Technique

We developed a flood-frequency, rating-curve technique to estimate streamflow sediment yield based loosely on the work of Strand (1975) and Strand and Pemberton (1982). This technique requires numerous assumptions, one of the most important of which is that the decadal streamflow sediment yield in a tributary can be described by several floods of recurrence intervals described by regional flood-frequency relations (table 7; Roeske, 1978; Thomas and others, 1997). Considering the intermittent-flow regime of these tributaries, which probably have flow less than one percent of the time, this is likely not to be an egregious assumption for most of the ungaged tributaries. Once flood-frequency has been established for a tributary, we use a relation between peak discharge and total-event sediment yield developed from hydrographs of floods on Bright Angel Creek (fig. 1) and sediment-rating curves from Black Mesa gaging stations (table 8).

Regional flood frequency

The regional-regression equations reported by Thomas and others (1997) for the southwestern United States (table 7) are not without significant problems when applied to the Grand Canyon region. Few small drainages from Grand Canyon have gaging records, and therefore these tributaries are not well represented in the regional flood-frequency relations. Webb and others (1999b) found that the equations for region 11 in central Grand Canyon overestimated flood frequency for the Prospect Valley drainage basin in western Grand Canyon. As an alternative, we evaluated

Table 7. Regional regression equations for streamflow flood frequency used for ungaged tributaries of the Colorado River in Grand Canyon, Arizona.

Flood frequency region*	Recurrence Interval (yrs)	Flood-frequency relation
	Thomas and others (1997)	
8	2	$Q = 598\ A^{0.501}\ (E_1/1{,}000)^{-1.02}$
	5	$Q = 2{,}620\ A^{0.449}\ (E_1/1{,}000)^{-1.28}$
	10	$Q = 5{,}310\ A^{0.425}\ (E_1/1{,}000)^{-1.40}$
10	2	$Q = 12\ A^{0.58}$
	5	$Q = 85\ A^{0.59}$
	10	$Q = 200\ A^{0.62}$
11	2	$Q = 26\ A^{0.62}$
	5	$Q = 130\ A^{0.56}$
	10	$Q = 0.10\ A^{0.52}\ E_2^{2.0}$
	Roeske (1978)	
1	2	$Q = 19\ A^{0.660}$
	5	$Q = 66.3\ A^{0.600}$
	10	$Q = 127\ A^{0.566}$
4	2	$Q = 1.35\ A^{0.491}\ (E_1/1{,}000)^{2.25}$
	5	$Q = 0.319\ A^{0.446}\ (E_1/1{,}000)^{3.60}$
	10	$Q = 0.143\ A^{0.423}\ (E_1/1{,}000)^{4.31}$

Q = peak discharge (ft^3/s); A = drainage area (mi^2); E_1 = mean basin elevation (ft); E_2 = mean annual evaporation (in.).

* For Thomas and others (1997), eastern Grand Canyon is mostly Region 8, western Grand Canyon is mostly Region 10, and the central part of Grand Canyon is mostly Region 11. For Roeske (1978), drainage areas east of the Colorado River and north of the Little Colorado River lie in Region 4, while the remainder of Grand Canyon falls within Region 1.

regional-regression equations calculated by Roeske (1978) for the state of Arizona (table 7). Values for the variables listed in table 7 were determined digitally using 1:250,000 digital elevation models and maps of free water-surface evaporation by Farnsworth and others (1982). Multiple zones of evaporation within any given tributary were weighted by area and averaged to define one evaporation value for the tributary.

We assumed an expected value for the number of floods to occur in a decade. This expected value calls for five 2-yr floods, two 5-yr floods, and one 10-yr flood to deliver most of the sediment to the Colorado River. Regional flood-frequency relations do not produce annual floods, so we have no means of determining the effect of neglecting the smallest events, and we chose not to include the influence of long recurrence-interval floods in the analysis.

Flood volumes and sediment-rating curves

Hydrographs for floods on Bright Angel Creek are the only available data concerning the form of streamflow floods in Grand Canyon. We assumed that the form of these hydrographs could be transferred to all ungaged tributaries if a method could be developed to relate flow volume to peak discharge. We digitized hydrographs from 22 summer and 20 winter floods recorded in Bright Angel Creek between 1924 and 1973. We attempted to generalize these hydrographs and apply them to all 768 tributaries of the Colorado River using the regional flood-frequency relations. Our attempt to scale these hydrographs according to peak discharge and duration of the flood failed because of the high degree of variability in the shapes of the hydrographs. Therefore, we used the hydrographs in combination with sediment-rating curves to calculate a total sediment delivery per event, as described in the next section.

Two sets of sediment-rating curves were available to apply to the hydrographs from Bright Angel Creek. Streamflow and sediment data were collected for Bright Angel Creek during the period from 1991 through 1993 (Rote and others, 1997). One hundred sediment samples were used to develop a rating curve, which had a maximum discharge of 11.75 m^3/s (table 9). However, the rating curve for Bright Angel Creek estimates sediment loads several orders of magnitude smaller

Table 8. Sediment rating curves for Bright Angel Creek and at five gaging stations on Black Mesa, Arizona.

Tributary	Years of data (Water years)	Drainage area (km^2)	Coefficient a	Exponent b	R^2	Maximum discharge (m^3/s)
Bright Angel Creek	*1991-1993	260.3	1.83	2.32	0.42	11.8
Moenkopi Wash #1	†1985-1997	29.2	2,540	1.52	0.80	65.1
Yellow Water Wash #1	†1985-1997	52.2	9,500	1.16	0.79	42.5
Coal Mine Wash #1	†1985-1997	77.1	5,730	1.28	0.84	93.5
Yellow Water Wash #2	†1985-1997	80.9	6,410	1.24	0.89	42.4
Coal Mine Wash #2	†1985-1997	112.7	4,050	1.28	0.89	24.9

The coefficient and exponent are for the equation $S_y = a \cdot Q^b$, where S_y = sediment yield (Mg/day) and Q = instantaneous discharge (m^3/s). Minimum discharge for the rating curves is 0.1 m^3/s.
* Data from Rote and others (1997).
† Unpublished data from Peabody Coal Company.

Table 9. Linear regression between peak discharge and sediment yield for 42 floods in Bright Angel Creek, Arizona.

	SEDIMENT RATING CURVE					
	Bright Angel Creek	Yellow Water Wash #1*	Yellow Water Wash #2*	Coal Mine Wash #1*	Coal Mine Wash #2*	Moenkopi Wash #1*
Coefficient (*a*)	0.18	1987	1258	1088	773	404
Exponent (*b*)	2.23	1.09	1.17	1.21	1.21	1.45
R^2	0.90	0.76	0.77	0.78	0.78	0.82

The coefficient and exponent are for the equation $Q_s = a\, Q_p{}^b$ where Q_s = sediment yield (Mg/event) and Q_p = instantaneous peak discharge (m^3/s). The Bright Angel Creek gage record runs from 1924 to 1973.
* Gaging stations on Black Mesa, Arizona (table 4).

than those of other rating curves from the region (table 8). This likely results in part from an over-representation of spring snow-melt floods in the small Bright Angel data set; over 70 percent of the data points were measured in the spring and snow-melt floods are typically less sediment-rich than floods at other times of the year. During the period of record (1924 - 1973), 55 percent of flood events in Bright Angel Creek occurred in summer (mean peak discharge of 13 m^3/s) while only 25 percent occurred in spring (mean peak discharge of 9 m^3/s). Given the small data set from Bright Angel Creek, removal of the spring floods would leave insufficient data points for effective modeling.

Rating curves were developed for 8 gaging stations operated by Peabody Coal Company on Black Mesa. These gaging stations (table 4) are on Coal Mine Wash (3 gaging stations), Yellow Water Wash (2 gaging stations), Moenkopi Wash (2 gaging stations), and Red Peak Valley Wash (1 gaging station). Although Black Mesa is about 100 kilometers east of Grand Canyon (fig. 1) and is underlain by different geologic formations, the paucity of data for smaller drainages from Grand Canyon compelled us to look elsewhere for suitable proxy data. The climate at Black Mesa is similar to that of Grand Canyon and both areas are underlain by primarily sedimentary bedrock. In general, the Cretaceous strata of Black Mesa are notably less competent than the Paleozoic strata of Grand Canyon and include none of the well-indurated carbonates typical of Grand Canyon (*e.g.*, the Redwall Limestone). Consequently, the drainages on Black Mesa likely yield a higher proportion of sediment per unit area than most of the ungaged tributaries of Grand Canyon. (The one exception may be upper Marble Canyon, where significant exposures of Mesozoic shales and sandstones are still present.) Any sediment-yield estimates based on these data are likely to overestimate Grand Canyon sediment yield and should be considered maximum values at best.

Using the 42 flood hydrographs from Bright Angel Creek, we applied five rating curves from Black Mesa to calculate total sediment yield per event. We separated base flow (0.4 to 1.0 m^3/s) from the runoff for each event. With regression analysis, we determined relations between peak discharge and the total sediment yield for each event (table 9). The relation of sediment yield to peak discharge took the form:

$$Q_e = a \cdot Q_p^{\,b}, \qquad (5)$$

where Q_e = sediment yield in Mg/event, Q_p = peak flood discharge in m^3/s, and a and b are regression coefficients. The R^2 values ranged from 0.76 to 0.82, indicating a high degree of relation between peak discharge and sediment yield per event (table 9).

In order to reduce the potential overestimation of Grand Canyon sediment yields, we elected to use the sediment yield-peak discharge relation that produced the smallest sediment yield: Moenkopi Wash #1. Of the five Black Mesa drainages, Moenkopi Wash #1 is also most similar to the average Grand Canyon tributary in terms of drainage area.

Calculations of sediment yield

We linked flood-frequency discharge estimates to sediment yield using

$$Q_s = [1 \cdot f(Q_{10}) + 2 \cdot f(Q_5) + 5 \cdot f(Q_2)] \,/\, 10, \qquad (6)$$

where Q_s is sediment yield in Mg/year, Q_t is the peak discharge of the t year flood in m^3/s, and $f(Q_t)$ is a regression equation relating peak discharge to sediment yield in Mg/event (Q_e). With this relation, we make the key assumption that total sediment yield per decade from a tributary can be approximated by the sum of sediment loads from one 10-year, two 5-year, and five 2-year floods.

Using the regional-regression equations of Thomas and others (1997) to estimate flood frequency, we calculated the annual sediment yield of all 768 tributaries in Grand Canyon for both the Bright Angel Creek and Moenkopi Wash #1 sediment-yield peak-discharge regression relations (table 9). As expected, sediment yield estimates based on the Bright Angel Creek data are two orders of magnitude smaller than those based on the Renard (1972) equation and regional data (fig. 8). Although Grand Canyon sediment yield may be somewhat smaller than estimates based on regional data, a difference of two orders of magnitude suggests that the Bright Angel data is not representative of Grand Canyon tributaries.

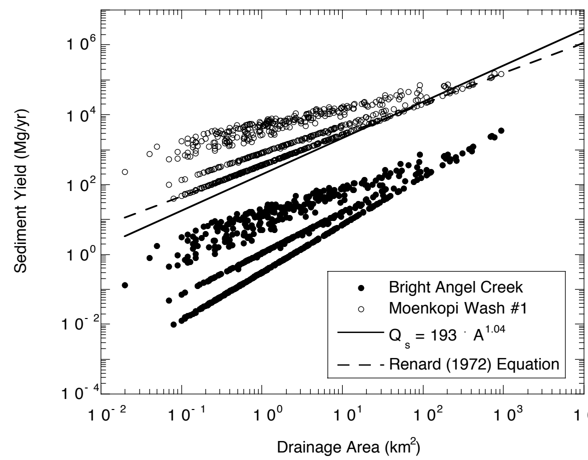

Figure 8. Streamflow sediment-yield estimates for 768 Grand Canyon tributaries calculated using the regional flood-frequency estimates of Thomas and others (1997) and sediment-rating data from Bright Angel Creek and Moenkopi Wash #1 compared to the data regression equation and the Renard (1972) equation.

Estimates derived from the Moenkopi Wash #1 relations exceeded estimates based on regional data and the Renard (1972) equation (fig. 8). Although we would expect estimates based on Black Mesa data to exceed actual Grand Canyon values, we do not expect them to exceed regional values in general. This overestimation likely results from the wide geographic extent of Thomas and others's (1997) flood regions. For example, only 10 of 109 gage stations used in the region 8 regressions are in Arizona; most of region 8 is southeastern Utah as well as parts of northwestern New Mexico and southwestern Colorado. In contrast, the flood-frequency regressions of Roeske (1978), although calculated with shorter gage records and fewer initial basin variables, use Arizona data exclusively and contain the same independent variables of drainage area and mean basin elevation used by Thomas and others (1997). Using the Roeske (1978) relations to calculate tributary streamflow sediment yield produced results similar to those derived from the Renard (1972) equation and the regional data regression equation (fig. 9). Again, the estimates based on the Bright Angel data are two orders of magnitude smaller than estimates based on regional data. Based on the above evaluations, we used the Roeske (1978) flood-frequency relations and Moenkopi Wash #1 sediment-discharge relations to calculate streamflow sediment yield from all 768 the ungaged tributaries and extra areas in Grand Canyon.

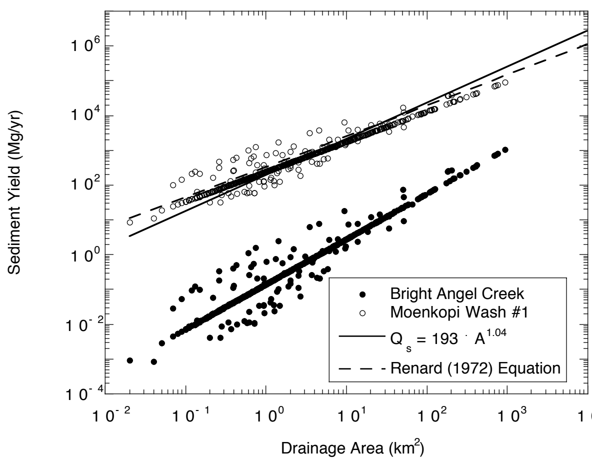

Figure 9. Streamflow sediment-yield estimates for 768 Grand Canyon tributaries calculated using the regional flood-frequency estimates of Roeske (1978) and sediment-rating data from Bright Angel Creek and Moenkopi Wash #1 compared to the data regression equation and the Renard (1972) equation.

The results of the flood-frequency, rating-curve method are smaller than the results from the data regression equation and the Renard (1972) equation (tables 5 and 10). For Reach B, the Marble Canyon reach, the flood-frequency, rating-curve method estimates $0.457 \cdot 10^6$ Mg/yr of sediment, compared with $0.610 \cdot 10^6$ Mg/yr estimated from the data regression equation and $0.593 \cdot 10^6$ Mg/yr estimated from the Renard (1972) equation. The total streamflow sediment yield from all ungaged drainage areas was $1.75 \cdot 10^6$, $2.65 \cdot 10^6$, and $2.65 \cdot 10^6$ Mg/yr from the flood-frequency, data regression, and Renard (1972) equations, respectively. Because all three methods produce reasonably similar numbers, we chose to use only the simplest relation, the regional data regression equation, for estimating total streamflow sediment yield and sand delivery rates from ungaged drainage areas. These results appear in table 5.

Particle-Size Distribution of Streamflow Sediment

Effective management of sediment resources of the Colorado River requires an estimate not only of total sediment yield but also of the particle-size distribution of that sediment. The size of the sand component is of particular interest for the management and restoration of sand bars in Grand Canyon (Schmidt and Rubin, 1995; U.S. Department of the Interior, 1995). Randle and Pemberton (1987), in constructing a sediment budget of the Colorado River, estimated that on average 15 percent of the total sediment yield is sand-sized particles, based on data from Kanab Creek and the Little Colorado River. Measurements of particle-size distributions at various other tributaries provide sand contents ranging from 1 - 99 percent of total yield with no discernible pattern (table 11). These data were collected from a large discharge range and thus highly variable sand contents would be expected.

Table 10. Annual streamflow sediment yield from ungaged tributaries of the Colorado River in Grand Canyon, Arizona, calculated using the flood-frequency rating-curve method.

Sediment -yield reach	River miles	Tributary sediment yield (Mg/yr)	Extra-area sediment yield (Mg/yr)	Total sediment yield (Mg/yr)
A	-15.5 to 0.9	40,700	4,530	45,200
B	0.9 to 61.5	431,000	25,600	457,000
C	61.5 to 87.8	74,200	8,100	82,300
D	87.8 to 143.5	218,000	21,500	240,000
E	143.5 to 156.8	33,100	7,500	40,500
F	156.8 to 225.8	460,000	27,800	488,000
G	225.8 to 276.0	384,000	13,200	397,000
	TOTAL	1,642,000	108,000	1,750,000

Table 11. Estimated or measured sand content of streamflow entering the Colorado River in Grand Canyon, Arizona.

Tributary	Site or gaging station	PARTICLE SIZE Sand (%)	PARTICLE SIZE Silt+Clay (%)	Source
General	na	15	85	Randle and Pemberton (1987)
Little Colorado River	near mouth	0.7-22.6 1-50	77.4-99.3 50-99	Garrett and others (1993) Rote and others (1997)
Bright Angel Creek	*near mouth near Grand Canyon	†87 1-64	13 36-99	Garrett and others (1993) Rote and others (1997)
Kanab Creek	near Fredonia above the mouth	0.1-4.5 0-36	85.5-99.9 64-100	Garrett and others (1993) Rote and others (1997)
Havasu Creek	above the mouth	1-89	11-99	Rote and others (1997)
National Canyon	*near mouth	†81-99	1-19	Garrett and others (993)
Ungaged tributaries§	various	30-100	8-10	collected by the authors

* not a gaging station, miscellaneous tributary flow in 1983 (Garrett and others, 1993)
† calculated from silt+clay% and assuming no particles > 2 mm were transported
§ 89 streamflow deposits in 21 ungaged tributaries sampled by the authors (fig. 10)
na, not applicable

Table 12. Sand delivery by streamflow from ungaged tributaries of the Colorado River in Grand Canyon, Arizona.

Sediment -yield reach	River miles	SAND YIELD* (10^6 Mg/yr) Data regression equation 15%	Data regression equation 50%	Data regression equation 75%	Renard (1972) equation 15%	Renard (1972) equation 50%	Renard (1972) equation 75%
A	-15.5 to 0.9	0.010	0.032	0.049	0.011	0.038	0.057
B	0.9 to 61.5	0.092	0.305	0.458	0.089	0.297	0.445
C	61.5 to 87.8	0.015	0.049	0.073	0.019	0.063	0.095
D	87.8 to 143.5	0.050	0.166	0.249	0.056	0.188	0.282
E	143.5 to 156.8	0.009	0.028	0.043	0.010	0.032	0.048
F	156.8 to 225.8	0.123	0.410	0.616	0.117	0.389	0.584
G	225.8 to 276.0	0.100	0.335	0.502	0.095	0.317	0.475
	TOTAL	0.398	1.33	1.99	0.397	1.32	1.99

* Sand is calculated as 15% of total sediment yield (Randle and Pemberton, 1987), 50%, and 75% to provide a range of possible input conditions. See text for more discussion of these assumptions.

We supplemented this data by collecting samples from 89 streamflow deposits in 21 tributaries in Glen and Grand Canyon and analyzing them with standard techniques (Kellerhals and Bray, 1971; Folk, 1974). Samples were dried, then passed through brass sieves at 0.25 ϕ intervals using a rotational shaker. Particles retained on each screen were weighed and the percent of the subsample in each ϕ class determined. Sand content in these samples ranged from 30 - 100 percent (Table 11). These data fit well within the range suggested by other tributaries, though the upper end is unlikely as high as 100 percent owing to a potential underrepresentation of silt and clay in the streamflow deposits.

In order to accommodate this wide range of sand content, we calculated streamflow sand delivery using three estimates. These include Randle and Pemberton's (1987) value of 15 percent, which we consider to be low, as well as 50 percent and 75 percent of total streamflow sediment yield. A sand content of 50 percent compares favorably with average sand content weighted by discharge for the Little Colorado and Paria Rivers, calculated as 30 percent and 50 percent respectively (D. Topping, U.S. Geological Survey, pers. commun., 1999). The estimated sand delivery by streamflow, using the data regression equation and Renard (1972) equation, is shown by reach in table 12. Assuming a 50 percent sand content, the sand

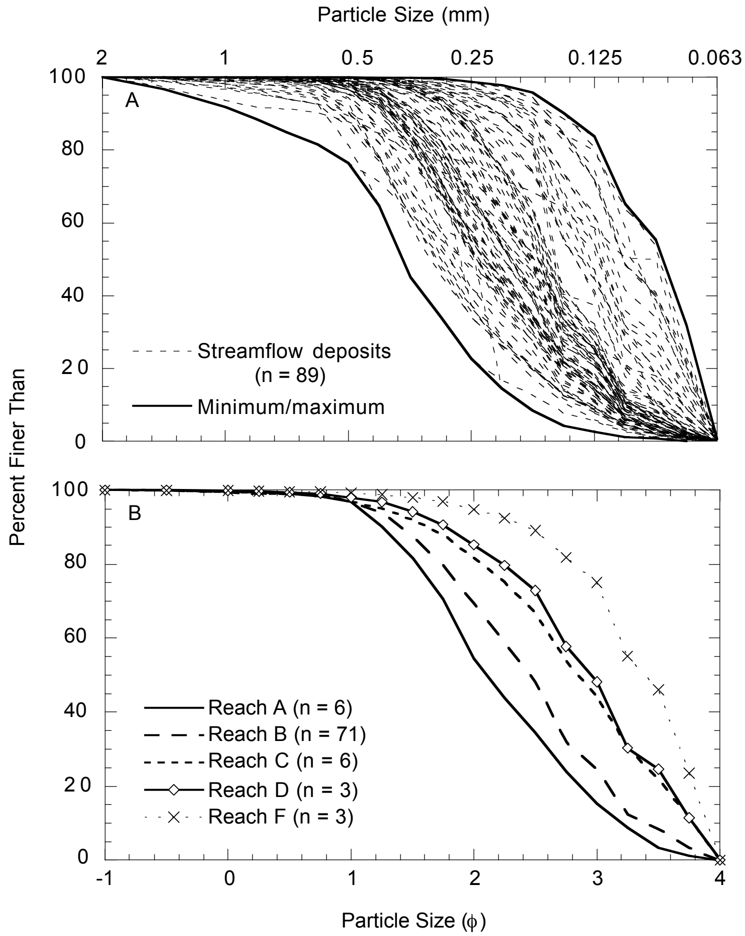

Figure 10. Particle-size distribution of sand delivered by streamflow from ungaged tributaries in Grand Canyon. A. All streamflow deposit samples. B. Reach-averaged distributions.

delivery in Glen and Marble Canyons (Reaches A and B) are $0.032 \cdot 10^6$ and $0.305 \cdot 10^6$ Mg/yr respectively.

The outcome of interaction between mainstem flows and tributary sediment input depends in part on the particle-size distribution of the sediment, with finer sand being more readily mobilized by a given discharge than coarser sand. Although tributary streamflow deposits may overrepresent total sand content, they can give an accurate picture of the composition of the sand fraction itself. Topping (1997) has found that the distribution of the sand fraction from this type of deposit is very similar to that of sand measured in suspension during flood peaks on the Paria River.

When examined by reach, sand contributed by tributaries in Glen Canyon is notably coarser (D_{50} = 0.24 mm) than sand from other reaches (D_{50} = 0.11 - 0.20 mm), including the Marble Canyon reach (D_{50} = 0.20 mm; table 13; fig. 10). The coarse sand in Glen Canyon derives from the Navajo Sandstone which strongly dominates the bedrock geology of the reach.

FREQUENCY OF HISTORICAL DEBRIS FLOWS IN GRAND CANYON

Evidence of Historical Debris Flows

Direct observations

We compiled notes from river runners on when debris flows, rockfalls, or significant streamflow floods occurred in Grand Canyon from 1984 through 1998. In addition, we examined all diaries of historical river trips for any reports of floods or

Table 13. Reach-averaged particle-size distribution of sand delivered by streamflow from ungaged tributaries of the Colorado River in Grand Canyon, Arizona.

Sediment -yield reach	River miles	Mean D_{20} (mm ± 1 SD)	Mean D_{50} (mm ± 1 SD)	Mean D_{80} (mm ± 1 SD)	n
A	-15.5 to 0.9	0.15 ± 0.03	0.24 ± 0.06	0.33 ± 0.09	6
B	0.9 to 61.5	0.13 ± 0.03	0.20 ± 0.06	0.29 ± 0.09	71
C	61.5 to 87.8	0.10 ± 0.02	0.15 ± 0.04	0.24 ± 0.10	6
D	87.8 to 143.5	0.09 ± 0.03	0.14 ± 0.05	0.21 ± 0.09	3
E	143.5 to 156.8	nd	nd	nd	0
F	156.8 to 225.8	0.07 ± 0.01	0.11 ± 0.09	0.13 ± 0.01	3
G	225.8 to 276.0	nd	nd	nd	
	TOTAL	0.13 ± 0.03	0.19 ± 0.06	0.28 ± 0.09	0

nd, no data

evidence of changes to rapids (Webb and Melis, 1996). Beginning with the first recorded trip in 1869, river trips typically encountered altered rapids, destroyed campsites, or obvious changes in the river channel after a debris flow. In some cases (*e.g.*, the 1993 Tanner Canyon debris flow), eye-witnesses described the floods (Melis and others, 1994). In this report, we update information contained in Melis and others (1994) and Webb and others (1999b). For the period of 1984-1998, we present a history of all debris flows in Grand Canyon that reached the Colorado River.

Photography

Repeat photography has been used successfully in Grand Canyon to document long-term changes in terrestrial ecology and geomorphology (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb, 1996; Webb and others, 1989, 1991, 1999b). Most of our frequency information for historical debris flows (1871 to 1998) used during this study was obtained from systematic, repeat photography and interpretation of historical photographs (appendix 2). Abundant historical photographs of the Colorado River corridor, dating to the Wheeler Expedition of 1871, allowed us to study many different debris fans for changes caused by debris flows, river-reworking associated with mainstem floods, and other geomorphic processes such as rockfall. Examples of repeat photography that document debris flows and the criteria used to identify them are given in Melis and others (1994), Webb (1996), Griffiths and others (1996), and Webb and others (1999b).

During our study, we matched and interpreted 1,297 historic photographs of the river corridor to determine significant canyon-wide changes to tributary channels, debris fans, and rapids. The years with the most abundant widespread coverage are 1890 and 1923, the years of well documented river expeditions. By using time series of historical photographs of specific debris fans, we were able to bracket when debris flows occurred in selected tributaries. For example, at Prospect Canyon (mile 179.3-L), 121 of 232 historical photographs were matched to provide detailed reconstruction of debris-flow occurrence and changes to the Lava Falls Rapid (Webb and others, 1999b). For some tributaries, the dates of debris flows could be determined to within 1 year. Detailed descriptions of the repeat photography collection are given in Melis and others (1994), Webb (1996), and Webb and others (1999b).

We also analyzed several sets of low-altitude aerial photographs taken between 1935 and 1999 for evidence of debris flows. In 1935, the Soil Conservation Service took black and white aerial photographs of Marble Canyon (river miles 0 to 61) and Diamond Creek to the Snap Canyon (river miles 225 to 280) at a scale of 1:31,800; these photographs are stored at the National Archives in College Park, Maryland. Another set of photographs, taken in November 1935 under the direction of John Maxon of the California Institute of Technology, recorded parts of the Inner Gorge from the vicinity of Bright Angel Creek to Specter

Chasm (river miles 87 to 129) and western Grand Canyon from about river mile 211 to Snap Canyon (river mile 280) in 1938. The scale of these photographs is unknown but probably is about 1:20,000. The 1965 aerial photography is available from the EROS Data Center in Sioux Falls, South Dakota, and 1973 aerial photography is stored at the U.S. Geological Survey in Tucson, Arizona. Aerial photography flown annually or more frequently between 1980 and 1998 is stored at the Grand Canyon Monitoring and Research Center in Flagstaff, Arizona.

Temporal and Spatial Distribution of Debris Flows

We documented 196 historical debris flows in Grand Canyon (appendix 2; fig. 11). Of these, 51 debris flows significantly affected the Colorado River during the past one-hundred years by creating rapids or increasing constrictions (table 14). From 1984 through 1998, four rapids or riffles were created and 13 were enlarged by debris flows. Sixty-two debris flows (32 percent) can only be dated as “historic” (1890-1990) and cannot be analyzed further for temporal distribution. With a few notable exceptions (*e.g.*, the debris flow in Badger Canyon that occurred between 1897 and 1909), most documented debris flows occurred after 1960 (table 14, fig. 5). The occurrence of debris flow is not random in Grand Canyon; debris flow activity is particularly concentrated in Marble Canyon and other reaches where the river trends towards the southwest (fig. 11). Where the river trends northwest, few historical debris flows were documented (Griffiths and others, 1996).

Repeat photography documented the distribution of debris flows during the last century in 171 tributaries (Webb, 1996; Griffiths and others, 1996). We identified 97 debris flows in historic photographs, indicating that 57 percent of the tributaries with repeat-photography records had debris flows sometime during the last 127 years. Debris flow in the remaining 43 percent of tributaries in Grand Canyon occur at a frequency of fewer than one per century. Using time series of repeat photography and other information, we found that approximately 10 percent of tributaries had two or more debris flows in the last one-hundred years, with a maximum of six debris flows at Lava Falls Rapid (Melis and others, 1994; Webb and others, 1999b). Twelve steep-angle chutes in extra areas outside of tributaries had debris flows during the last century indicating that these areas can be occasionally be active producers of small debris flows.

Climatic Variability and Debris-Flow Initiation

Historically, most Grand Canyon debris flows have occurred during localized, convective summer thunderstorms that affect only one or two drainage basins at a time. These storms typically occur in July through October (Melis and others, 1994). Rainfall from summer thunderstorms typically is intense, but localized, and has a duration of less than several hours. Debris flows in summer months are not related to the level of seasonal precipitation; instead, debris flows are equally likely to occur in wet, average, or dry summers (Griffiths and others, 1996; Webb and others, 1999b). In contrast, a few of the largest debris flows have occurred during prolonged winter precipitation from unusually warm frontal systems (Cooley and others, 1977; Griffiths and others, 1996; Webb and others, 1999b). Winter storms mostly affect large drainage basins (Cooley and others, 1977; Webb and others, 1989), and the occurrence of winter debris flows is unrelated to the amount of seasonal precipitation.

Although monthly precipitation was high when most historic debris flows occurred (Webb and others, 1999b), seasonal precipitation was not consistently high. Grand Canyon debris flows do not necessarily require season-long buildup of antecedent soil moisture; however, the importance of above-average rainfall in the days preceding the debris flow is reflected in the recurrence intervals for storm precipitation (Griffiths and others, 1997). Recurrence intervals of daily precipitation for summer debris flows are not well known because summer storms are localized and weather stations typically are kilometers from affected drainage basins. Storms that produce debris flows typically end in a strong microburst of intense rainfall, thus hourly precipitation data are required to determine triggering rainfall (Griffiths and others, 1996; Webb and others, 1999b). Because of these

Table 14. Debris flows that have had significantly changed debris fans and rapids during the last century in Grand Canyon.

[A full list of debris flows observed or recorded in repeat photography in Grand Canyon is in appendix 2.]

Tributary name	Name of rapid	River mile	Side	Year(s) or year range of debris flow(s)	Method used
Jackass Canyon	†Badger Creek	7.9	L	1994	1
Badger Canyon	Badger Creek	7.9	R	1897 to 1909	2
Soap Creek	Soap Creek	11.2	R	1923 to 1934	2
House Rock Canyon	House Rock	16.8	R	1966	1
Unnamed canyon	#New riffle	18.0	L	1987	1
Unnamed canyon	Unnamed riffle	21.5	L	1890 to 1990	2
Unnamed canyon	†24-Mile	24.2	L	1989	1
Tiger Wash	Tiger Wash	26.6	L	1890 to 1990	2
Unnamed canyon	No rapid	30.2	R	1989	2
South Canyon	Unnamed riffle	31.6	R	1940 to 1965	2
Unnamed canyon	Unnamed riffle	42.9	L	1983	2, 3
Tatahoysa Wash	"Boulder"	43.2	L	1983	2, 3
Unnamed canyon	#New rapid	62.5	R	1990	1
Palisades Creek	†Lava Canyon	65.5	L	1966, 1984, 1987, 1990	1, 2
Comanche Creek	Unnamed riffle	67.2	L	1999	1
Tanner Canyon	†Tanner	68.5	L	1993	1, 3
Basalt Canyon	Unnamed riffle	69.6	R	1999	1
Unnamed canyon	#New riffle	72.1	R	1984	1, 3
75-Mile Creek	Nevills	75.5	L	1959	2
75-Mile Creek	†Nevills	75.5	L	1987, 1990	1
Hance Creek	Sockdolager	78.7	L	1890 to 1990	2

complications, we did not find a useful relation between climate and debris-flow initiation that can be extrapolated to all tributaries, despite indications that debris-flow activity is related to variation in long-term precipitation (fig.5).

DEBRIS-FLOW SEDIMENT YIELD

Our model of debris-flow sediment yield in Grand Canyon involves four distinct elements: (1) frequency model for all 736 tributaries in Grand Canyon that produce debris flows, (2) a model of the expected volumes of debris flows reaching the Colorado River, (3) the particle-size distribution of debris flows, and (4) a depiction of river reworking that accounts for storage of debris-flow deposits on debris fans because of operations of Glen Canyon Dam.

Debris-Flow Frequency

Griffiths and others (1996) developed a logistic-regression model of debris-flow frequency in Grand Canyon between Lee's Ferry and Diamond Creek (river miles 0 to 225.8). For this report, that model was extended to the Grand Wash Cliffs (mile 276). Logistic regression predicts the probability of a binomial outcome from continuous, discrete, and (or) binomial independent variables, x. In the case of Grand Canyon debris flows, the outcome is whether or not debris flows have occurred during the last one-hundred years in each tributary (yes or no). The independent variables were 22 drainage-basin parameters related to morphometric, climatic, and lithologic characteristics (Griffiths and others, 1996). A total of 160 tributaries had debris-flow frequency information.

Table 14. Debris flows that have had significantly changed debris fans and rapids during the last century in Grand Canyon (continued).

Tributary name	Name of rapid	River mile	Side	Year(s) or year range of debris flow(s)	Method used*
Monument Creek	†Granite	93.5	L	1960s	2
Monument Creek	†Granite	93.5	L	1984, 1996	1
Hermit Creek	†Hermit	95.5	L	1996	1
Boucher Creek	Boucher	96.7	L	1951 to 1952	1, 2
Crystal Creek	Crystal	98.2	R	1966	1, 2, 3
Waltenberg Canyon	Waltenberg	112.2	R	1938 to 1987	2
Unnamed canyon	New rapid	127.6	L	1989	1
128-Mile Creek	128-Mile	128.5	R	1890 to 1923	2
Specter Chasm	†Specter	129.0	L	1989	1
Bedrock Canyon	†Bedrock	130.5	R	1989	1
Unnamed canyon	Unnamed riffle	133.0	L	1890 to 1923	2
Kanab Canyon	Kanab	143.5	R	1923 to 1942	2
Unnamed canyon	#New rapid	160.8	R	1993	1
Prospect Canyon	Lava Falls	179.4	L	1939	2
Prospect Canyon	Lava Falls	179.4	L	1954, 1955, 1963, 1966	2, 3
Prospect Canyon	†Lava Falls	179.4	L	1995	1
194-Mile Canyon	†Unnamed riffle	194.5	L	1998	1
205-Mile Canyon	205-Mile	205.5	L	1937 to 1956	2
205-Mile Canyon	†205-Mile	205.5	L	1998	1
Unnamed canyon	Unnamed riffle	222.6	L	1890 to 1990	2
Diamond Creek	Diamond Creek	225.8	L	1984	1
Unnamed canyon	231-Mile	231.0	R	1890 to 1990	2

*1 = Direct observation; 2 = Repeat photography; 3 = Aerial photography.
†Enlarged an existing riffle or rapid after 1984.
#Created a new riffle or rapid after 1984.

With logistic regression, the probability that an event will occur, $\pi(x)$, is:

$$\pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}} , \qquad (7)$$

where

$$g(x) = \beta_0 + \beta_i x_i + \ldots + \beta_n x_n,\ i = 1,\ldots, n, \qquad (8)$$

and x_i are the variables, β_i are the modeled variable coefficients, and β_0 is the y-axis intercept. Each variable was chosen based on the statistical significance of its contribution to the model (Griffiths and others, 1996). Owing to the high degree of spatial variability in tributary variables, Grand Canyon tributaries were grouped into eastern and western sets at Hermit Creek basin (mile 95). For both the eastern and western Grand Canyon models, n = 5 variables (table 15). Noteworthy among the significant variables are several terms that reflect the topographic relations of shale-bearing formations to the Colorado River as well as the aspect of the river corridor, which affects how storms interact with canyon walls (Griffiths and others, 1996). Fitted models explain about 74 percent of observed debris flow occurrences.

These logistic-regression probabilities derive from a cumulative-distribution function that can be related to the cumulative-distribution function for the binomial distribution. As such, these probabilities must be converted into a more useful form that reflects the magnitude-frequency relation for debris flow in Grand Canyon. For large numbers of data, such as the Colorado River tributaries, in Grand Canyon the cumulative-binomial distribution can be described by a cumulative-distribution function for the normal distribution (Haan, 1977). Because lognormally

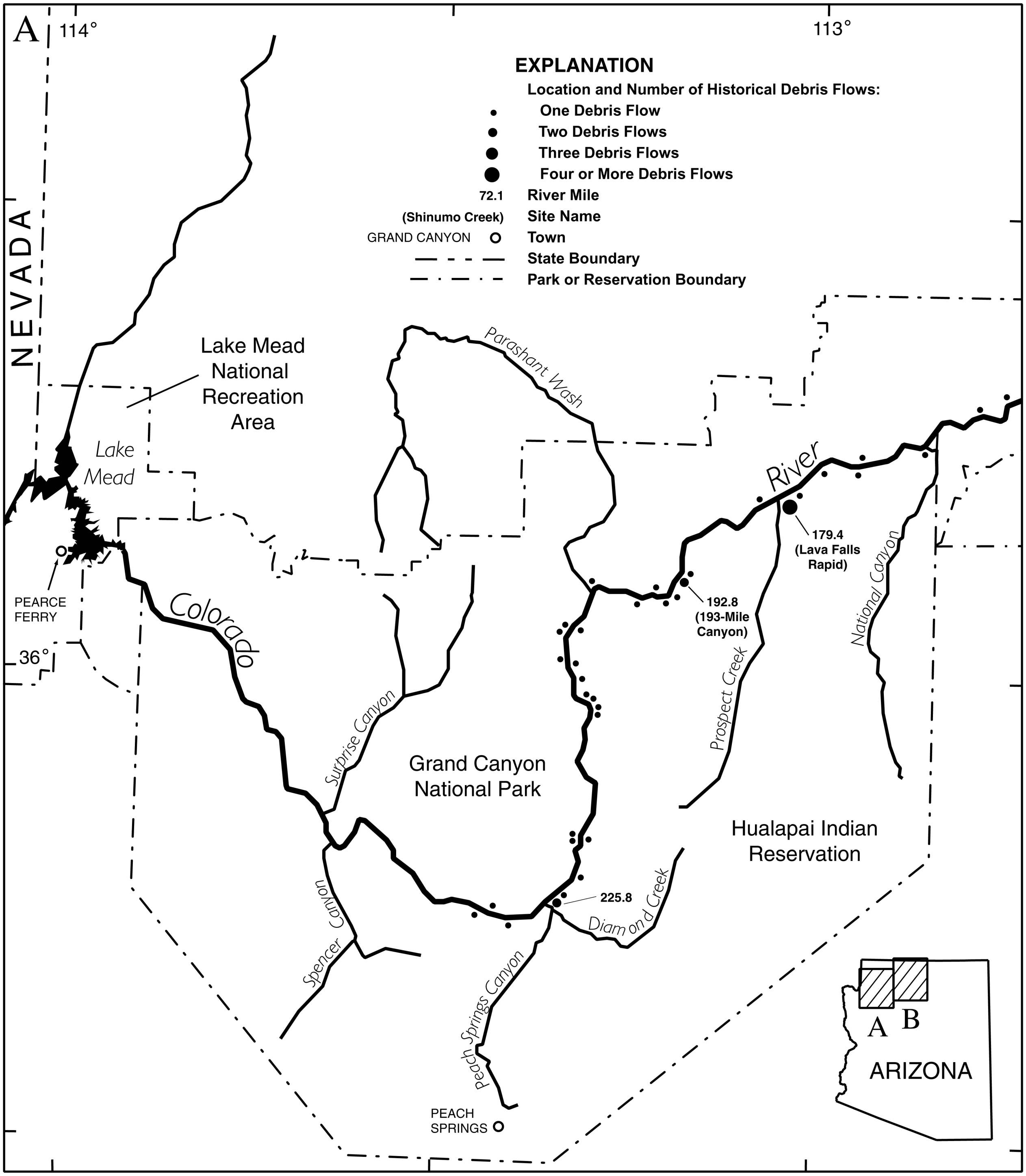

Figure 11. Geographic distribution of historical debris flows (1872-1999) in Grand Canyon. A. Western Grand Canyon.

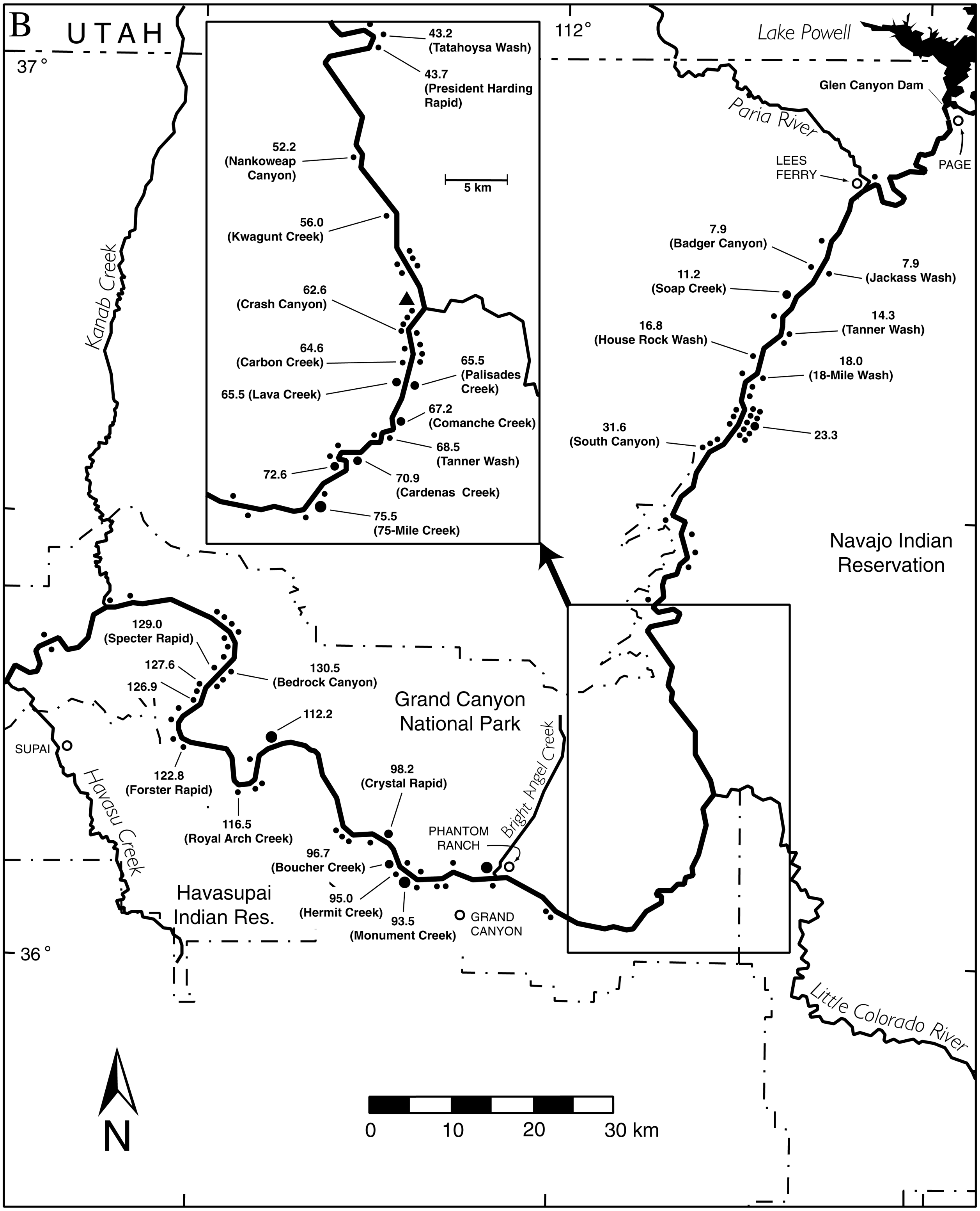

Figure 11–cont. B. Eastern Grand Canyon.

Table 15. Model for frequency of debris-flow occurrence in tributaries of the Colorado River in Grand Canyon, Arizona (from Griffiths and others, 1996).

Variable	Units	Intercept β_0	Variable Coefficients β_i
Eastern Grand Canyon			
River aspect	--	2.981	3.246
Log of drainage-basin area	km^2		2.192
Log of channel gradient to Hermit Shale	--		0.955
Log of main channel gradient	--		3.558
Elevation of Hermit Shale	m		-0.002
Western Grand Canyon			
Log of drainage-basin area	km^2	3.367	-2.226
Log of channel gradient to Hermit Shale	--		0.715
Log of main channel gradient	--		-5.221
Elevation of Muav Limestone	m		-0.003
Log of channel gradient to Muav Limestone	--		0.768

--, variable has no units

distributed variables are always greater than 0, we transformed the logistic-regression probabilities into a lognormal space to reflects true debris-flow frequency.

We adopted a frequency-factor approach similar to that used in traditional flood-frequency analysis (Kite, 1988). The frequency factor, F, is:

$$F = e^{(\mu + K[\pi(x)] \cdot \sigma)}, \quad (9)$$

where F = expected number of debris flows per century, $K[\pi(x)]$= standard normal deviate, and μ and σ are the mean and standard deviation of a lognormal distribution describing all debris-flow frequencies in Grand Canyon tributaries.

The values of μ and σ can not be known directly. Instead, values were chosen for μ and σ so as to constrain the distribution of F to the known characteristics of debris flows in Grand Canyon: (1) all 736 Grand Canyon tributaries produce debris flows, albeit some at a low frequency ($F > 0$ for all tributaries); (2) about 60 percent of tributaries produce one or more debris flows per century ($F \geq 1$ for 60 percent of tributaries); (3) about 5 percent of tributaries produce 2 or more debris flows per century ($F \geq 2$ for 5 percent of tributaries); and (4) no tributary has produced more than 6 debris flows in the last century (F is never greater than 6). Using these constraints, and $\mu = 0.95$ and $\sigma = 1.75$, we calculated a histogram of F for all Grand Canyon tributaries (fig. 12).

Debris-Flow Volumes

Estimation techniques

Debris-flow volumes were estimated by the product of fan area and an average thickness. We determined area of debris fans using several techniques. Some fans were surveyed directly. In most cases, we measured fan areas on rectified vertical and oblique aerial photographs. The most numerous oblique aerial photographs were taken from low altitudes by P.T. Reilly between 1950 and 1965. Other photographs were taken by the Bureau of Reclamation and are stored in its offices in Salt Lake City, Utah. Photographs were rectified using surveyed control points on the debris fans and image-processing software (Webb and others, 1999b). Control points were established at the corners of easily identified boulders or other sharp points that were clearly visible in the photographs. These points were surveyed using an arbitrary coordinate system or were tied into the Universal Transverse Mercator System using geographical positioning system (GPS) technology or established benchmarks. The resulting areas compared favorably with areas estimated directly from surveying data. All debris-fan areas are rounded to the nearest 100 m^2 (Webb and others, 1999b).

Thicknesses of debris fans were estimated using several techniques. The thickness of some recent debris flows was determined easily by comparison with previous surveys of the debris fan. In other cases, the surfaces of historical debris-flow deposits were projected over the reworked debris fan, and photographic evidence was used to identify boulders or terraces that had not been eroded or buried by subsequent debris flows. Boulders visible in historical photographs that were covered by later debris flows but not moved by subsequent Colorado River floods provided minimum thicknesses for the deposits. We could not estimate the accuracy of the estimated thicknesses.

In some cases, the volumes of historic debris flows were estimated by projection of remnant deposits over reworked debris fans (Webb and others, 1999b). Deposits were surveyed to estimate the slope on remnant deposits, and surveying of both sides of the Colorado River allowed projection over water.

Volumes of debris flows

Debris flow volumes vary considerably when plotted as a function of drainage area (fig. 13). Lacking sufficient data to describe a magnitude-frequency relation for all tributaries (we have debris-flow magnitude-frequency relation for only one tributary, Prospect Canyon; Webb and others, 1999b), we assumed that, like large streamflow floods (Enzel and others, 1993), the volume of sediment delivered by debris flows is a function of drainage area and its upper limit can be described by an enveloping curve of the form:

$$V(A) = a \cdot A^b, \qquad (10)$$

where V = total debris-flow volume (m^3), A = drainage area of tributary (km^2), and a and b are empirical coefficients. We defined the enveloping curve using the highest five points in figure 12 and fitting a power function using least-squares regression (fig. 13). We also determined an average volume by fitting a power function to the scattered data (fig. 13). We then estimated maximum and average debris flow volumes using the envelope curve and the average regression respectively. The volume of sediment transported to the river is also related to storm type but is only weakly related to the peak discharges of debris flows (Melis and others, 1994).

Particle-Size Distributions of Debris Flows

To account for boulder-size particles (larger than -8 ϕ), accurate determination of the particle-size distributions using weight-based determinations (*e.g.*, sieve analysis) are problematic because

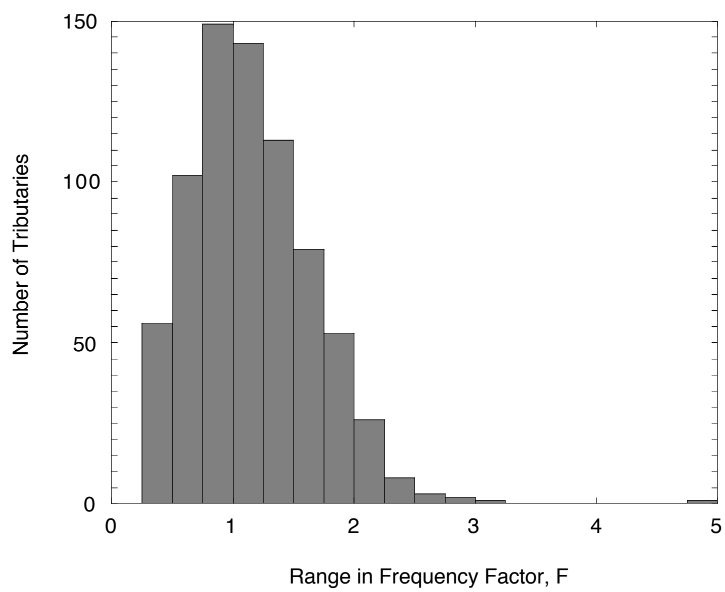

Figure 12. Distribution of debris-flow frequency factors (F) for 736 ungaged tributaries in Grand Canyon.

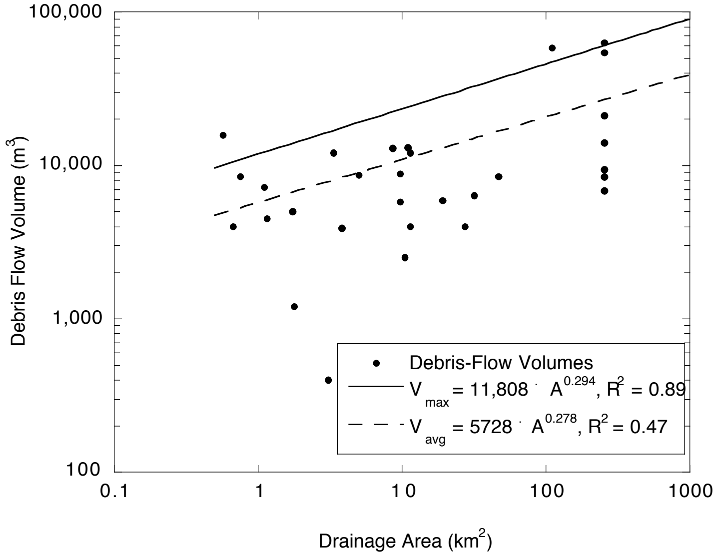

Figure 13.The relation of tributary drainage area to debris-flow volume for 30 historical debris flows in Grand Canyon, with linear regressions of both maximum and average debris-flow volumes.

large sample sizes are required. Representative samples of Grand Canyon debris-flow deposits for laboratory sieving cannot be easily collected because of a prohibitively large sample weight. Therefore, we used several methods in combination with sample collection to estimate the particle-size distributions of Grand Canyon debris flows.

Point counts

Point counts (Wolman, 1954; Rice and Church, 1996) were used in conjunction with sieve analysis to describe the particle-size distributions of most debris-flow deposits (Melis and others, 1994). We stretched tape measures over the surfaces of the debris-flow deposits to form a sampling grid. The length of a transect ranged from 50 to 100 m, and the spacing between tape measures was 0.5 to 2.0 m. At preselected intervals, which ranged from 0.5 to 2.0 m, depending on the size of the largest particles on the surface, we measured the intermediate (b-axis) diameter of the particle directly beneath the tape. Particles were not double-counted; if the same particle was measured twice, the second measurement was discarded.

Measured intermediate (b-axis) diameters were aggregated into single ϕ categories (*e.g.*, -1 to -2ϕ (2 to 4 mm)). One hundred to four hundred particles were measured during each point count. Use of 100 particles in each point count theoretically results in standard errors of estimate of less than ±20 percent (Rice and Church, 1996).

Pit excavations

At “Crash Canyon” (mile 62.6-R), Tanner Canyon (mile 68.5-L), and Prospect Canyon (mile 179.3-L), we directly measured particle size in pit excavations. We excavated a 1 m^3 volume into recent debris-flow deposits. All particles >64 mm were either weighed in the field or the particle was assumed to be an elliptical solid and its weight was calculated, assuming a density of 2,650 kg/m^3 for limestone and sandstone and 2,700 Kg/m^3 for basalt. We retained at least 1 kg of the remaining particles for laboratory sieve analysis.

Dry-sieve analysis

We collected large, representative samples of debris-flow deposits for sieve analysis in conjunction with point counts or pit excavations. The amount and size fraction of the sample depended on the extent of the deposit and the logistics of transporting the sample. To complement the point counts, we typically collected only those particles having diameters <64 mm.

We analyzed particle-size distributions using standard techniques (Kellerhals and Bray, 1971; Folk, 1974). Samples were dried, then a representative split was sieved using standard, brass sieves at 1 ϕ intervals from 4 to -5 ϕ (0.064 to 32 mm). Particles retained on each sieve were weighed and the percent of the subsample in each ϕ class was determined.

Particle-size distribution of debris flows

Particle-size distributions were determined by reconstructing the percentage of particles in each ϕ class on the basis of sample weight or by occurrence in point counts. If particle diameters were measured in the field, the particle-size distribution determined using sieve analysis was adjusted for these particles after the particle weight was calculated. If point counts were made on the surface of the deposit from which the sample was collected, the two types of data were combined. Although point counts are made using surface exposure and dry-sieve analyses are based on weight percent of a sample, the order of magnitude of the resulting percentages is similar (Kellerhals and Bray, 1971). We assumed that point counts accurately measure particle diameters in excess of 64 mm; therefore, the distribution of particles >64 mm was determined using point counts, whereas the distribution of particles <64 mm was determined by combining point count and dry-sieve data. The percentage of particles <64 mm determined by point count was adjusted by the particle-size distribution of the collected sample.

We determined particle-size distribution for 41 fresh, unaltered debris-flow deposits left by debris flows that occurred between 1965 and 1999 (fig. 14). The deposits are very poorly sorted. Pebbles are the most abundant particles at 41 percent by weight (table 16). Boulder content is highly variable, but typically accounts for about 14 percent of debris-flow deposits. On average, about 22 percent of all particles are smaller than gravel, and particles finer than sand account for only 4 percent of the distribution. The average sand content of debris flows is about 18.2 percent with a range of 2.4 to 47 percent.

We found no significant statistical relation between sand content and other factors that might contribute to the high variability, such as drainage area, watershed lithology, or the volume of the debris flow. The strongest correlations obtained were between sand-and-finer particles and debris-flow volume ($R^2 = 0.20$) and tributary drainage area ($R^2 = 0.20$). For the sand fraction, alone the highest R^2 value with any variable was 0.04.

Table 16. Percentage of boulders, cobbles, pebbles, sand, and silt+clay in debris flow in Grand Canyon.

Size Class	Debris-flow deposits (weight% ± 1 SD)
Number of samples	41
Boulders (>256 mm)	13.9 ± 18.7
Cobbles (64-256 mm)	24.4 ± 19.3
Pebbles (2-64 mm)	40.6 ± 20.6
Sand (0.063-2 mm)	18.2 ± 11.3
Silt + Clay (< 0.0063 mm)	3.7 ± 3.1

Bulk density of debris flows

The bulk density of debris flow deposits is required to convert deposit volume, as calculated using equation (10), to deposit mass. We calculate bulk density from particle-size information, by assuming that the volume occupied by particles larger than 2 mm has a density equivalent to rock, about 2.65 Mg/m^3. We further assume that the aggregate debris finer than gravel has a density of 1.5 Mg/m^3, a density typical of a non-compacted sandy soil. The bulk density of a debris-flow deposit can therefore be estimated from:

$$\gamma = 2.65 \cdot \Sigma(W_\phi, \phi < -1) + 1.50 \cdot \Sigma(W_\phi, \phi > -1), \quad (11)$$

where γ = the density of debris-flow deposits and W_ϕ = a weight percent fraction for a particle-size range. Using the values presented in table 16, we calculated an average value of γ = 2.4 Mg/m^3, which corresponds to a solids concentration of 85 percent by volume. This estimate is high compared to measured values for debris-flow deposits in other regions (Pierson, 1980; Major, and Voight, 1980; Gallino and Pierson, 1985; Iverson, 1997), which

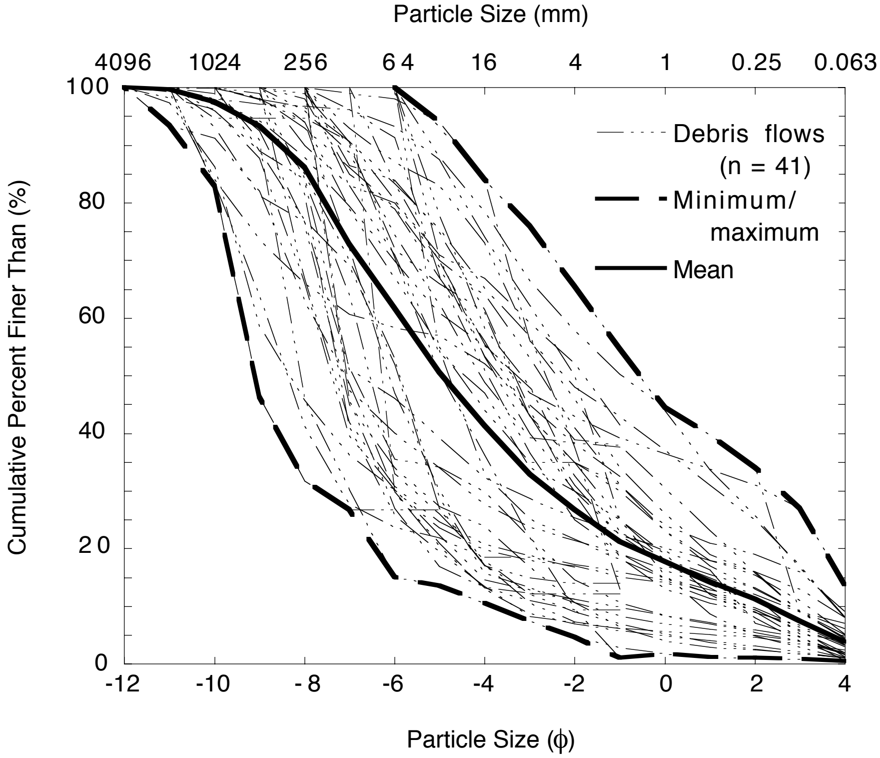

Figure 14. Particle-size distributions of 41 historical debris flows in Grand Canyon.

range from 1.5 to 2.0 Mg/m^3. The larger value of this estimate most likely results from underestimation of macro-pore spaces between larger particles. We therefore used the upper limit of measured densities, 2.0 Mg/m^3 (60 percent solids by volume), to calculate debris-flow sediment yields.

Reworking of Debris Fans by the Colorado River

Reworking of debris fans by the Colorado River is a complicated process that has been rarely documented in Grand Canyon (Kieffer, 1985; Webb and others, 1999a, 1999b; Pizzuto and others, 1999). Reworking releases sediment stored in debris fans — particularly sediment finer than gravel size — into the river, which rearranges the sediment into sandbars and debris bars. In order to understand sediment yield to the Colorado River from debris flows, some estimate must be made of the amount of sediment that is stored in debris fans versus what is expected to be released into the Colorado River. The technique must be such that all debris fans in Grand Canyon can be considered, if only on a reach-average basis. In the pre-dam Colorado River, the 10-yr flood had a discharge of 3,940 m^3/s, which is more than sufficient to overtop and rework most historic debris fans in Grand Canyon (Melis, 1997). Therefore, we assume that in the pre-dam era all fine sediment delivered by debris flow entered the river every decade.

After completion of Glen Canyon Dam, discharges decreased substantially and powerplant releases caused only minor reworking of debris fans (Melis and others, 1994). Large dam releases, such as the 1983 discharge and the 1996 controlled flood, significantly reworked debris fans (Kieffer, 1985; Webb and others, 1989, 1999a, 1999b). The 10-yr flood on the post-dam river is 1,430 m^3/s, about the size of the 1996 controlled flood. Using debris fan volume data contained in Kieffer (1985) and Webb and others (1989, 1999a, and 1999b), we estimated that 25±30 percent of the volumes of 13 debris fans was reworked by dam releases between 1966 and 1996. Reworking of these debris fans occurred during three dam releases that created discharges in Grand Canyon greater than powerplant capacity of 890 m^3/s. Historically, Glen Canyon Dam has released one significant discharge above powerplant capacity per decade. Therefore, we assume that for the post-dam era, the average volume reduction of aggraded debris fans is 25 percent per decade.

Sediment-Yield Model

The expected value of total annual sediment yield by debris flow for a given tributary is estimated as:

$$E[Q_{sdf}] = 0.02 \cdot F \cdot V(A) \cdot R, \qquad (12)$$

where $E[Q_{sdf}]$ = the expected value of annual sediment yield from debris flow, F = the frequency factor (the expected number of debris flows per century), $V(A)$ = the maximum (V_{max}) or average (V_{avg}) volume-enveloping curve, R = the fraction of debris fans reworked by the Colorado River (either 1 or 0.25/decade), and 0.02 is a volume-to-mass and century-to-annual conversion factor. Debris-flow occurrence varies considerably from year-to-year, both in terms of numbers of events and the volume of sediment delivered (table 14, fig. 13). The expected value of debris-flow sediment yield is computed using a conversion factor to convert the frequency information, which has a temporal unit of per century, to an annual unit that is compatible with streamflow sediment yield.

Debris flows contribute between 141,000 and 295,000 Mg/yr of sediment to debris fans in Grand Canyon (table 17). Reach B (Marble Canyon) contributes the greatest amount of debris-flow sediment, which is consistent with both the empirical observations on where historical debris flows have occurred in the last century (fig. 11) as well as the mapped distribution of logistical probabilities in Grand Canyon (Griffiths and others, 1996). Depending on the volume model used and the amount of debris-fan reworking, computations indicate that debris flows yield 6,440 to 53,700 Mg/yr of sand to the river corridor.

The debris-flow sediment-yield model requires a number of important assumptions. We assume that all debris flows from a given tributary are the same size, which means our model does not realistically depict a true magnitude-frequency relation. The only magnitude-frequency relation for Grand Canyon debris flows is for Prospect Canyon, a tributary that arguably is not representative of most of the ungaged tributaries (Webb and others, 1999b). The sediment-yield model produces an expected value of debris-flow sediment yield; therefore, extreme events not included in our historical record are not accounted for and small events are inadequately represented. Some of these problems could be resolved using a fully stochastic model of debris-flow frequency, but objectively determining model constraints based on the limited data from the ungaged tributaries would be difficult.

TOTAL SEDIMENT YIELD OF UNGAGED TRIBUTARIES

We combined sediment-yield estimates for streamflow (data regression equation; table 6) and debris flow (table 17) to estimate total annual sediment yield from the ungaged drainage areas (table 18). Depending upon the assumptions of the debris-flow sediment-yield model (whether V_{max} or V_{avg} is used), sediment yield by debris flow ranges from about 4 to 23 percent of total sediment yield. The total sediment yield is highest in Reach F (river miles 156.8-226.6), reflecting the high streamflow sediment yield. The percent contribution of debris-flow sediment yield is highest in Reaches B, C, and D because of the high frequency of debris flows in those reaches (Griffiths and others, 1996).

We calculated a range of possible sand yields given the assumptions of percent sand content (15, 50, and 75 percent) and debris-flow volumes (V_{max} or V_{avg}) and report low, average, and maximum sand delivery by the ungaged tributaries (table 18). We then added the variable of reworking of debris fans to simulate the impacts of Glen Canyon Dam on sediment storage in debris fans. The sand delivery rate from fully reworked debris fans, which reflects pre-dam conditions, averages about $1.3 \cdot 10^6$ Mg/yr for all ungaged tributaries. In Reaches A, B, and C (Glen and Marble Canyons,

Table 17. Annual sediment yield and sand delivery by debris flow in Grand Canyon.

	VOLUME AND WEIGHT YIELD			
Reach	**Maximum volume model (m^3/yr)**	**Maximum volume model (Mg/yr)**	**Average volume model (m^3/yr)**	**Average volume model (Mg/yr)**
Reach A	0[*]	0[*]	0[*]	0[*]
Reach B	40,100	80,300	19,000	38,000
Reach C	14,800	29,600	7,220	14,400
Reach D	24,900	49,900	12,000	24,000
Reach E	2,640	5,290	1,200	2,510
Reach F	36,000	72,000	17,100	34,100
Reach G	29,200	58,300	14,200	28,400
All Reaches	148,000	295,000	70,700	141,000

	SAND YIELD			
	FULLY REWORKED DEBRIS FANS[†]		PARTIALLY REWORKED DEBRIS FANS[#]	
Reach	**Maximum volume model (Mg/yr)**	**Average volume model (Mg/yr)**	**Maximum volume model (Mg/yr)**	**Average volume model (Mg/yr)**
Reach A	0[*]	0[*]	0[*]	0[*]
Reach B	14,600	6,910	3,650	1,730
Reach C	5,380	2,630	1,350	657
Reach D	9,070	4,370	2,270	1,090
Reach E	960	460	240	110
Reach F	13,100	6,210	3,280	1,550
Reach G	10,600	5,170	2,650	1,290
All Reaches	53,700	25,800	13,400	6,440

[*] Tributaries in Reach A (Glen Canyon) do not produce debris flows.
[†] Assumes that all debris flows average 18.2% sand content and that all sand enters the Colorado River (see Table 15).
[§] Assumes that every decade 25% of the volume of the average debris fan is reworked by a post-dam Colorado River flood and only the reworked debris reaches the river (see text). We then distribute the reworked sand on an expected annual basis.

and Grand Canyon upstream from Bright Angel Creek) the average total sand delivery is $0.030 \cdot 10^6$, $0.296 \cdot 10^6$, and $0.050 \cdot 10^6$ Mg/yr, respectively. Limited reworking of debris fans associated with the operation of Glen Canyon Dam reduces sand delivery in Reaches B and C to 0.288 and $0.047 \cdot 10^6$ Mg/yr, respectively (table 18). The combined average post-dam sand yield from ungaged tributaries in Reaches A and B is about $0.318 \cdot 10^6$ Mg/yr, or 20 percent of the approximately $1.5 \cdot 10^6$ Mg/yr of sand delivered annually by the Paria River. Sand contributed by tributaries in Glen Canyon is notably coarser (D_{50} = 0.24 mm) than sand from other reaches (D_{50} = 0.11 - 0.20 mm), including the Marble Canyon reach (D_{50} = 0.20 mm; table 13; fig. 10).

CLIMATIC VARIABILITY AND STREAMFLOW SEDIMENT YIELD

Sediment yield in the Grand Canyon region occurs mostly in discrete events. The relation between the magnitude and frequency of discrete events and regional climate is complex for geomorphic processes such as debris flows, as discussed above. Streamflow, however, is strongly related to seasonal climate, and streamflow sediment yield should be related to climatic variability (Graf and others, 1991). In Bright Angel Creek, for example, most flood events (55 percent) occur in summer, summer floods have a higher mean discharge (13 m^3/s) than floods in other seasons, and winter floods occur mostly in El Niño years. We assumed that other small tributaries in

Grand Canyon respond similarly and developed a climatic variability relation between summer rainfall (fig. 4a) and sediment yield.

We evaluated the effects of climatic variability on streamflow in eight small drainages on Black Mesa for which annual sediment-yield data are available for 10-12 years of record (table 4). Equation (2) was used to develop a standardized summer (July-September) rainfall index for 1985-1997, which corresponds to the period of record for sediment yield for the Black Mesa gaging stations. Data came from weather stations surrounding Black Mesa — Betatakin National Monument, Chinle, Keams Canyon, and Monument Valley — instead of the weather stations in the Grand Canyon region (table 3). We then standardized the sediment-yield data for Black Mesa with the regression equation:

$$Q_{sBM} = -0.046 + 0.888 \cdot P_{BM},\ R^2 = 0.41, \qquad (13)$$

where Q_{sBM} = standardized Black Mesa annual sediment yields and P_{BM} is the standardized precipitation index for the weather stations near Black Mesa. Similar regression equations developed for winter precipitation and annual precipitation were not significant.

We assume that equation (14) represents the expected sediment-yield response to climatic variability in Grand Canyon, and that the interannual variability of sediment yield in Grand Canyon was of a similar magnitude to the interannual variability of sediment yield on Black Mesa. The time series of sediment yield from the ungaged tributaries in a reach was calculated as:

$$Q_s(t) = Q_s \cdot (C_v \cdot (-0.046 + 0.888 \cdot P_s(t)) + 1), \qquad (14)$$

where $Q_s(t)$ = the time series of sediment yield for each year t, Q_s = the average annual sediment yield for a reach (table 6), C_v = a coefficient of variation for the sediment data, and $P_s(t)$ = the time series of standardized precipitation presented in figure 4a. The average C_v for the eight sediment records from Black Mesa is 1.3; the C_v for the Paria River is 0.9. Using this method, we calculated the annual variation in streamflow sediment yield for Reaches A and B (fig. 15). The larger peaks (1940 and 1980) and troughs (mid 1970s) replicate a pattern seen in Topping's (1997) calculations for fine sediment input from the Paria River. Total sediment yield is increased 5 to 20 percent when accounting for debris flows, (table 11) which are assumed not to vary with climate.

This approach clearly has problems that diminish its usefulness. Among them, we assume that climate can be adequately measured by rain gages that are fairly distant from a watershed, and that the variability in summer rainfall is reasonably synchronous across the region of interest. Given the localized nature of the summer thunderstorms, that may not always be the case. We also assume that the relation between sediment yield and summer precipitation for Black Mesa, which is relatively weak, is directly transferable to the Grand Canyon region and adequately describes the relation between sediment yield in ungaged tributaries and regional climate. In addition, we assume that the coefficient of variation of sediment yield in Grand Canyon tributaries is similar to that of Black Mesa. Finally, we assume that annual variation in sediment yield is completely controlled by variability in summer precipitation.

DISCUSSION AND CONCLUSIONS

Sediment input to the Colorado River in Grand Canyon, Arizona, is a valuable resource required to sustain terrestrial and aquatic ecosystems. Since the closure of Glen Canyon Dam in 1963, sediment enters Grand Canyon from 4 major tributaries with gaging stations and 768 small, ungaged tributaries. Estimation of sediment yield from ungaged tributaries is a critical element in the development of a sediment mass balance for Grand Canyon. However, estimation of sediment yield is complicated by the fact that sediment is delivered by debris flows as well as by streamflow floods, requiring development of new techniques for assessing sediment yield.

A total of 768 tributaries deliver sediment to the Colorado River between Glen Canyon Dam and the Grand Wash Cliffs (river miles -15 to 276). The 32 tributaries between the dam and Lee's Ferry produce only streamflow floods whereas 736 tributaries in Grand Canyon produce streamflow floods and debris flows. We used three techniques to estimate annual streamflow sediment yield from ungaged tributaries to Grand Canyon, all of which gave very similar results. The flood-frequency technique depends on numerous untested

Table 18. Total sediment yield and sand delivery from ungaged tributaries of the Colorado River in Grand Canyon, Arizona.

Sediment-yield reach	River miles	Maximum volume model (10^6 Mg/yr)	Amount contributed by debris flows (%)	Average volume model (10^6 Mg/yr)	Amount contributed by debris flows (%)
			TOTAL SEDIMENT YIELD		
A	-15.5 to 0.9	0.065	0	0.065	0
B	0.9 to 61.5	0.691	12	0.648	6
C	61.5 to 87.8	0.127	23	0.112	13
D	87.8 to 143.5	0.381	13	0.356	7
E	143.5 to 156.8	0.062	9	0.059	4
F	156.8 to 225.8	0.893	8	0.855	4
G	225.8 to 276.0	0.728	8	0.698	4
	All Reaches	2.947	10	2.793	5

Sediment-yield reach	River miles	Low (10^6 Mg/yr)	Amount in debris flows (%)	Maximum (10^6 Mg/yr)	Amount in debris flows (%)	Average (10^6 Mg/yr)	Amount in debris flows (%)
				SAND YIELD FROM FULLY REWORKED DEBRIS FANS			
A	-15.5 to 0.9	0.010	0.0	0.049	0.0	0.030	0.0
B	0.9 to 61.5	0.098	1.5	0.472	13.8	0.296	5.4
C	61.5 to 87.8	0.017	3.5	0.079	26.9	0.050	11.2
D	87.8 to 143.5	0.054	1.7	0.258	15.4	0.162	6.1
E	143.5 to 156.8	0.009	1.1	0.044	10.1	0.027	3.9
F	156.8 to 225.8	0.129	1.0	0.629	9.6	0.393	3.7
G	225.8 to 276.0	0.106	1.0	0.513	9.6	0.320	3.7
	All Reaches	0.423	1.3	2.043	11.9	1.277	4.6
				SAND YIELD FROM PARTIALLY REWORKED DEBRIS FANS			
A	-15.5 to 0.9	0.010	0.0	0.049	0.0	0.030	0.0
B	0.9 to 61.5	0.093	0.4	0.462	3.8	0.288	1.4
C	61.5 to 87.8	0.015	0.9	0.075	8.4	0.047	3.2
D	87.8 to 143.5	0.051	0.4	0.251	4.4	0.156	1.6
E	143.5 to 156.8	0.009	0.3	0.043	2.7	0.027	1.0
F	156.8 to 225.8	0.125	0.3	0.619	2.6	0.385	1.0
G	225.8 to 276.0	0.102	0.3	0.505	2.6	0.314	1.0
	All Reaches	0.404	0.3	2.002	3.3	1.247	1.2

assumptions, such as equating decadal sediment yield with the sum of sediment yield from one ten-year, two five-year, and five two-year floods. The technique was adjusted to fit the data regression relation and is not strictly an independent approach.

Nevertheless, close agreement with the other two methods suggests that the technique has strong potential as a new method for estimating streamflow-sediment yield. The data regression technique and the empirical approach of Renard (1972), derived from different data sets and methodologies, are independent methods that provide similar sediment-yield estimates. Of the three methods, we selected the regional regression relation for calculating sediment-yield estimates because it is derived specifically from Colorado Plateau data. This technique indicates that the Glen and Marble Canyon reaches (river miles -15 to 61.5) deliver $0.065 \cdot 10^6$ and $0.610 \cdot 10^6$ Mg/yr of streamflow sediment, respectively, ($0.68 \cdot 10^6$ total) to the Colorado River. This amount is 20 percent of the sediment yield of the Paria River, the only gaged tributary in the reach.

Sand delivery by streamflow from the Glen and Marble Canyon reaches is about $0.032 \cdot 10^6$ and $0.305 \cdot 10^6$ Mg/yr, respectively ($0.340 \cdot 10^6$ total), depending on the sand content of streamflow sediment. Sand input to Glen Canyon is significantly coarser (D_{50} = 0.24 mm) than sand in other reaches (D_{50} 0.15 mm). A relation is given relating the possible variation of this sediment delivery with climatic variability.

Debris flows transport poorly-sorted sediment onto debris fans in the Colorado River. In the pre-dam era, most debris fans were extensively reworked during Colorado River floods, liberating most fine-grained sediment to the river. In the post-dam river, an average of only 25 percent of debris-fan volume is reworked, leading to storage of sand in the matrix of debris fans. We used a logistic-regression model of debris-flow frequency in Grand Canyon based on the interpretation of 1,297 historical photographs of the river corridor. This analysis yielded information on the frequency of debris flows in 168 of the 736 tributaries (23 percent). Of the 168 tributaries, 96 (~60 percent) had debris flows during the last one hundred years.

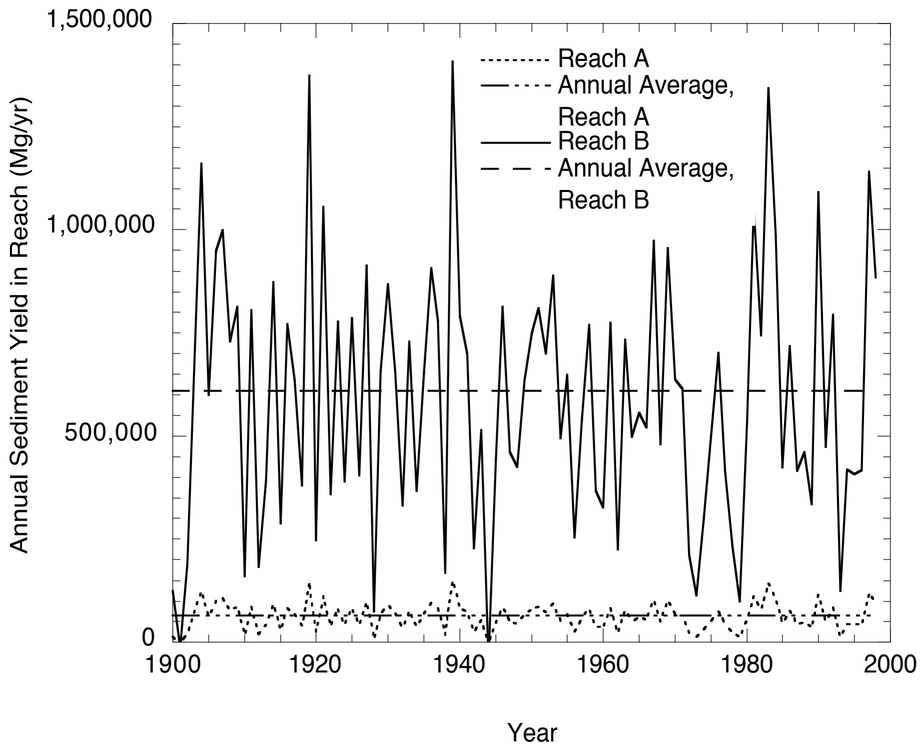

Figure 15. Estimated time series of streamflow sediment yields in Reaches A and B based on climatic variability (Fig. 4a) and using a Cv = 1.3.

Using probabilities estimated from logistic regression, we developed a statistical relation for debris-flow frequency in which all 736 tributaries had a probability greater than zero of producing a debris flow each century; 60 percent of the tributaries had a frequency of at least 1 debris flow per century; and about 5 percent of the tributaries had a frequency of more than 2 debris flows per century. Analysis of particle-size distributions of 41 intact deposits, suggests that debris flows in Grand Canyon typically contain about 18 percent sand. We developed a regression equation relating debris-flow volumes to tributary drainage area to calculate the amount of sand delivered by debris flow. By combining our frequency model with relations for debris-flow volume and particle-size distribution, we developed a sediment-yield model for debris flow in Grand Canyon. On average, debris flows deliver between $0.14 \cdot 10^6$ and $0.30 \cdot 10^6$ Mg/yr of sediment to the main channel. Of that yield, between 6,440 and 13,400 Mg/yr of sand reaches the regulated Colorado River; while 23,000 to 48,400 Mg/yr is stored in unreworked parts of debris fans. Although debris flows deliver only 21,000 to 44,000 Mg/yr of boulders (particles > 256 mm) to the river, these few boulders have a critical impact on the geomorphic framework of the river, defining debris fans, rapids and related sand bars, and are unlikely to be removed by regulated flows.

The total sediment yield by streamflow and debris flow from the ungaged drainage areas is $2.8\text{-}3.0 \cdot 10^6$ Mg/yr. Between 4 percent and 23 percent of the total is delivered by debris flow; the remainder is delivered in streamflow. Of this total sediment yield, $0.4 \cdot 10^6$ to $2.0 \cdot 10^6$ Mg/yr is sand, although a small amount of this sand is stored in unreworked debris fans. Even with storage in debris fans, between $0.1 \cdot 10^6$ and $0.5 \cdot 10^6$ Mg/yr of sand are added to the reaches between Glen Canyon Dam and the Little Colorado River annually. This amount is up to 33 percent of the sand delivered by the Paria River, the only other source of sand-sized particles in this critical section of Grand Canyon, and double the $0.17 \cdot 10^6$ Mg/yr estimated in the 1995 environmental impact statement for the operation of Glen Canyon Dam (U.S. Department of the Interior, 1995). Sand delivered by debris flows contributes up to 8 percent of the total sand yields. Particles larger than sand — particularly the boulders and cobbles delivered by debris flow — are largely unaffected by regulated flows from Glen Canyon Dam and continue to aggrade the Colorado River in Grand Canyon.

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APPENDIX I

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994)

[Tributary names are taken from U.S. Geological Survey 7.5-minute quadrangle maps and river guides (Stevens, 1990), or are informally used. Drainage area was digitized from 1:24,000 scale quadrangle maps. Rapid names are usually taken from Stevens (1990) or are informal; rapids not included are Nixon Rock (99.9) and Lower Lava Falls (179.7). Rapid ratings are for a 10,000 ft^3/s discharge (Stevens, 1990). Water-surface fall is from U.S. Geological Survey survey data collected in 1923 that was adjusted to a 10,000 ft^3/s discharge. U.S. Geological Survey 7.5-minute quadrangle map refers to the tributary juncture with the Colorado River. (-), indicates no data, that tributary is unnamed, or that no riffle or rapid exist at the site.]

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute USGS quadrangle name
REACH 0: GLEN CANYON							
-14.9	L	-	2.01	-	-	-	Page
-13.0	L	Honey Draw	33.72	-	-	-	Page
-11.5	R	-	6.84	-	-	-	Ferry Swale
-11.3	R	Ferry Swale Canyon	91.80	-	-	-	Ferry Swale
-9.8	L	Ninemile Draw	3.70	-	-	-	Ferry Swale
-9.0	L	-	13.87	-	-	-	Ferry Swale
-6.7	R	-	6.87	-	-	-	Lees Ferry
-6.5	R	-	0.25	-	-	-	Ferry Swale
-6.4	R	-	1.66	-	-	-	Ferry Swale
-6.3	R	-	1.95	-	-	-	Lees Ferry
-6.2	R	-	0.35	-	-	-	Lees Ferry
-5.6	L	-	0.20	-	-	-	Lees Ferry
-5.4	L	-	0.93	-	-	-	Lees Ferry
-5.4	R	-	0.14	-	-	-	Lees Ferry
-5.2	R	-	0.18	-	-	-	Lees Ferry
-5.1	L	-	0.34	-	-	-	Lees Ferry
-5.1	R	-	0.62	-	-	-	Lees Ferry
-4.1	L	Water Holes Canyon	66.54	Unnamed riffle	-	0.31	Lees Ferry
-3.3	R	-	0.30	-	-	-	Lees Ferry
-3.2	R	-	0.15	-	-	-	Lees Ferry
-3.1	R	-	0.16	-	-	-	Lees Ferry
-3.0	L	Cave Canyon	18.49	-	-	-	Lees Ferry
-2.5	L	Fall Creek	34.08	-	-	-	Lees Ferry
-2.1	L	-	0.44	-	-	-	Lees Ferry
-2.0	R	-	0.43	Unnamed riffle	-	0.31	Lees Ferry
-1.7	L	-	0.94	-	-	-	Lees Ferry
-1.5	L	-	0.54	-	-	-	Lees Ferry
-1.4	L	-	0.58	-	-	-	Lees Ferry
-0.3	R	-	0.35	-	-	-	Lees Ferry
-0.2	L	-	0.71	-	-	-	Lees Ferry
-0.1	L	-	0.96	-	-	-	Lees Ferry
-0.1	R	-	0.47	-	-	-	Lees Ferry

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
REACH 1: UPPER WIDE 1							
1.0	R	-	9.18	-	-	-	Lees Ferry
2.2	L	-	2.53	-	-	-	Lees Ferry
2.2	R	-	7.71	-	-	-	Lees Ferry
2.8	R	Cathedral Wash	17.27	Unnamed riffle	-	1.5	Lees Ferry
3.4	L	-	5.26	-	-	-	Navajo Bridge
3.5	L	-	0.61	-	-	-	Navajo Bridge
3.9	L	-	4.29	-	-	-	Navajo Bridge
4.5	L	-	5.87	-	-	-	Navajo Bridge
5.1	L	5-Mile Wash	4.64	-	-	-	Navajo Bridge
5.7	R	Seven Mile Draw	18.65	Unnamed riffle	-	0.3	Navajo Bridge
7.9	L	Jackass Creek	52.24	Badger Creek	6	3.9	Navajo Bridge
7.9	R	Badger Canyon	47.01	Badger Creek	6	3.9	Navajo Bridge
REACH 2: UPPER NARROW I							
8.6	R	-	2.09	Unnamed riffle	-	0.3	Navajo Bridge
10.0	L	-	1.90	-	-	-	Bitter Springs
10.2	L	-	1.37	-	-	-	Bitter Springs
11.2	R	Soap Creek	90.26	Soap Creek	5	5.1	Bitter Springs
11.8	L	Salt Water Wash	9.60	Unnamed riffle	-	0.3	Bitter Springs
12.1	L	-	9.81	Unnamed riffle	-	0.3	Bitter Springs
12.3	R	-	1.36	-	-	-	Bitter Springs
12.8	R	-	7.99	13-Mile	1	-	Bitter Springs
13.0	L	-	1.13	-	-	-	Bitter Springs
13.0	R	-	1.19	-	-	-	Bitter Springs
13.6	L	-	2.58	-	-	-	Bitter Springs
14.3	L	Tanner Wash	182.55	Sheer Wall	2	2.9	Bitter Springs
15.1	L	-	7.40	-	-	-	Bitter Springs
15.3	L	-	2.52	-	-	-	Bitter Springs
16.3	L	Hanaa Ninadzidzahi	28.84	Unnamed riffle	-	0.3	Bitter Springs
16.8	R	House Rock Wash	770.52	House Rock	7	2.8	Bitter Springs
17.4	L	-	3.75	Redneck	3	-	Bitter Springs
18.0	L	18-Mile Wash	5.06	Unnamed riffle	-	0.3	Bitter Springs
18.1	L	-	3.83	Unnamed riffle	-	0.3	Bitter Springs
19.0	R	19-Mile Canyon	1.12	-	-	-	Emmett Wash
19.1	L	-	1.42	-	-	-	Emmett Wash
19.3	R	-	2.48	-	-	-	Emmett Wash
19.9	L	-	3.78	-	-	-	Emmett Wash
20.5	R	North Canyon	407.72	North Canyon	5	3.7	North Canyon Point
21.1	L	-	0.04	21-Mile	5	1.8	Emmett Wash

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
21.1	R	-	0.39	21-Mile	5	1.8	Emmett Wash
21.4	L	-	13.96	Unnamed riffle	-	0.3	North Canyon Point
21.5	L	22-Mile Wash	1.59	Unnamed riffle	-	0.3	North Canyon Point
21.8	R	-	0.27	-	-	-	North Canyon Point
22.2	L	-	3.05	-	-	-	North Canyon Point
22.9	L	-	7.87	-	-	-	North Canyon Point
23.2	R	-	0.12	-	-	-	North Canyon Point
23.3	L	-	0.27	Indian Dick	5	1.8	North Canyon Point
23.4	R	-	0.15	Indian Dick	5	1.8	North Canyon Point
23.5	L	-	0.82	23.5-Mile	4	-	North Canyon Point
24.0	L	-	1.71	-	-	-	North Canyon Point
24.2	L	-	0.22	24-Mile	6	1.4	North Canyon Point
24.2	R	-	0.35	24-Mile	6	1.4	North Canyon Point
24.4	L	Sheep Spring Wash	26.12	24.5-Mile	5	2.5	North Canyon Point
24.7	L	-	1.16	25-Mile	5	1.8	North Canyon Point
25.0	L	-	2.01	Unnamed riffle	-	0.9	North Canyon Point
25.3	L	-	0.74	Cave Springs	5	1.5	North Canyon Point
25.3	R	-	1.24	Cave Springs	5	1.5	North Canyon Point
25.4	L	-	0.07	-	-	-	North Canyon Point
25.4	R	-	0.11	-	-	-	North Canyon Point
26.6	L	Tiger Wash	51.89	Tiger Wash	4	2.0	North Canyon Point
26.6	R	-	3.42	Tiger Wash	4	2.0	North Canyon Point
26.8	R	-	0.02	MNA	1	1.0	North Canyon Point
27.2	L	-	1.24	-	-	-	North Canyon Point
28.2	L	To Hajisho	20.22	Unnamed riffle	-	0.9	North Canyon Point
29.2	L	Shinumo Wash	186.55	29-Mile	2	1.8	North Canyon Point
30.2	L	-	6.03	Unnamed riffle	-	1.2	North Canyon Point
30.2	R	-	0.29	-	-	1.2	North Canyon Point
30.5	R	-	0.95	-	-	-	North Canyon Point
31.0	R	-	3.08	-	-	-	North Canyon Point
31.6	R	South Canyon	193.12	Unnamed riffle	-	1.2	North Canyon Point
31.8	R	-	0.49	-	-	-	North Canyon Point
32.0	R	-	1.19	Unnamed riffle	-	0.3	Tatahatso Point
32.6	L	-	0.14	-	-	-	Tatahatso Point
32.8	L	-	1.01	-	-	-	Tatahatso Point
34.2	R	-	0.94	-	-	-	Tatahatso Point
34.7	L	Nautiloid Canyon	10.59	Unnamed riffle	-	0.9	Tatahatso Point
34.9	L	-	0.09	-	-	-	Tatahatso Point
35.2	L	-	0.70	-	-	0.3	Tatahatso Point
35.6	L	-	0.78	-	-	0.9	Tatahatso Point
36.0	L	-	2.01	36-Mile	3	2.5	Tatahatso Point
36.7	R	-	20.50	-	-	-	Tatahatso Point

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
37.4	L	Tatahatso Wash	202.60	Unnamed riffle	-	0.3	Tatahatso Point
37.6	L	-	0.95	-	-	-	Tatahatso Point
37.7	L	-	1.49	Unnamed riffle	-	0.3	Tatahatso Point
REACH 3: MIDDLE WIDE II							
38.6	R	-	0.79	-	-	-	Tatahatso Point
39.0	R	Redbud Alcove	1.41	Unnamed riffle	-	0.3	Tatahatso Point
41.0	R	Buck Farm Canyon	31.15	Unnamed riffle	-	0.5	Buffalo Ranch
41.3	R	Berts Canyon	1.81	Unnamed riffle	-	0.3	Buffalo Ranch
42.9	L	-	1.33	Unnamed riffle	-	0.3	Buffalo Ranch
43.0	L	-	0.65	-	-	-	Buffalo Ranch
43.1	L	-	0.26	-	-	-	Buffalo Ranch
43.2	L	Tatahoysa Wash	50.77	President Harding	4	1.4	Tatahatso Point
43.7	L	-	6.10	-	-	-	Tatahatso Point
44.6	L	-	2.66	Unnamed riffle	-	0.3	Tatahatso Point
44.8	L	-	1.26	-	-	-	Tatahatso Point
45.8	L	-	0.61	-	-	-	Tatahatso Point
46.7	R	-	1.46	-	-	-	Tatahatso Point
46.8	R	-	1.30	-	-	-	Tatahatso Point
47.0	R	Saddle Canyon	29.30	-	-	-	Point Imperial
47.4	L	-	0.71	-	-	-	Nankoweap Mesa
47.4	R	-	0.49	-	-	-	Nankoweap Mesa
47.8	L	-	0.28	-	-	-	Nankoweap Mesa
47.8	R	-	0.77	-	-	-	Nankoweap Mesa
48.5	R	-	1.31	Unnamed riffle	-	0.3	Nankoweap Mesa
49.4	R	-	4.36	Unnamed riffle	-	0.3	Nankoweap Mesa
49.6	L	-	2.22	Unnamed riffle	-	0.3	Nankoweap Mesa
49.8	R	-	3.39	-	-	-	Nankoweap Mesa
49.9	L	-	0.15	-	-	-	Nankoweap Mesa
50.0	L	-	0.12	-	-	-	Nankoweap Mesa
50.1	L	-	0.13	-	-	-	Nankoweap Mesa
50.3	L	-	0.26	-	-	-	Nankoweap Mesa
50.4	L	-	0.43	-	-	-	Nankoweap Mesa
50.8	L	-	0.36	-	-	-	Nankoweap Mesa
51.2	L	-	0.37	-	-	-	Nankoweap Mesa
51.7	R	Little Nankoweap Creek	10.59	-	-	-	Nankoweap Mesa
52.2	R	Nankoweap Canyon	84.58	Nankoweap	3	7.7	Nankoweap Mesa
52.5	L	-	3.49	Nankoweap	3	7.7	Nankoweap Mesa
53.1	R	-	1.23	Unnamed riffle	-	0.3	Nankoweap Mesa
53.5	R	-	0.26	-	-	-	Nankoweap Mesa
53.8	R	-	0.75	-	-	-	Nankoweap Mesa

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
54.0	R	-	0.39	-	-	-	Nankoweap Mesa
54.5	R	-	1.66	-	-	-	Nankoweap Mesa
55.0	L	-	0.60	-	-	-	Nankoweap Mesa
55.4	R	-	0.70	-	-	-	Nankoweap Mesa
56.0	R	Kwagunt Creek	39.25	Kwagunt	6	2.0	Nankoweap Mesa
56.3	L	-	4.58	Unnamed riffle	-	2.2	Nankoweap Mesa
56.6	R	-	0.12	-	-	-	Nankoweap Mesa
56.8	R	-	0.10	-	-	-	Nankoweap Mesa
56.9	L	-	0.93	-	-	-	Nankoweap Mesa
57.3	L	-	0.61	-	-	-	Nankoweap Mesa
57.5	R	Malgosa Canyon	6.98	Unnamed riffle	-	0.3	Cape Solitude
57.7	L	-	0.39	-	-	-	Cape Solitude
57.8	R	-	0.14	-	-	-	Cape Solitude
58.0	R	Awatubi Canyon	5.54	-	-	-	Cape Solitude
58.5	L	-	0.74	-	-	-	Cape Solitude
58.8	R	-	1.19	-	-	-	Cape Solitude
59.4	R	-	0.15	-	-	-	Cape Solitude
59.6	L	-	9.49	60-Mile	4	1.7	Cape Solitude
59.6	R	60-Mile Canyon	9.69	60-Mile	4	1.7	Cape Solitude
59.7	L	-	0.39	-	-	-	Cape Solitude
60.2	R	-	0.40	-	-	-	Cape Solitude
60.3	L	-	1.42	-	-	-	Cape Solitude
60.5	L	-	0.40	-	-	-	Cape Solitude
60.6	R	-	0.94	-	-	-	Cape Solitude
61.1	R	-	0.66	-	-	-	Cape Solitude
61.7	R	-	0.66	-	-	-	Cape Solitude
61.9	L	-	0.24	-	-	-	Cape Solitude
62.0	R	-	0.09	-	-	-	Cape Solitude
62.1	L	-	0.21	-	-	-	Cape Solitude
62.2	R	-	0.37	-	-	-	Cape Solitude
62.5	R	-	0.67	Unnamed riffle	-	0.3	Cape Solitude
62.6	L	-	0.19	-	-	-	Cape Solitude
62.6	R	Crash Canyon	1.79	-	-	-	Cape Solitude
63.0	L	-	0.64	-	-	-	Cape Solitude
63.3	L	-	0.26	-	-	-	Cape Solitude
63.3	R	-	0.66	Unnamed riffle	-	0.3	Cape Solitude
63.5	L	-	0.40	-	-	-	Cape Solitude
63.5	R	-	0.05	-	-	-	Cape Solitude
63.8	L	-	0.37	-	-	-	Cape Solitude
63.8	R	-	0.31	-	-	-	Cape Solitude
64.0	L	-	0.61	-	-	-	Cape Solitude
64.5	L	-	0.33	-	-	-	Cape Solitude

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
64.6	R	Carbon Creek	11.40	-	-	-	Cape Solitude
65.3	L	-	0.60	-	-	-	Cape Solitude
65.5	L	Palisades Creek	4.06	Lava Canyon	4	2.3	Cape Solitude
65.5	R	Lava Canyon	54.71	Lava Canyon	4	2.3	Cape Solitude
66.3	L	-	1.15	-	-	-	Desert View
66.3	R	-	1.47	-	-	-	Desert View
66.8	L	Espejo Creek	1.73	-	-	-	Desert View
67.2	L	Comanche Creek	5.40	Unnamed riffle	-	0.3	Desert View
67.6	R	-	1.22	-	-	-	Desert View
67.8	L	-	0.28	-	-	-	Desert View
68.0	L	-	0.63	-	-	-	Desert View
68.5	L	Tanner Canyon	19.25	Tanner	4	3.7	Desert View
68.8	R	-	0.15	-	-	-	Desert View
69.6	R	Basalt Canyon	14.06	Unnamed riffle	-	0.3	Desert View
70.0	L	-	4.74	-	-	-	Desert View
70.3	R	-	0.88	-	-	-	Desert View
70.7	L	-	0.65	-	-	-	Desert View
70.9	L	Cardenas Creek	3.87	Unnamed riffle	-	0.3	Desert View
70.9	R	-	2.45	-	-	-	Desert View
71.2	R	-	1.11	-	-	-	Desert View
72.1	R	-	1.16	-	-	-	Cape Royal
72.6	R	Unkar Creek	37.26	Unkar	6	6.5	Desert View
73.3	L	-	1.32	Unnamed riffle	-	0.3	Desert View
73.9	R	-	3.56	-	-	-	Cape Royal
74.5	R	-	0.39	-	-	-	Cape Royal
75.0	L	Escalante Creek	4.76	Unnamed riffle	-	0.3	Cape Royal
75.0	R	-	1.11	Unnamed riffle	-	0.3	Cape Royal
75.5	L	75-Mile Creek	11.47	Nevills	6	4.8	Cape Royal
75.5	R	-	0.44	Nevills	6	4.8	Cape Royal
76.0	L	Papago Creek	6.57	Unnamed riffle	-	0.3	Cape Royal
76.7	L	Red Canyon	10.52	Hance	9	8.3	Cape Royal
76.9	R	-	2.89	Hance	9	8.3	Cape Royal
REACH 4: MIDDLE NARROW II							
78.0	L	Mineral Canyon	3.58	Unnamed riffle	-	1.2	Cape Royal
78.3	R	Asbestos Canyon	8.71	Unnamed riffle	-	0.3	Cape Royal
78.7	L	Hance Creek	23.54	Sockdolager	9	5.9	Cape Royal
79.0	R	-	1.32	Unnamed riffle	-	0.3	Cape Royal
79.4	L	-	0.51	-	-	-	Cape Royal
79.6	R	-	3.07	Unnamed riffle	-	1.2	Cape Royal
79.7	L	-	2.21	-	-	-	Cape Royal

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
80.2	R	-	0.26	-	-	-	Cape Royal
80.6	L	Cottonwood Creek	10.14	-	-	-	Cape Royal
81.2	R	Vishnu Creek	13.56	-	-	-	Cape Royal
81.5	L	Grapevine Creek	30.82	Grapevine	8	5.1	Phantom Ranch
81.6	R	-	7.01	Grapevine	8	5.1	Phantom Ranch
82.2	R	-	1.17	-	-	-	Phantom Ranch
82.3	L	-	1.09	-	-	-	Phantom Ranch
82.8	L	Boulder Creek	5.38	-	-	-	Phantom Ranch
83.1	L	-	1.03	-	-	-	Phantom Ranch
83.6	R	-	4.67	83-Mile	4	2.2	Phantom Ranch
83.9	L	Lonetree Canyon	2.61	-	-	-	Phantom Ranch
84.1	R	Clear Creek	93.14	Unnamed riffle	-	0.3	Phantom Ranch
84.5	L	-	0.62	-	-	-	Phantom Ranch
84.6	R	Zoroaster Canyon	4.10	Zoroaster	6	2.3	Phantom Ranch
85.0	L	-	0.36	85-Mile	3	1.8	Phantom Ranch
85.0	R	-	0.94	85-Mile	3	1.8	Phantom Ranch
85.6	L	Cremation Creek	12.07	Unnamed riffle	-	0.6	Phantom Ranch
85.7	R	-	2.17	-	-	-	Phantom Ranch
86.7	R	-	3.79	-	-	-	Phantom Ranch
86.9	L	-	0.12	-	-	-	Phantom Ranch
87.2	L	-	1.05	-	-	-	Phantom Ranch
87.8	R	Bright Angel Creek	260.33	Bright Angel	4	5.9	Phantom Ranch
87.9	L	-	1.89	-	-	5.9	Phantom Ranch
88.9	L	Pipe Creek	17.31	Pipe Springs	4	4.3	Phantom Ranch
88.9	R	-	2.27	Pipe Springs	4	4.3	Phantom Ranch
89.3	R	-	0.93	Unnamed riffle	-	0.3	Phantom Ranch
90.2	L	Horn Creek	4.28	Horn Creek	8	2.8	Grand Canyon
91.1	R	91-Mile Creek	5.69	-	-	-	Grand Canyon
91.5	R	Trinity Creek	20.05	-	-	0.6	Grand Canyon
92.0	R	-	1.22	Unnamed riffle	-	0.3	Grand Canyon
92.7	L	Salt Creek	3.22	Salt Creek	4	0.9	Grand Canyon
93.3	L	-	0.87	-	-	-	Grand Canyon
93.5	L	Monument Creek	9.73	Granite	9	5.2	Grand Canyon
93.5	R	-	2.27	Granite	9	5.2	Grand Canyon
94.3	L	-	0.51	-	-	-	Grand Canyon
94.3	R	94-Mile Creek	9.42	Unnamed riffle	-	0.3	Grand Canyon
95.0	L	Hermit Creek	31.98	Hermit	9	4.5	Grand Canyon
95.6	L	Travertine Canyon	3.84	-	-	-	Grand Canyon
96.0	R	-	2.88	-	-	-	Grand Canyon
96.7	L	Boucher Creek	16.79	Boucher	4	3.7	Grand Canyon
97.4	R	-	3.44	-	-	-	Shiva Temple
98.2	L	Slate Creek	12.12	Crystal	10	5.2	Shiva Temple

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
98.2	R	Crystal Creek	111.64	Crystal	10	5.2	Shiva Temple
99.3	R	Tuna Creek	59.62	Tuna Creek	6	4.3	Havasupai Point
99.6	L	-	0.83	Willies Necktie	4	1.2	Havasupai Point
99.7	R	-	4.96	Willies Necktie	4	1.2	Havasupai Point
100.6	L	Agate Canyon	4.36	Agate	3	0.6	Havasupai Point
101.3	L	Sapphire Canyon	7.78	Sapphire	7	2.3	Havasupai Point
101.3	R	-	2.02	Sapphire	7	2.3	Havasupai Point
102.0	L	Turquoise Canyon	14.64	Turquoise	4	0.6	Havasupai Point
102.0	R	-	0.29	Turquoise	4	0.6	Havasupai Point
102.6	L	-	3.62	Unnamed riffle	-	1.5	Havasupai Point
103.0	R	-	2.15	-	-	-	Havasupai Point
103.1	L	-	1.24	-	-	-	Havasupai Point
103.9	L	-	0.21	104-Mile	6	0.9	Havasupai Point
103.9	R	Emerald Canyon	4.08	104-Mile	6	0.9	Havasupai Point
104.3	R	-	1.72	-	-	0.3	Havasupai Point
104.6	L	Ruby Canyon	7.47	Ruby	6	2.3	Havasupai Point
104.6	R	Monodnock Amphitheater	9.65	Ruby	6	2.3	Havasupai Point
104.9	L	-	2.12	Unnamed riffle	-	1.2	Havasupai Point
105.7	L	-	1.54	-	-	-	Havasupai Point
105.7	R	-	0.93	-	-	-	Havasupai Point
106.0	L	Serpentine Canyon	3.96	Serpentine	7	3.2	Havasupai Point
106.3	R	-	2.07	Unnamed riffle	-	0.3	Havasupai Point
107.6	L	Bass Canyon	7.28	Bass	4	1.2	Havasupai Point
107.8	R	Hotauta Canyon	7.13	Bass	4	-	Havasupai Point
108.6	R	Shinumo Creek	221.98	Shinumo	4	2.5	Havasupai Point
109.6	R	-	0.67	110-Mile	-	3.5	Havasupai Point
109.8	L	-	1.05	110-Mile	1	1.2	Havasupai Point
110.2	L	Copper Canyon	6.06	-	-	1.4	Havasupai Point
110.2	R	-	0.76	-	-	-	Havasupai Point
110.4	L	-	0.25	-	-	-	Explorers Monument
110.8	R	Hakatai Canyon	9.48	Hakatai	4	1.5	Explorers Monument
111.2	R	-	0.68	-	-	-	Explorers Monument
111.3	L	-	0.52	-	-	-	Explorers Monument
112.2	L	-	1.78	Waltenburg	7	4.3	Explorers Monument
112.2	R	Waltenberg Canyon	14.27	Waltenburg	7	4.3	Explorers Monument
112.5	L	-	0.63	112.5-Mile	2	2.2	Explorers Monument
112.5	R	-	1.99	112.5-Mile	2	2.2	Explorers Monument
113.0	R	-	1.33	Rancid Tuna	6	-	Explorers Monument
113.3	R	-	0.67	-	-	-	Explorers Monument
113.6	L	-	1.12	-	-	-	Explorers Monument
113.9	R	-	0.53	-	-	-	Explorers Monument
114.4	R	-	0.37	-	-	-	Explorers Monument

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
114.5	L	Garnet Canyon	15.83	Unnamed riffle	-	0.3	Explorers Monument
115.1	L	-	4.93	Unnamed riffle	-	0.8	Explorers Monument
115.5	L	-	4.07	Unnamed riffle	-	0.3	Explorers Monument
115.8	R	-	0.67	-	-	-	Explorers Monument
116.1	L	-	1.00	-	-	-	Explorers Monument
116.5	L	Royal Arch Creek	30.86	Unnamed riffle	-	1.2	Explorers Monument
116.8	L	-	2.12	Unnamed riffle	-	0.3	Explorers Monument
117.7	L	-	1.88	Unnamed riffle	-	0.3	Explorers Monument
117.7	R	-	0.68	-	-	-	Explorers Monument
118.0	R	-	1.02	-	-	-	Explorers Monument
118.3	R	-	0.23	-	-	-	Explorers Monument
118.6	L	-	0.24	-	-	-	Explorers Monument
118.7	R	-	1.40	119-Mile	2	0.6	Explorers Monument
119.0	R	119-Mile Creek	2.77	-	-	-	Explorers Monument
119.2	L	-	0.62	-	-	-	Explorers Monument
119.2	R	-	1.86	-	-	-	Explorers Monument
119.7	R	-	0.51	-	-	-	Explorers Monument
120.1	R	Blacktail Canyon	24.15	Blacktail	3	2.2	Explorers Monument
120.6	L	-	1.73	-	-	-	Explorers Monument
120.8	L	-	0.40	-	-	-	Explorers Monument
121.7	L	-	7.96	122-Mile	5	1.2	Explorers Monument
122.2	R	122-Mile Creek	8.03	Unnamed riffle	-	0.3	Topocoba Hilltop
122.3	L	-	2.39	-	-	-	Topocoba Hilltop
122.5	L	-	0.44	-	-	-	Topocoba Hilltop
122.7	L	Forster Canyon	10.04	Forster	6	2.2	Topocoba Hilltop
123.1	L	-	0.19	-	-	-	Fossil Bay
123.3	L	-	0.42	-	-	-	Fossil Bay
123.5	L	-	2.29	Unnamed riffle	-	0.8	Fossil Bay
123.6	L	-	0.21	-	-	-	Fossil Bay
124.0	L	-	0.97	-	-	-	Fossil Bay
124.4	L	-	3.06	Unnamed riffle	-	0.9	Fossil Bay
125.0	L	Fossil Canyon	34.39	Fossil	6	4.6	Fossil Bay
125.5	R	-	0.30	-	-	-	Fossil Bay
125.6	L	-	0.29	-	-	-	Fossil Bay
125.8	R	-	4.44	-	-	0.6	Fossil Bay
126.3	L	-	0.53	Randys Rock	2	1.1	Fossil Bay
126.6	R	-	0.29	-	-	-	Fossil Bay
126.7	R	-	0.10	-	-	-	Powell Plateau
126.9	L	-	0.57	127-Mile	3	1.2	Powell Plateau
126.9	R	127-Mile Creek	6.09	127-Mile	3	1.2	Powell Plateau
127.2	R	-	0.65	-	-	-	Powell Plateau
127.3	L	-	0.76	Unnamed riffle	-	0.3	Powell Plateau

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
127.5	R	-	0.98	-	-	-	Powell Plateau
127.6	L	127.6-Mile Canyon	1.75	127.6-Mile	-	0.9	Powell Plateau
127.9	L	-	0.98	-	-	-	Powell Plateau
128.5	R	128-Mile Creek	7.93	128-Mile	5	2.2	Powell Plateau
129.0	L	Specter Chasm	8.25	Specter	6	1.8	Powell Plateau
130.0	R	130-Mile Creek	6.40	-	-	-	Powell Plateau
130.5	R	Bedrock Canyon	21.14	Bedrock	8	2.5	Powell Plateau
130.9	L	-	2.01	Unnamed riffle	-	0.3	Powell Plateau
131.1	R	-	1.69	-	-	-	Powell Plateau
131.7	R	Galloway Canyon	12.27	Dubendorff	8	4.6	Powell Plateau
131.9	R	Stone Creek	6.76	Dubendorff	8	4.6	Powell Plateau
132.3	L	-	0.83	-	-	0.6	Powell Plateau
132.5	L	-	0.16	-	-	-	Powell Plateau
133.0	L	-	2.52	Unnamed riffle	-	1.2	Powell Plateau
133.0	R	133-Mile Creek	6.63	Unnamed riffle	-	1.2	Powell Plateau
133.4	L	-	0.31	-	-	-	Powell Plateau
133.8	R	Tapeats Creek	216.34	Tapeats	6	1.8	Powell Plateau
134.2	L	-	1.18	-	-	2.2	Tapeats Amphitheater
134.2	R	Bonita Creek	5.73	134-Mile	3	0.3	Tapeats Amphitheater
134.3	L	-	4.64	Unnamed riffle	-	0.3	Tapeats Amphitheater
134.8	R	-	0.86	135-Mile	5	3.4	Tapeats Amphitheater
135.4	R	-	0.22	-	-	-	Tapeats Amphitheater
135.9	L	-	1.60	-	-	-	Fishtail Mesa
136.2	R	Deer Creek	43.63	Unnamed riffle	-	2.8	Fishtail Mesa
136.5	L	-	0.07	-	-	-	Fishtail Mesa
136.7	L	-	4.07	-	-	-	Fishtail Mesa
136.8	L	-	0.41	-	-	-	Fishtail Mesa
137.6	L	-	0.11	-	-	-	Fishtail Mesa
137.7	R	-	0.78	-	-	-	Fishtail Mesa
137.8	L	-	0.81	137.5-Mile	6	0.3	Fishtail Mesa
138.3	L	-	0.53	-	-	0.6	Fishtail Mesa
138.4	L	-	0.17	-	-	-	Fishtail Mesa
138.5	R	-	5.20	138.5-Mile	4	0.9	Fishtail Mesa
138.9	L	-	1.44	-	-	-	Fishtail Mesa
139.1	R	Fishtail Canyon	19.63	Fishtail	6	3.1	Fishtail Mesa
139.5	R	-	0.26	-	-	0.6	Fishtail Mesa
139.9	L	140-Mile Canyon	25.76	Unnamed riffle	-	1.4	Fishtail Mesa
139.9	R	-	0.65	Unnamed riffle	-	1.4	Fishtail Mesa
140.9	L	-	0.59	-	-	-	Fishtail Mesa
141.3	L	-	0.88	-	-	-	Fishtail Mesa
141.3	R	-	2.08	141-Mile	2	-	Fishtail Mesa
143.1	L	-	3.42	-	-	-	Kanab Point

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
143.5	R	Kanab Creek	-	Kanab Rapid	3	5.6	Kanab Point
144.2	R	-	1.06	-	-	0.6	Kanab Point
144.8	R	-	7.14	144.5-Mile	2	0.6	Kanab Point
145.0	L	-	0.19	-	-	0.9	Havasu Falls
145.6	L	Olo Canyon	32.95	Unnamed riffle	-	0.8	Havasu Falls
147.9	L	Matkatamiba Canyon	86.84	Matkatamiba	2	1.4	Havasu Falls
148.5	L	-	2.81	-	-	-	Havasu Falls
148.6	L	-	0.72	-	-	-	Havasu Falls
149.7	R	150-Mile Canyon	81.04	Upset	8	4.5	Havasu Falls
152.4	R	-	1.60	Unnamed riffle	-	0.9	Havasu Falls
153.1	L	-	0.70	-	-	-	Havasu Falls
153.3	L	Sinyella Canyon	12.28	Unnamed riffle	4	0.9	Havasu Falls
153.5	L	-	0.50	Sinyala	-	1.2	Havasu Falls
153.8	L	-	0.90	-	-	-	Havasu Falls
153.9	L	-	0.22	-	-	-	Havasu Falls
155.6	R	-	5.49	Unnamed riffle	-	0.6	SB Point
156.8	L	Havasu Canyon	-	Havasu	3	1.2	SB Point
157.6	R	-	11.11	Unnamed riffle	-	0.5	SB Point
158.2	R	-	2.40	-	-	0.6	SB Point
159.2	L	-	5.12	Unnamed riffle	-	1.5	SB Point
159.5	L	-	3.13	Unnamed riffle	-	0.3	SB Point
159.6	L	-	1.28	-	-	-	SB Point
160.8	R	-	3.37	Unnamed riffle	-	0.9	SB Point
161.6	L	-	15.18	Unnamed riffle	-	0.6	SB Point
163.3	R	-	1.29	-	-	-	SB Point
163.8	L	-	28.91	Unnamed riffle	-	0.3	SB Point
164.5	R	Tuckup Canyon	175.68	164-Mile	3	1.4	SB Point
166.4	L	National Canyon	407.12	National	2	1.5	Fern Glen Canyon
167.0	L	-	2.16	-	-	-	Fern Glen Canyon
167.2	L	-	6.08	-	-	-	Fern Glen Canyon
168.0	R	Fern Glen Canyon	39.97	Fern Glen	3	1.7	Fern Glen Canyon
168.3	R	-	2.58	-	-	-	Fern Glen Canyon
169.8	L	-	3.86	-	-	-	Gateway Rapids
REACH 5: LOWER WIDE III							
170.2	L	-	7.49	-	-	-	Gateway Rapids
171.1	R	Stairway Canyon	7.97	Gateway	3	3.2	Gateway Rapids
171.5	L	Mohawk Canyon	214.40	Gateway	3	3.2	Gateway Rapids
172.1	L	-	0.53	-	-	-	Gateway Rapids
172.7	L	-	3.28	-	-	-	Gateway Rapids
173.0	L	-	1.80	-	-	-	Vulcans Throne

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
173.0	R	Big Cove	2.02	Unnamed riffle	-	1.1	Gateway Rapids
174.0	R	-	0.46	-	-	-	Vulcans Throne
174.4	R	Cove Canyon	26.62	Unnamed riffle	-	2.5	Vulcans Throne
175.4	R	-	1.82	-	-	-	Vulcans Throne
175.9	L	-	22.71	Unnamed riffle	-	0.8	Vulcans Throne
176.4	R	Saddle Horse Canyon	3.80	Unnamed riffle	-	1.2	Vulcans Throne
177.1	L	-	5.00	-	-	-	Vulcans Throne
177.7	L	-	6.68	-	-	1.2	Vulcans Throne
178.6	R	-	379.22	-	-	-	Vulcans Throne
179.1	R	-	1.83	-	-	-	Vulcans Throne
179.4	L	Prospect Canyon	257.22	Lava Falls	10	4.3	Vulcans Throne
179.4	R	-	24.74	Lava Falls	10	4.3	Vulcans Throne
179.8	R	-	1.23	-	-	-	Vulcans Throne
180.8	L	-	0.97	Unnamed riffle	-	1.2	Vulcans Throne
180.9	R	-	10.93	Unnamed riffle	-	0.3	Vulcans Throne
181.8	R	-	12.77	Unnamed riffle	-	1.2	Vulcans Throne
182.5	R	-	0.58	-	-	-	Vulcans Throne
182.6	L	Hells Hollow	23.12	-	-	-	Vulcans Throne
183.1	L	-	7.60	Unnamed riffle	-	1.5	Whitmore Rapids
183.7	L	-	1.60	-	-	-	Whitmore Rapids
184.0	R	-	0.70	-	-	-	Whitmore Rapids
184.5	L	-	0.28	-	-	-	Whitmore Rapids
184.6	L	-	0.56	-	-	-	Whitmore Rapids
184.6	R	-	1.97	-	-	-	Whitmore Rapids
185.3	R	-	3.35	185-Mile	3	1.2	Whitmore Rapids
186.1	L	-	7.32	-	-	-	Whitmore Rapids
186.2	L	-	1.42	-	-	-	Whitmore Rapids
187.0	L	-	2.09	187-Mile	4	0.3	Whitmore Rapids
187.0	R	-	3.15	187-Mile	4	0.3	Whitmore Rapids
187.4	R	-	7.93	-	-	-	Whitmore Rapids
187.6	R	-	0.96	-	-	-	Whitmore Rapids
188.1	R	Whitmore Wash	312.28	Whitmore	3	0.9	Whitmore Rapids
188.5	R	-	3.76	Unnamed riffle	-	-	Whitmore Rapids
189.5	L	-	1.46	-	-	-	Whitmore Rapids
189.7	L	-	10.51	Unnamed riffle	-	3.4	Vulcans Throne SW
190.3	L	-	24.22	-	-	-	Vulcans Throne SW
190.8	L	-	0.45	Unnamed riffle	-	1.4	Vulcans Throne SW
190.8	R	-	2.54	Unnamed riffle	-	1.4	Vulcans Throne SW
191.1	R	-	4.86	Unnamed riffle	-	0.3	Vulcans Throne SW
191.2	L	-	1.20	-	-	-	Vulcans Throne SW
191.8	L	192-Mile Canyon	16.25	-	-	0.6	Vulcans Throne SW
192.8	L	193-Mile Creek	57.89	Unnamed riffle	-	0.3	Vulcans Throne SW

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
193.1	R	Boulder Wash	1.84	Unnamed riffle	-	1.1	Vulcans Throne SW
193.7	L	-	0.60	-	-	-	Whitmore Point SE
194.0	R	-	0.97	-	-	-	Whitmore Point SE
194.1	L	-	2.95	-	-	-	Whitmore Point SE
194.5	L	194-Mile Canyon	8.64	Unnamed riffle	-	0.6	Whitmore Point SE
194.6	L	-	1.30	-	-	-	Whitmore Point SE
194.9	R	-	0.49	-	-	0.9	Whitmore Point SE
195.2	L	-	0.54	-	-	-	Whitmore Point SE
195.3	R	-	0.56	-	-	0.8	Whitmore Point SE
196.0	R	-	3.67	-	-	-	Whitmore Point SE
196.1	R	-	18.23	-	-	-	Whitmore Point SE
196.5	L	196-Mile Creek	11.74	Unnamed riffle	-	0.9	Whitmore Point SE
196.6	R	-	0.89	-	-	-	Whitmore Point SE
196.7	R	-	0.64	-	-	-	Whitmore Point SE
197.0	L	-	0.22	-	-	-	Whitmore Point SE
198.0	R	-	2.26	-	-	-	Whitmore Point SE
198.5	L	-	1.82	Unnamed riffle	-	0.8	Whitmore Point SE
198.5	R	Parashant Wash	934.12	Unnamed riffle	-	2.6	Whitmore Point SE
198.8	L	-	0.19	Unnamed riffle	-	2.2	Whitmore Point SE
198.8	R	-	2.09	Unnamed riffle	-	2.2	Whitmore Point SE
199.5	R	-	0.93	Unnamed riffle	-	0.3	Whitmore Point SE
200.0	R	-	0.30	-	-	-	Whitmore Point SE
200.3	R	-	0.98	Unnamed riffle	-	0.3	Whitmore Point SE
200.9	R	-	1.11	-	-	-	Whitmore Point SE
201.1	L	-	0.87	-	-	1.4	Whitmore Point SE
201.1	R	-	4.76	-	-	1.4	Whitmore Point SE
202.0	R	-	10.99	Unnamed riffle	-	0.9	Whitmore Point SE
202.1	L	-	0.55	-	-	-	Whitmore Point SE
202.4	R	-	0.94	-	-	-	Whitmore Point SE
202.5	R	-	1.41	-	-	1.1	Whitmore Point SE
203.0	L	-	0.94	-	-	-	Whitmore Point SE
203.0	R	-	0.54	-	-	-	Whitmore Point SE
204.0	R	-	4.26	-	-	-	Whitmore Point SE
204.2	L	-	0.75	-	-	-	Whitmore Point SE
204.3	L	-	0.49	-	-	-	Whitmore Point SE
204.3	R	Spring Canyon	50.38	Unnamed riffle	-	1.5	Whitmore Point SE
205.5	L	205-Mile Creek	27.54	205-Mile	7	2.8	Whitmore Point SE
206.0	R	-	2.04	Unnamed riffle	-	2.2	Granite Park
206.5	R	Indian Canyon	9.84	Unnamed riffle	-	0.3	Granite Park
207.4	L	-	0.40	Unnamed riffle	-	0.9	Granite Park
207.6	L	-	1.40	-	-	-	Granite Park
207.8	L	-	3.09	-	-	-	Granite Park

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
208.6	L	-	8.35	Unnamed riffle	-	0.3	Granite Park
208.6	R	209-Mile Canyon	95.46	209-Mile	7	3.7	Granite Park
208.8	L	Granite Park Canyon	126.22	209-Mile	7	3.7	Granite Park
209.8	R	-	1.71	Unnamed riffle	-	0.3	Granite Park
210.8	R	-	0.99	-	-	-	Granite Park
211.2	L	-	1.71	-	-	-	Granite Park
211.5	L	-	0.47	-	-	-	Granite Park
211.5	R	Fall Canyon	11.48	Unnamed riffle	-	1.2	Granite Park
212.2	L	-	0.48	Little Bastard	3	1.2	Granite Park
212.2	R	-	0.08	Little Bastard	3	1.2	Granite Park
212.7	R	-	3.45	-	-	-	Granite Park
REACH 6: LOWER NARROW III							
213.8	L	-	2.00	-	-	-	Granite Park
214.0	R	214-Mile Creek	8.22	-	-	-	Granite Park
214.2	R	-	2.74	Unnamed riffle	-	0.3	Granite Park
214.5	L	-	0.55	Unnamed riffle	-	0.3	Granite Park
215.0	L	215-Mile Creek	5.89	-	-	-	Granite Park
215.7	L	Three Springs Canyon	24.17	Three Springs	2	1.5	Granite Park
215.7	R	-	0.60	Three Springs	2	1.5	Granite Park
216.2	R	-	2.45	Unnamed riffle	-	0.3	Granite Park
216.5	R	-	0.72	-	-	-	Diamond Peak
216.8	L	-	9.76	Unnamed riffle	-	0.3	Diamond Peak
217.4	L	217-Mile Canyon	23.98	217-Mile	7	3.7	Diamond Peak
217.7	R	-	1.46	Unnamed riffle	-	0.8	Diamond Peak
218.0	L	-	0.81	-	-	-	Diamond Peak
218.6	L	-	0.96	-	-	-	Diamond Peak
219.4	R	Trail Canyon	50.08	Trail Canyon	3	0.8	Diamond Peak
219.9	L	-	0.59	-	-	-	Diamond Peak
220.0	R	220-Mile Canyon	26.94	Unnamed riffle	-	0.6	Diamond Peak
220.4	L	Granite Spring Canyon	37.14	Granite Spring	2	3.1	Diamond Peak
221.3	R	-	0.94	-	-	0.6	Diamond Peak
222	L	222-Mile Canyon	5.06	-	-	1.1	Diamond Peak
222.3	L	-	0.26	-	-	-	Diamond Peak
222.5	R	-	2.99	-	-	-	Diamond Peak
222.6	L	222.6-Mile Canyon	0.58	Unnamed riffle	-	1.2	Diamond Peak
223.1	L	-	1.04	Unnamed riffle	-	0.9	Diamond Peak
223.2	R	-	0.53	-	-	-	Diamond Peak
223.5	L	224-Mile Canyon	12.78	224-Mile	3	1.8	Diamond Peak
223.9	R	-	0.68	-	-	-	Diamond Peak
224.5	L	224.5-Mile Canyon	0.45	-	-	-	Diamond Peak

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
224.6	R	-	2.73	-	-	-	Diamond Peak
225.3	R	-	23.32	-	-	-	Diamond Peak
225.8	L	Diamond Creek	716.74	Diamond Creek	4	8.3	Diamond Peak
225.9	R	-	0.27	-	-	-	Travertine Rapids
226.1	R	-	0.77	-	-	-	Travertine Rapids
226.2	L	-	0.13	-	-	-	Travertine Rapids
226.6	L	-	0.28	Unnamed riffle	-	0.3	Travertine Rapids
226.7	L	-	0.31	-	-	-	Travertine Rapids
226.9	L	-	0.48	-	-	-	Travertine Rapids
227.0	L	-	1.24	-	-	-	Travertine Rapids
227.1	R	-	1.14	Unnamed riffle	-	0.3	Travertine Rapids
227.4	L	-	0.11	-	-	-	Travertine Rapids
228.1	L	228-Mile	6.78	Unnamed riffle	-	1.8	Travertine Rapids
228.1	R	-	1.89	Unnamed riffle	-	1.8	Travertine Rapids
228.4	L	-	0.36	-	-	-	Travertine Rapids
228.4	R	-	0.41	-	-	-	Travertine Rapids
228.7	L	-	1.45	-	-	-	Travertine Rapids
228.8	L	-	0.38	-	-	-	Travertine Rapids
229.0	L	Travertine Canyon	14.76	Travertine Rapid	3	2.5	Travertine Rapids
229.3	L	-	0.22	-	-	-	Travertine Rapids
229.3	R	-	7.47	-	-	-	Travertine Rapids
230.4	L	Travertine Falls	1.50	Unnamed riffle	-	0.5	Travertine Rapids
230.8	R	-	33.47	-	-	-	Travertine Rapids
231.0	L	-	1.70	231 Mile Rapid	5	3.5	Travertine Rapids
231.2	R	-	1.01	Unnamed riffle	-	0.3	Travertine Rapids
231.5	L	-	2.61	Unnamed riffle	-	1.1	Travertine Rapids
231.5	R	-	0.28	Unnamed riffle	-	1.1	Travertine Rapids
232.3	L	-	1.66	232 Mile Rapid	5	2.0	Travertine Rapids
232.3	R	-	1.64	-	-	-	Travertine Rapids
232.9	R	-	4.95	Unnamed riffle	-	0.3	Travertine Rapids
233.4	L	-	1.96	-	-	-	Travertine Rapids
233.4	R	-	0.36	-	-	-	Travertine Rapids
233.6	R	-	1.01	-	-	-	Travertine Rapids
233.7	L	-	15.19	234 Mile Rapid	4	2.6	Separation Canyon
234.1	R	-	0.53	-	-	-	Separation Canyon
234.2	L	-	0.76	Unnamed riffle	-	0.9	Separation Canyon
235	R	-	0.84	-	-	-	Separation Canyon
235.2	L	-	21.59	-	-	-	Separation Canyon
235.2	R	Bridge Canyon	0.29	Bridge Canyon Rapid	4	3.7	Separation Canyon
235.9	L	Gneiss Canyon	7.25	Gneiss Canyon Rapid	4	3.1	Separation Canyon
236	R	-	18.11	-	-	-	Separation Canyon
236.6	L	-	0.64	-	-	-	Separation Canyon

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
236.8	R	-	1.30	Unnamed riffle	-	0.3	Separation Canyon
237	L	-	3.52	-	-	-	Separation Canyon
237.2	R	-	1.13	237 Mile Rapid	4	2.8	Separation Canyon
237.5	R	-	0.24	-	-	-	Separation Canyon
237.6	L	-	0.41	-	-	-	Separation Canyon
237.7	L	-	0.42	-	-	-	Separation Canyon
237.7	R	-	0.62	-	-	-	Separation Canyon
238	L	-	0.60	-	-	-	Separation Canyon
238.1	R	-	0.29	-	-	-	Separation Canyon
238.2	L	-	0.40	-	-	-	Separation Canyon
238.6	L	-	4.87	-	-	-	Separation Canyon
239	R	-	0.79	-	-	-	Separation Canyon
239.3	R	-	9.85	-	-	-	Separation Canyon
239.5	L	Separation Canyon	10.11	Separation Rapid	-	5.2	Separation Canyon
239.5	R	Separation Canyon	123.85	Separation Rapid	-	5.2	Separation Canyon
239.8	L	-	0.34	-	-	-	Separation Canyon
240.4	L	-	1.01	240 Mile Rapid	-	2.5	Separation Canyon
240.4	R	-	0.87	240 Mile Rapid	-	2.5	Separation Canyon
240.6	L	-	0.30	-	-	-	Separation Canyon
240.6	R	-	0.19	-	-	-	Separation Canyon
241.2	R	-	1.11	-	-	-	Separation Canyon
241.4	L	-	1.67	241 Mile Rapid	-	2.8	Separation Canyon
241.6	L	-	0.57	-	-	-	Separation Canyon
242	R	-	2.53	-	-	-	Separation Canyon
242.2	R	-	3.66	-	-	-	Separation Canyon
242.3	R	-	22.68	-	-	-	Separation Canyon
242.7	R	-	0.87	-	-	2.9	Separation Canyon
243	R	-	1.42	-	-	-	Separation Canyon
243.1	L	-	5.06	-	-	-	Separation Canyon
243.8	R	-	1.71	-	-	-	Separation Canyon
244.4	L	-	0.65	-	-	-	Separation Canyon
244.8	L	-	2.4	-	-	-	Spencer Canyon
245.1	L	-	1.91	-	-	-	Spencer Canyon
245.3	L	-	2.18	-	-	-	Spencer Canyon
245.6	R	-	0.30	-	-	-	Spencer Canyon
246	L	Spencer Canyon	689.40	Lava Cliff Rapid	-	4.5	Spencer Canyon
246	R	-	0.25	Lava Cliff Rapid	-	4.5	Spencer Canyon
246.3	R	-	0.42	-	-	-	Spencer Canyon
246.5	R	-	0.34	-	-	-	Spencer Canyon
246.7	L	-	0.37	-	-	-	Spencer Canyon
246.9	L	-	0.86	-	-	-	Spencer Canyon
246.9	R	-	0.37	-	-	-	Spencer Canyon

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
247.4	L	-	32.71	-	-	-	Spencer Canyon
247.4	R	-	0.52	-	-	-	Spencer Canyon
247.7	R	-	1.10	-	-	-	Spencer Canyon
248.2	L	-	0.32	-	-	-	Spencer Canyon
248.4	L	-	0.38	-	-	-	Spencer Canyon
248.4	R	Surprise Canyon	423.19	Surprise Rapid	-	2.6	Spencer Canyon
248.9	R	-	0.21	-	-	-	Spencer Canyon
249.0	L	Clay Tank Canyon	116.37	Lost Creek Rapid	-	1.2	Spencer Canyon
249.1	R	-	0.80	-	-	-	Spencer Canyon
249.4	R	-	0.10	-	-	-	Spencer Canyon
249.6	L	-	0.14	-	-	-	Spencer Canyon
249.7	L	-	0.15	-	-	-	Spencer Canyon
249.7	R	-	12.92	-	-	-	Spencer Canyon
249.8	L	-	0.53	-	-	-	Spencer Canyon
250.1	R	-	0.11	-	-	-	Spencer Canyon
250.3	R	-	0.17	-	-	-	Devils Slide Rapids
250.5	R	-	0.38	-	-	-	Devils Slide Rapids
250.6	L	-	1.87	-	-	-	Devils Slide Rapids
250.8	R	-	2.34	-	-	0.9	Devils Slide Rapids
251.0	L	-	0.18	-	-	-	Devils Slide Rapids
251.3	L	-	0.22	-	-	-	Devils Slide Rapids
251.4	L	-	0.81	-	-	-	Devils Slide Rapids
251.5	R	-	0.26	-	-	-	Devils Slide Rapids
251.8	L	-	6.31	-	-	-	Devils Slide Rapids
251.9	L	-	0.53	-	-	-	Devils Slide Rapids
252.1	L	-	0.13	-	-	-	Devils Slide Rapids
252.2	L	-	0.21	-	-	-	Devils Slide Rapids
252.3	L	Reference Point Creek	114.94	Reference Point Rapid	-	0.9	Devils Slide Rapids
252.6	R	-	0.23	-	-	-	Devils Slide Rapids
252.7	R	-	0.46	-	-	0.6	Devils Slide Rapids
252.9	R	-	1.15	Last Chance Rapid	-	1.4	Devils Slide Rapids
253.1	L	-	0.34	-	-	-	Devils Slide Rapids
253.3	L	-	0.57	-	-	-	Devils Slide Rapids
253.6	R	-	2.59	-	-	-	Devils Slide Rapids
253.7	L	-	2.93	-	-	-	Devils Slide Rapids
253.9	R	-	0.15	-	-	-	Devils Slide Rapids
254.1	L	-	0.58	-	-	-	Devils Slide Rapids
254.2	R	-	0.46	-	-	-	Devils Slide Rapids
254.3	L	-	1.87	-	-	-	Devils Slide Rapids
254.6	R	-	1.84	-	-	0.9	Devils Slide Rapids
254.9	R	-	1.07	-	-	0.6	Devils Slide Rapids
255.2	L	-	0.45	-	-	-	Devils Slide Rapids

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
255.2	R	-	0.21	-	-	-	Devils Slide Rapids
255.4	R	Salt Creek	35.08	Devils Slide Rapid	-	1.4	Devils Slide Rapids
256.0	L	-	0.27	-	-	-	Devils Slide Rapids
256.2	R	-	0.27	-	-	-	Devils Slide Rapids
256.3	R	-	0.18	-	-	-	Devils Slide Rapids
256.5	R	-	1.01	-	-	-	Devils Slide Rapids
256.6	R	-	0.12	-	-	-	Devils Slide Rapids
256.8	L	Jackson Canyon	23.69	Triumphal Arch Rapid	-	0.9	Devils Slide Rapids
257.1	L	-	0.40	-	-	0.6	Devils Slide Rapids
257.2	L	-	0.26	-	-	-	Devils Slide Rapids
257.4	L	-	6.60	-	-	-	Devils Slide Rapids
257.6	L	-	0.86	-	-	0.8	Devils Slide Rapids
257.8	R	-	0.35	-	-	-	Devils Slide Rapids
258.2	R	-	0.79	-	-	-	Devils Slide Rapids
258.6	R	-	2.11	-	-	-	Devils Slide Rapids
258.8	L	-	0.65	-	-	-	Devils Slide Rapids
259.2	R	-	0.26	-	-	-	Devils Slide Rapids
259.5	R	Burnt Spring Canyon	109.82	Water Fall Rapid	-	4.3	Devils Slide Rapids
260.0	L	Quartermaster Canyon	85.17	-	-	-	Quartermaster Canyon
260.4	L	-	2.70	-	-	-	Quartermaster Canyon
260.5	L	-	0.29	-	-	-	Quartermaster Canyon
260.5	R	-	0.26	-	-	-	Quartermaster Canyon
260.8	L	-	1.73	-	-	-	Quartermaster Canyon
260.9	R	-	1.15	-	-	1.4	Quartermaster Canyon
261.0	L	-	0.46	-	-	-	Quartermaster Canyon
261.2	R	-	1.09	-	-	-	Quartermaster Canyon
261.4	L	-	0.56	-	-	-	Quartermaster Canyon
261.6	L	-	0.46	-	-	-	Quartermaster Canyon
261.8	L	-	0.26	Wards Cave Rapid	-	1.5	Quartermaster Canyon
262.1	R	-	1.95	-	-	-	Quartermaster Canyon
262.3	L	-	6.26	-	-	-	Quartermaster Canyon
262.3	R	-	0.35	-	-	-	Quartermaster Canyon
262.4	L	-	1.93	-	-	0.6	Bat Cave
262.6	R	-	0.15	-	-	-	Bat Cave
262.8	L	-	0.45	-	-	-	Bat Cave
262.8	R	-	0.21	-	-	-	Bat Cave
263.1	R	-	0.51	-	-	-	Bat Cave
263.3	L	-	0.78	-	-	-	Bat Cave
263.4	L	-	0.36	-	-	-	Bat Cave
263.7	L	-	0.18	-	-	-	Bat Cave
263.7	R	Tincanebitts Canyon	77.75	-	-	0.9	Bat Cave

Appendix 1. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile and side		Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
264.3	R	-	3.19	-	-	-	Bat Cave
264.6	R	Dry Canyon	50.67	Helldiver Rapid	-	6.0	Bat Cave
265.1	L	-	3.67	-	-	-	Bat Cave
265.3	R	-	0.15	-	-	-	Bat Cave
265.7	R	-	0.39	-	-	-	Bat Cave
265.8	L	-	1.73	-	-	-	Bat Cave
266.2	R	-	0.86	-	-	-	Bat Cave
266.5	L	-	2.15	-	-	-	Bat Cave
266.6	R	-	13.84	Flour Sack Rapid	-	1.2	Bat Cave
266.9	L	-	0.44	-	-	-	Bat Cave
267.0	R	-	0.60	-	-	-	Bat Cave
267.3	L	-	4.41	-	-	-	Bat Cave
267.3	R	-	1.00	-	-	-	Bat Cave
267.4	R	-	5.96	-	-	-	Bat Cave
267.9	L	-	1.41	-	-	-	Bat Cave
268.1	R	Travertine Cleft	2.61	-	-	-	Bat Cave
268.3	L	-	1.85	-	-	-	Bat Cave
268.3	R	-	0.2	-	-	-	Bat Cave
268.4	R	-	0.22	-	-	-	Bat Cave
268.6	R	-	0.35	-	-	-	Bat Cave
268.7	L	-	0.24	-	-	-	Bat Cave
269.0	L	Travertine Spring	48.98	-	-	0.9	Bat Cave
269.2	R		10.38	-	-	0.6	Bat Cave
269.6	R	-	0.21	-	-	-	Bat Cave
269.7	L	-	0.30	-	-	-	Bat Cave
270.0	R	-	0.18	-	-	0.9	Bat Cave
270.3	L	-	1.43	-	-	-	Columbine Falls
270.7	L	-	4.84	-	-	-	Columbine Falls
271.0	R	-	2.26	-	-	1.2	Columbine Falls
271.3	L	-	1.15	-	-	-	Columbine Falls
271.4	R	-	0.49	-	-	-	Columbine Falls
271.9	L	-	4.45	-	-	0.3	Columbine Falls
272.4	R	-	6.33	-	-	0.3	Columbine Falls
273.1	R	-	0.87	-	-	-	Columbine Falls
273.4	L	-	1.63	-	-	-	Columbine Falls
273.4	R	-	2.27	-	-	-	Columbine Falls
274.3	R	-	0.60	-	-	-	Columbine Falls
274.5	L	Cave Canyon	122.23	-	-	-	Columbine Falls
274.6	L	-	3.65	-	-	-	Columbine Falls
274.9	L	-	0.86	-	-	0.3	Columbine Falls
275.3	R	-	1.15	-	-	-	Columbine Falls
275.9	R	-	1.97	-	-	-	Columbine Falls

APPENDIX II

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994)

[These changes are our observations, reported by river-runners, in historical accounts (*e.g.*, Cooley and others, 1977), from repeat photography (*e.g.*, Webb, 1996), or from aerial photographs taken between 1935 and 1998. No data from stratigraphic analyses are included. More thorough documentation of historical rockfalls appears in Ford and others (1974), Hereford and Huntoon (1990), and Webb (1996). Types of evidence include: (1) direct observation by the authors or other river runners; (2) analysis of historical photographs and (or) repeat photography; (3) aerial photography; and(or) (4) gaging record. Confidence is indicated as: (1), a change or event has occurred; (2), though a change or event has occurred, the evidence is not strong; or (3), low confidence in the reported change or its cause.]

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
5.7	R	Seven Mile Draw	Debris flow	1987	1	1
7.0	L	E-area	Rockfall	1970	1	1
7.9	R	Badger Canyon	Debris flow	1897-1909	2	1
7.9	R	Badger Canyon	Tributary-channel changes	1973-1984	3	1
7.9	R	Jackass Canyon	Debris flow	1994	1	1
11.2	R	Soap Creek	Debris flow	1935-1941	2,3	1
11.2	R	Soap Creek	Debris flow	1973-1984	3	1
11.2	R	Soap Creek	Tributary-channel changes	1973-1984	3	1
11.2	R	Soap Creek	Streamflow flood	1987	1	1
11.8	L	Salt Water Wash	Tributary-channel changes	1935-1965	3	2
11.8	L	Salt Water Wash	Tributary-channel changes	1973-1984	3	2
16.8	R	House Rock Wash	Debris flow	1966-1971	3	1
17.4	L	Redneck Rapid	Rockfall	1973-1974	1	1
18.0	L	18 Mile Wash	Debris flow	1987	1	1
19.1	L	Unnamed tributary	Debris flow	1987	1	1
19.9	L	Unnamed tributary	Debris flow	1987	1	1
24.0	L	Unnamed tributary	Debris flow	1989	1	1
23.3	L	Indian Dick Rapid	Debris flow	1890-1990	2	1
23.3	L	Indian Dick Rapid	Debris flow	1993	1	1
24.0	L	Unnamed tributary	Debris flow	1989	1	1
24.2	R	Unnamed tributary	Debris flow	1989	1	1
24.2	L	Unnamed tributary	Debris flow	1989	1	1
24.4	L	Sheep Spring Wash	Debris flow	1989	1	1
24.7	L	Unnamed tributary	Streamflow flood	1989	1	1
26.8	R	Unnamed chute	Rockfall	1975	1	1
30.2	L	Unnamed tributary	Hyperconcentrated flow	1989	1	1
30.2	L	Unnamed tributary	Hyperconcentrated flow	1990	1	1
30.2	R	Unnamed tributary	Debris flow	1989	1	1
30.5	R	Unnamed tributary	Debris flow	1989	1	1
31.6	R	South Canyon	Debris flow	1890-1940	2	2
31.6	R	South Canyon	Tributary-channel changes	1965-1973	3	2
34.7	L	Nautiloid Canyon	Debris flow	1980-1984	3	2
35.6	L	Unnamed tributary	Debris fan changes	1973-1984	3	1
37.4	L	Tatahatso Wash	Rockfall	1977	1	1
37.4	L	Tatahatso Wash	Tributary-channel changes	1973-1984	3	2
41.0	R	Buck Farm Canyon	Debris flow	1981-1983	1	1

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
41.3	R	Bert's Canyon	Tributary-channel changes	1973-1984	3	2
43.2	L	Tatahoysa Wash	Debris flow	1983	1	1
43.7	L	Unnamed tributary	Debris flow	1983	1	1
43.7	R	Cliff	Rockfall	1998	1	1
44.1	L	E-area	Debris fan changes	1983	1	1
44.6	L	Unnamed tributary	Debris fan changes	1983	1	1
44.8	L	Unnamed tributary	Debris fan changes	1983	1	1
52.2	R	Nankoweap Canyon	Channel change	1935-65	3	1
52.2	R	Nankoweap Canyon	Streamflow flood	1966	1	1
52.2	R	Nankoweap Canyon	Tributary-channel changes	1973-1984	3	1
62.2	R	Unnamed tributary	Debris flow	1990	1	1
62.5	R	Unnamed tributary	Debris flow	1990	1	1
62.6	R	Crash Canyon	Debris flow	1990	1	1
63.0	L	Unnamed tributary	Debris flow	1990	1	1
63.3	R	Unnamed tributary	Debris flow	1990	1	1
64.5	L	Unnamed tributary	Debris flow	1990	1	1
65.3	L	Unnamed tributary	Hyperconcentrated flow	1990	1	1
65.5	L	Palisades Creek	Debris flow	1965-1973	3	1
65.5	L	Palisades Creek	Tributary-channel changes	1973-1984	3	1
65.5	L	Palisades Creek	Debris flow	1987	1	1
65.5	L	Palisades Creek	Hyperconcentrated flow	1990	1	1
65.5	R	Lava Canyon	Debris flow	1966	1	1
65.5	R	Lava Canyon	Debris flow	1973-1984	3	1
66.3	R	Unnamed tributary	Debris fan changes	1965-1984	3	1
66.3	L	Unnamed tributary	Tributary-channel changes	1965-1973	3	1
66.8	L	Espejo Creek	Debris fan changes	1984	1	1
67.2	L	Comanche Creek	Debris flow	1890-1990	2	1
67.2	L	Comanche Creek	Debris fan changes	1973-1984	3	1
67.2	L	Comanche Creek	Debris flow	1999	2	1
67.8	L	Unnamed tributary	Debris fan changes	1973-1984	3	1
68.0	L	Unnamed tributary	Debris fan changes	1973-1984	3	1
68.5	L	Tanner Canyon	Debris flow	1993	1	1
69.6	R	Basalt Canyon	Streamflow flood	1983	1	1
69.6	R	Basalt Canyon	Debris flow	1999	1	1
70.0	R	E-area	Debris fan changes	1973-1984	3	1
70.2	R	E-area	Debris fan changes	1965-1984	3	1
70.3	R	Unnamed tributary	Debris fan changes	1965-1984	3	1
70.4	L	E-area	Debris fan changes	1973-1984	3	1
70.5	L	E-area	Debris fan changes	1973-1984	3	1
70.7	L	Unnamed tributary	Debris fan changes	1973-1984	3	1
70.9	L	Cardenas Creek	Debris flow	1984	1	1
70.9	L	Cardenas Creek	Debris flow	1993	1	1

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
70.9	R	Unnamed tributary	Debris fan changes	1973-1984	3	2
71.1	R	E-area	Debris fan changes	1965-1984	3	1
71.2	R	Unnamed tributary	Debris flow	1984	1	1
71.8	R	E-area	Debris fan changes	1973-1984	3	1
72.1	R	Unnamed tributary	Debris flow	1984	1	1
72.6	R	Unkar Creek	Streamflow flood	1966	1	1
72.6	R	Unkar Creek	Tributary-channel changes	1973-1984	3	1
72.6	R	Unkar Creek	Debris flow	1998	1	1
73.3	L	Unnamed tributary	Tributary-channel changes	1965-1984	3	2
73.5	L	E-area	Debris fan changes	1973-1984	3	1
73.7	R	E-area	Debris fan changes	1973-1984	3	1
73.9	R	Unnamed tributary	Debris fan changes	1973-1984	3	1
74.5	R	Unnamed tributary	Debris fan changes	1965-1984	3	2
75.0	L	Escalante Creek	Debris fan changes	1973-1984	3	1
75.5	L	75-Mile Creek	Debris flow	1987	1	1
75.5	L	75-Mile Creek	Debris flow	1990	1	1
76.0	L	Papago Creek	Streamflow flood	1987	1	1
76.7	L	Red Canyon	Tributary-channel changes	1973-1984	3	2
78.7	L	Hance Creek	Debris flow	1983	1	1
84.1	R	Clear Creek	Streamflow flood	1966	1	1
87.8	R	Bright Angel Creek	Debris flow	1936	2,4	2
87.8	R	Bright Angel Creek	Debris flow	1966	1,2,4	1
87.8	R	Bright Angel Creek	Tributary-channel changes	1973-1984	3	1
87.8	R	Bright Angel Creek	Debris flow	1995	1	1
87.8	R	Bright Angel Creek	Streamflow flood	1999	1	1
88.9	L	Pipe Creek	Tributary-channel changes	1973-1984	3	2
91.5	R	Trinity Creek	Streamflow flood or debris flow	1985	1	1
92.2	L	E-area	Tributary-channel changes	1973-1984	3	2
92.7	L	Salt Creek	Tributary-channel changes	1973-1984	3	2
93.5	L	Monument Creek	Debris flow	1966-1967	2	1
93.5	L	Monument Creek	Debris flow	1984	1	1
93.5	L	Monument Creek	Debris flow	1996	1	1
95.0	L	Hermit Creek	Streamflow flood	1992	1	1
95.0	L	Hermit Creek	Debris flow	1996	1	1
96.7	L	Boucher Creek	Debris flow	1951-1952	2	1
96.7	L	Boucher Creek	Debris flow	1984	2,3	1
96.9	L	E-area	Tributary-channel changes	1973-1984	3	3
98.2	R	Crystal Creek	Debris flow	1966	1	1
98.2	R	Crystal Creek	Debris flow	1973-1986	3	2
99.3	R	Tuna Creek	Streamflow flood	1966	1	1
100.6	L	Agate Canyon	Tributary-channel changes	1973-1984	3	1
102.0	L	Turquoise Canyon	Tributary-channel changes	1973-1984	3	2

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
107.6	L	Bass Canyon	Streamflow flood	1989	1	1
108.6	R	Shinumo Creek	Tributary-channel changes	1973-1984	3	2
108.6	R	Shinumo Creek	Streamflow flood	1989	1	1
112.2	R	Waltenberg Canyon	Debris flow	1890-1923	2	1
112.2	R	Waltenberg Canyon	Debris flow	1938-1942	2	2
112.2	R	Waltenberg Canyon	Debris flow	1973-1984	3	1
115.5	R	Unnamed tributary	Tributary-channel changes	1985	1	1
116.5	L	Royal Arch Creek	Debris flow	1985	1	1
119.0	R	119 Mile Creek	Tributary-channel changes	1973-1984	3	1
121.7	L	Unnamed tributary	Tributary-channel changes	1973-1984	3	1
122.3	L	Unnamed tributary	Tributary-channel changes	1973-1984	3	1
122.7	L	Forster Canyon	Tributary-channel changes	1973-1984	3	1
122.7	L	Forster Canyon	Debris flow	1991	1	1
123.6	L	Unnamed tributary	New debris fan	1989	1	1
125.0	L	Fossil Canyon	Debris flow and streamflow flood	1989	1	1
126.9	L	Unnamed tributary	Debris flow	1989	1	1
127.2	R	Unnamed tributary	Hyperconcentrated flow	1989	1	1
127.3	L	Unnamed tributary	Debris flow	1989	1	1
127.5	R	Unnamed tributary	Hyperconcentrated flow	1989	1	1
127.6	L	127.6 Mile Canyon	Debris flow	1989	1	1
127.6	L	127.6 Mile Canyon	Hyperconcentrated flow	1990	1	1
127.6	L	127.6 Mile Canyon	Streamflow flood	1993	1	1
127.6	L	127.6 Mile Canyon	Streamflow flood	1996	1	1
127.9	R	Unnamed tributary	Debris flow	1989	1	1
128.5	R	128-Mile Creek	Tributary-channel changes	1973-1984	3	1
129.0	L	Specter Chasm	Tributary-channel changes	1973-1984	3	1
129.0	L	Specter Chasm	Debris flow	1989	1	1
130.5	R	Bedrock Canyon	Debris flow	1989	1	1
131.9	R	Stone Creek	Tributary-channel changes	1973-1984	3	2
132.0	L	E-area	New debris fan	1872-1968	2	1
133.8	R	Tapeats Creek	Debris flow	1961	1	1
133.8	R	Tapeats Creek	Streamflow flood	1975	1	1
133.8	R	Tapeats Creek	Streamflow flood	1984	1	1
136.2	R	Deer Creek	Debris flow	1985	1	1
136.2	R	Deer Creek	Streamflow flood	1988	1	1
137.2	R	E-area	Debris flow	1973-1984	3	1
143.5	R	Kanab Creek	Large streamflow flood	1883	1	1
143.5	R	Kanab Creek	Large streamflow flood	1909	1	1
143.5	R	Kanab Creek	Debris flow	1923-1942	1	1
143.5	R	Kanab Creek	Tributary-channel changes	1973-1984	3	1
143.5	R	Kanab Creek	Streamflow flood	1988	1	1
143.5	R	Kanab Creek	Streamflow flood	1991	1	1

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
147.9	L	Matkatamiba Canyon	Streamflow flood	1989	1	1
156.8	L	Havasu Creek	Large streamflow flood	1911	1	1
156.8	L	Havasu Creek	Large streamflow flood	1918	1	1
156.8	R	Havasu Creek	Large streamflow flood	1920	1	1
156.8	L	Havasu Creek	Large streamflow flood	1990	1	1
156.8	L	Havasu Creek	Large streamflow flood	1993	1	1
157.6	R	Unnamed tributary	Debris flow	1993	1	1
160.8	R	Unnamed tributary	Debris flow	1993	1	1
166.4	L	National Canyon	Tributary-channel changes	1984	1	1
168.0	R	Fern Glen Canyon	Tributary-channel changes	1973-1984	3	2
174.4	R	Cove Canyon	Tributary-channel changes	1973-1984	3	1
176.4	R	Saddle Horse	Tributary-channel changes	1973-1984	3	1
178.1	L	E-area	Debris flow	1973-1984	3	1
179.4	L	Prospect Canyon	Debris flows	1939	2	1
179.4	L	Prospect Canyon	Debris flows	1954, 1955	2,3	1
179.4	L	Prospect Canyon	Hyperconcentrated flow	1956	3	1
179.4	L	Prospect Canyon	Debris flows	1963, 1966	2,3	1
179.4	L	Prospect Canyon	Streamflow floods	1993	1	1
179.4	L	Prospect Canyon	Debris flows	1995	1	1
179.4	L	Prospect Canyon	Streamflow flow	1996, 1998	1	1
181.3	R	E-area	Debris flow	1973	1	1
189.7	L	Unnamed canyon	Debris flow	1998	1	1
190.3	L	Unnamed canyon	Debris flow	1998	1	1
190.3	L	Unnamed canyon	Debris flow	1998	1	1
191.8	L	Unnamed canyon	Debris flow	1998	1	1
192.8	L	93-Mile Canyon	Debris flow	1890-1990	2	1
192.8	L	193-Mile Canyon	Debris flow	1998	1	1
194.5	L	194-Mile Canyon	Debris flow	1998	1	1
198.5	R	Parashant Wash	Streamflow flood	1993	1	1
202.1	L	Unnamed canyon	Debris flow	1998	1	1
202.4	R	Unnamed canyon	Debris flow	1973-1984	3	2
202.5	R	Unnamed canyon	Debris flow	1973-1984	3	1
204.0	R	Unnamed canyon	Debris flow	1973-1984	3	3
204.2	L	Unnamed canyon	Tributary-channel changes	1973-1984	3	2
204.3	R	Spring Canyon	Streamflow flood	1993	1	1
205.5	L	205-Mile Canyon	Debris flow	1937-1956	2	1
205.5	L	205-Mile Canyon	Tributary-channel changes	1983	1	1
205.5	L	205-Mile Canyon	Debris flow	1998	1	1
207.8	L	Unnamed canyon	Tributary-channel changes	1973-1984	3	3
207.8	L	Unnamed canyon	Debris flow	1991	1	1
208.6	L	Unnamed canyon	Debris flow	1991	1	1
208.8	L	Granite Park Canyon	Streamflow flood	1995	1	1

Appendix 2. Historical debris flows, rockfalls, and other changes in tributaries of the Colorado River in Grand Canyon (modified from Melis and others, 1994) - continued

River mile	Side	Tributary name	Type of change	Year or range	Evidence	Confi-dence
208.8	L	Granite Park Canyon	Debris flow	1999	1	1
209.0	R	E-area	Rockfall	1978-1979	1	1
211.5	R	Fall Canyon	Tributary-channel changes	1973-1984	3	1
220.0	R	220 Mile Canyon	Tributary-channel changes	1984	1	1
222.6	L	Unnamed canyon	Debris flow	1890-1952	2,3	1
224.5	L	Unnamed canyon	Debris flow	1890-1952	2,3	1
225.8	L	Diamond Creek	Debris flow	~1883	2	1
225.8	L	Diamond Creek	Debris flow	1984	1	1
225.8	L	Diamond Creek	Streamflow flooding	1986	1	1
231.0	R	Unnamed canyon	Debris flow	1890-1990	2	1

Webb, Griffiths, Melis, and Hartley—SEDIMENT DELIVERY BY UNGAGED TRIBUTARIES OF THE COLORADO RIVER IN GRAND CANYON, ARIZONA—U.S. Geological Survey Water-Resources Investigations Report 00–4055

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