Prepared in cooperation with the Grand Canyon Monitoring and Research Center

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

Introduction

Sediment supply and transport in Grand Canyon is an important management issue because of the presence and operation of Glen Canyon Dam on the Colorado River (U.S. Department of the Interior, 1995). Most of the fine-grained sediment that formerly entered the canyon from upstream is trapped in Lake Powell; this sediment once replenished beaches and provided substrate for the riverine ecosystem in Grand Canyon. With the closure of the dam in 1963, sources of fine-grained sediment have been limited to major tributaries, such as the Paria and Little Colorado Rivers and Kanab and Havasu Creeks, and numerous small tributaries. Small tributaries are also the source of coarse-grained sediment (cobbles and boulders), which forms debris fans and rapids, defines pools and eddies that trap and store fine sediment, and provides substrate for aquatic and terrestrial habitats throughout the river channel. Between Glen Canyon Dam and the Grand Wash Cliffs (fig. 1) 768 small tributaries were designated, most of which range from 1 through 5 km^2 in area. All of these tributaries produce streamflow, but only the 736 tributaries between Lee's Ferry and the Grand Wash Cliffs produce debris flows (fig. 2). With the exception of Bright Angel Creek and the major tributaries, these small tributaries between Glen Canyon Dam and the Grand Wash Cliffs were ungaged before 1999.

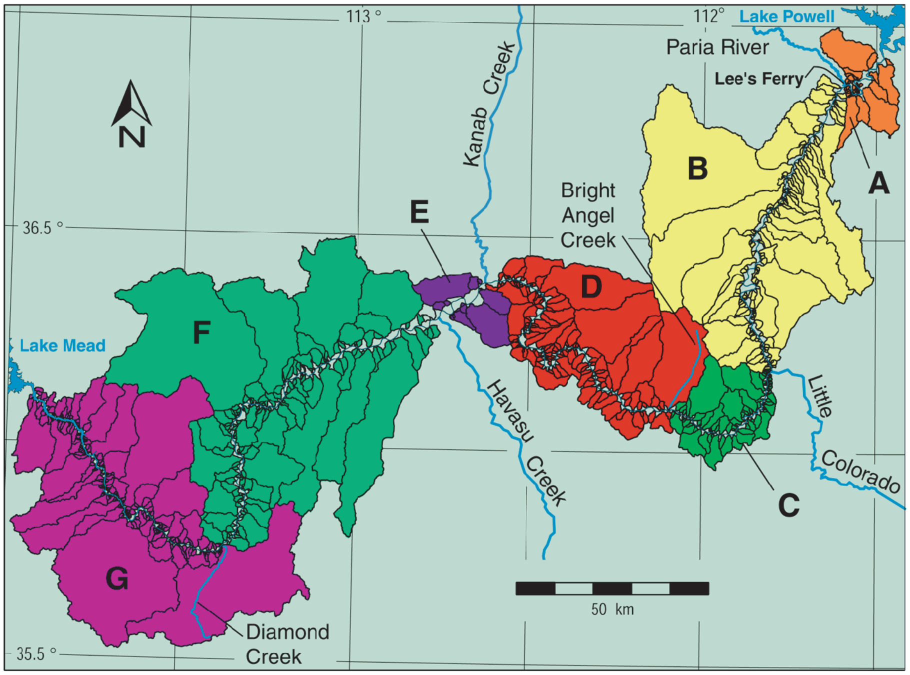

Figure 1. 768 ungaged tributaries of the Colorado River between Glen Canyon Dam and Lake Mead. Sediment-yield reaches are indicated by letter.

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 both streamflow, which occurs annually in all tributaries, and debris flow, which occurs rarely. Debris flows are slurries of clay- to boulder-sized sediment with sediment concentrations of 70 to 90 percent by volume. In contrast, streamflow typically has a sediment concentration by weight of less than 40 percent. A total of 12,072 km^2 in 736 tributaries produces debris flow, and 12,900 km^2 produce streamflow. The tributaries were organized into seven sediment-yield reaches that correspond to river segments between major tributaries with gaging records or other estimates of sediment input (fig. 1).

Development of a sediment budget for the Colorado River through Grand Canyon requires an estimate of the long-term sediment yields for both coarse and fine particles from all 768 tributaries but particularly from tributaries in Reaches A and B (fig. 1), where sand bar resources are most threatened. Because the size of particles transported by the river vary with discharge, data on the particle-size distribution of sediment delivered by both debris flow and streamflow are also needed. Increased knowledge of debris flow and mainstem processes in Grand Canyon will contribute to efforts to operate Glen Canyon Dam in ways that minimize downstream impacts. This Fact Sheet summarizes a report (Webb and others, 2000) that presents the total sediment yield and sand delivery rates for the ungaged tributaries.

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Streamflow Sediment Yield

Prior to this study, streamflow sediment yield from the ungaged tributaries was either unknown or assumed. Three methods were used to estimate streamflow sediment yield from the ungaged tributaries: (1) an empirical equation relating drainage area to sediment yield for all sites measured in 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. These methods are described in detail in Webb and others (2000) and proved to be reasonably consistent. Only the empirical sediment-yield equation is discussed here.

Other than at gaging stations on the Colorado River and its major tributaries, few sediment-transport data have been collected in Grand Canyon. To develop a regression equation of sediment yield versus drainage area and to determine which other sediment-yield estimation techniques might be appropriate, sediment-yield data from the region were assembled. Then a power function was fit to these data (fig. 3A) to obtain

$$Q_s = 193 \cdot A^{1.04}, R^2 = 0.86,$$

where Q_s = sediment yield (Mg/yr), A = drainage area (km^2), and n = 37. A variety of empirical approaches developed by other workers were evaluated and produced estimates of sediment yield ranging from 43-4,110 Mg km^{-2}yr^{-1}. Results compared most favorably with the method given by Renard (1972), who developed a similar empirical relation for southern Arizona rangelands (fig. 3B).

Using this equation, it is estimated that Reaches A and B (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 ($0.68 \cdot 10^6$ Mg/yr total), to the Colorado River. This amount is 20 percent of the total sediment yield of the Paria River, the major tributary contributing sediment to this part of Grand Canyon, and is much larger than previous estimates of sediment yield from these tributaries. A relation is given in Webb and others (2000) relating the possible variation of this sediment delivery with climatic variability.

Figure 2. The Comanche Creek drainage basin (mile 67.2 L), from river right, in 1994. The debris fan at Comanche Creek was aggraded by a debris flow in July 1999.

Debris-flow Sediment Yield

The model of debris-flow sediment yield in Grand Canyon in this study is composed of three elements: (1) a frequency model for all 736 tributaries in Grand Canyon that produce debris flows (from Griffiths and others, 1996), (2) a model of the expected volumes of debris flows reaching the Colorado River, and (3) an accounting for river reworking that stores sediment on debris fans because of operations of Glen Canyon Dam. This model and the assumptions used to produce it are given in Webb and others (2000).

A statistical relation for debris-flow frequency using probabilities estimated by logistic regression was developed in which the 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. Using data updated from Melis and others (1994), a regression equation relating debris-flow volumes to tributary drainage area was developed to calculate the amount of sand delivered by debris flow. By combining the frequency and volume components, a sediment-yield model for debris flow in Grand Canyon was developed. In the pre-dam era, floods in the Colorado River removed essentially all fine-grained sediment from debris fans; in the post-dam era, on average only 25 percent of the volume of debris fans are reworked each decade to introduce fine-grained sediment into the river (Webb and others, 1999).

The results of this model indicate that debris flows deliver 0.14-0.30$\cdot 10^6$ Mg/yr of sediment to the main channel. Reach B (Marble Canyon) contributes the greatest amount of debris-flow sediment, which is consistent with both the empirical observations on where debris flows have occurred in the last century as well as the mapped distribution of probabilities in Grand Canyon (Griffiths and others, 1996). Depending upon the assumptions of the debris-flow sediment-yield model, sediment yield by debris flow ranges from 4 to 23 percent of total sediment yield.

Particle-Size Distributions

The size of the sand fraction is of particular interest for the management and restoration of sand bars in Grand Canyon. Measurements of particle-size distributions stored in stream terraces in various tributaries, as well as suspended sediment samples from Bright Angel Creek and other small tributaries, provide sand contents ranging from 1 to 99 percent with no discernible pattern. These data were collected from a large discharge range and thus highly variable sand contents would be expected. An average sand content of 50 percent of total streamflow sediment yield was used in this study, which compares favorably with average sand content weighted by discharge for the Little Colorado and Paria Rivers (30 and 50 percent, respectively). Sand contents of 15, 50, and 75 percent are reported. Sand delivery by streamflow from the Glen and Marble Canyon reaches averages about 0.032$\cdot 10^6$ and 0.305$\cdot 10^6$ Mg/yr, respectively (0.34$\cdot 10^6$ total), with a combined total of the two reaches ranging from 0.10-0.51$\cdot 10^6$ Mg/yr, depending on the assumed sand content. Sand contributed by tributaries in Glen Canyon is notably coarser (D_{50}=0.24 mm) than sand in other reaches (D_{50}=0.11 - 0.20 mm), including the Marble Canyon reach (D_{50}=0.20 mm) (fig. 4).

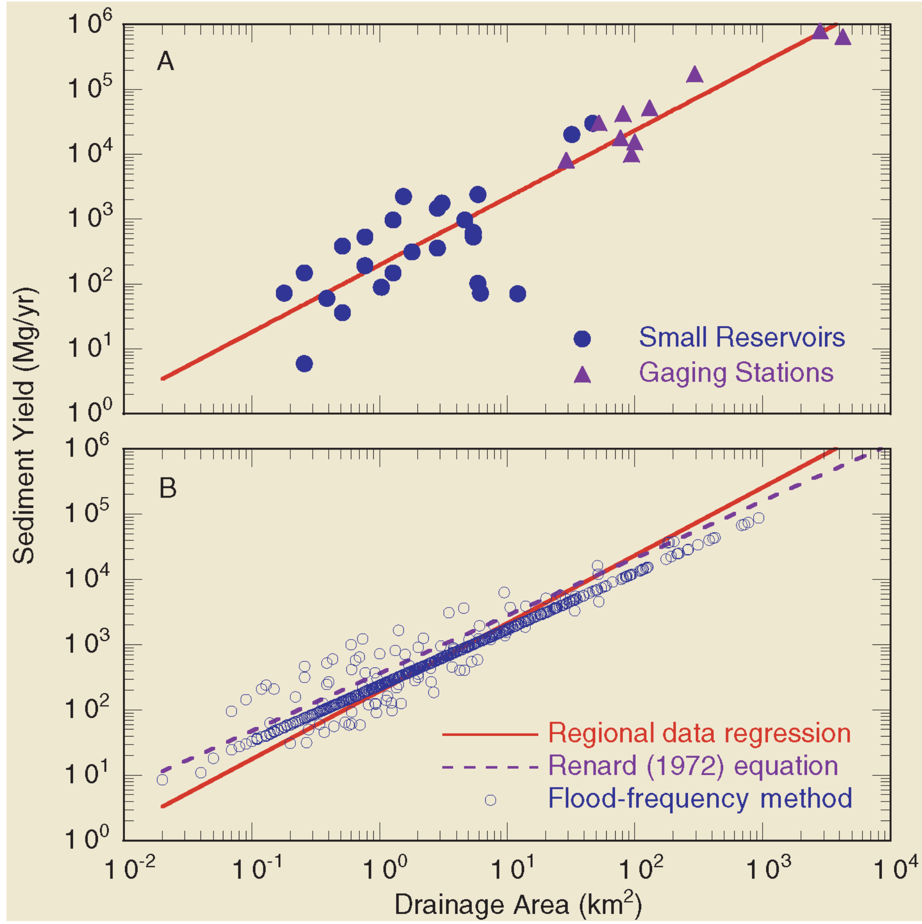

Figure 3. Comparison of methods for calculating streamflow sediment yield. *A*. Gaging station and reservoir data from the Colorado Plateau region (r^2 = 0.86). *B*. Comparison of regional data regression equation, Renard (1972) equation, and estimates for 768 ungaged tributaries by the flood-frequency rating-curve method.

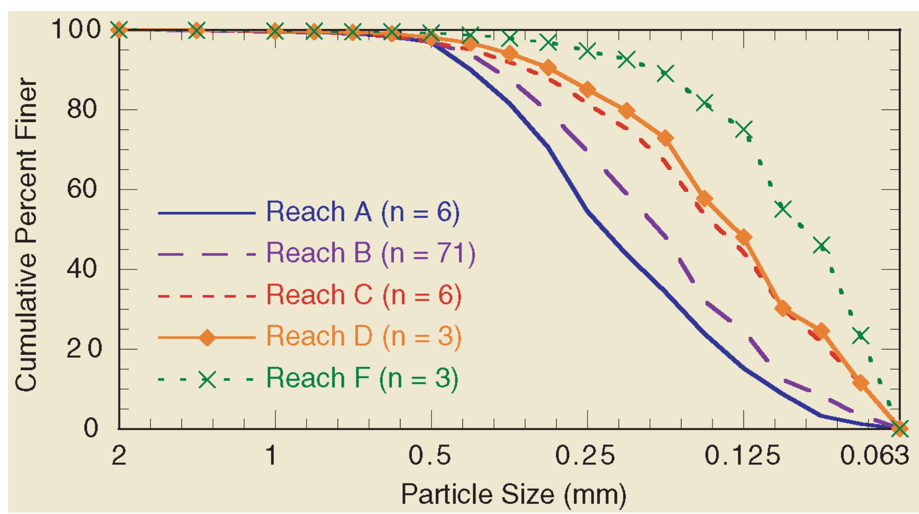

Figure 4. Particle-size distribution of sand delivered by streamflow from ungaged tributaries. Sand input by streamflow is increasingly finer downstream from the dam.

The particle-size distributions of 41 fresh, unaltered deposits of debris flows that occurred between 1965 and 1999 were determined. Pebbles are the most abundant particles at 41 percent by weight, and boulders typically account for about 14 percent. The sand content of debris flows averages about 18.2 percent and ranges from 2 to 47 percent. With debris-fan reworking limited by the operation of Glen Canyon Dam, debris flows transport 0.006-0.013$\cdot 10^6$ Mg/yr of sand to the regulated Colorado River, while 0.023-0.048$\cdot 10^6$ Mg/yr is stored in unreworked parts of debris fans. Depending on the volume model used and the amount of debris-fan reworking, the total sand yield of debris flows in all reaches ranges from 0.006-0.054$\cdot 10^6$ Mg/yr. Although debris flows deliver only $0.021\text{-}0.44 \cdot 10^6$ Mg/yr of boulders (B_{axis}>256 mm), these 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.

Total Sediment Yield to the Colorado River

Sediment-yield estimates for streamflow and debris flow were combined to estimate total annual sediment yield from the ungaged drainage areas (fig. 5A). The total sediment yield is highest in Reach F (fig. 1), which has the highest 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 flow in those reaches (Griffiths and others, 1996).

A range of possible sand yields was calculated given the range of streamflow sand content and assumptions in the debris-flow sediment-yield model and low, average, and maximum sand delivery from the ungaged tributaries are reported (5b). The sand delivery rate from fully reworked debris fans, which reflects pre-dam conditions, averages $1.3 \cdot 10^6$ Mg/yr for all ungaged tributaries in Grand Canyon. In Reaches A, B, and C (fig. 1), 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 $0.288 \cdot 10^6$ and $0.047 \cdot 10^6$ Mg/yr, respectively.

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. 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. Of this total sediment yield, $0.4\text{-}2.0 \cdot 10^6$ Mg/yr is sand, although a small amount of this sand is stored in unreworked debris fans.

Even with storage in debris fans, $0.1\text{-}0.5 \cdot 10^6$ 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 by the 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.

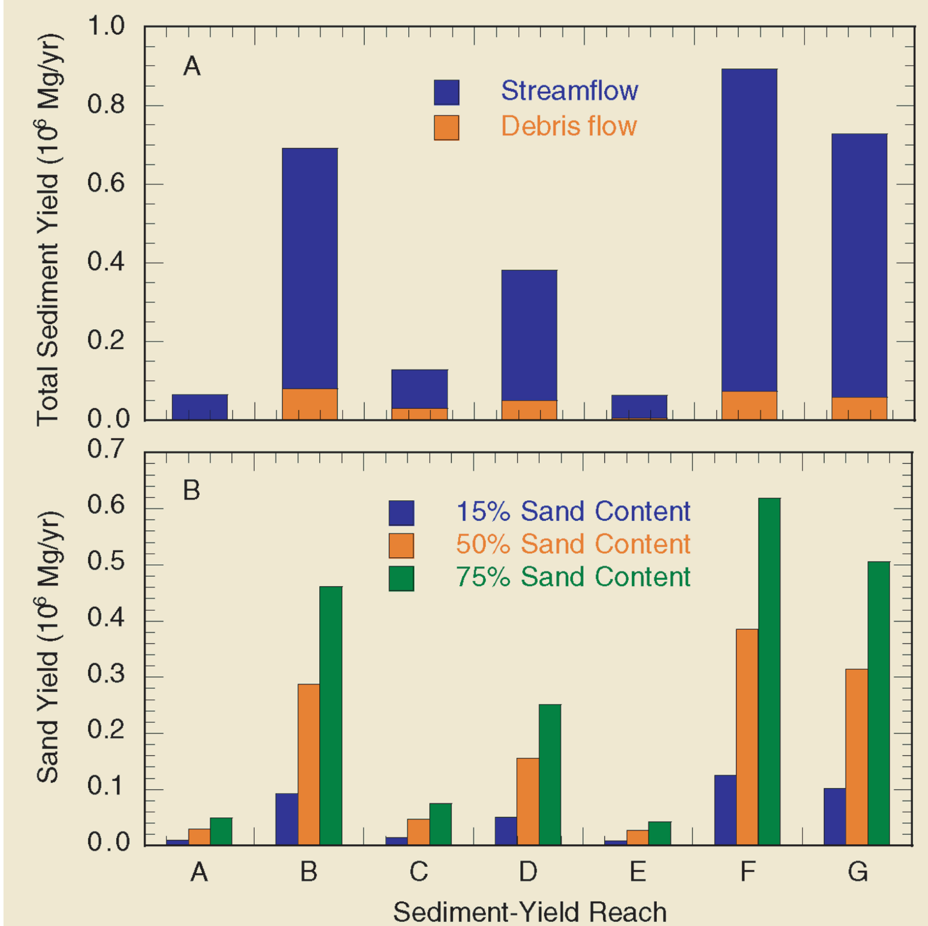

Figure 5. Estimates of annual sediment yield from ungaged tributaries by reach. *A.* Total sediment yield delivered by debris flow and streamflow. *B.* Total sand delivered by streamflow and debris flow to the river under a regulated flow regime. Estimates are given for 15%, 50%, and 75% sand content.

– Robert H. Webb and Peter G. Griffiths

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