TECHNIQUES FOR ESTIMATING SEDIMENT YIELD OF UNGAGED TRIBUTARIES ON THE SOUTHERN COLORADO PLATEAU

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Abstract: Numerous regional sediment transport data are used to evaluate three techniques for estimating streamflow sediment yield from ungaged tributaries of the Colorado River in Grand Canyon. These techniques include: (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) selected from 8 potentially relevant methods, and (3) a new procedure that combines regional flood-frequency analysis with sediment-rating curves. Results based on techniques (1) and (2) are not significantly different. The third technique requires numerous assumptions, most notably that sediment yield on a decadal average can be described by several floods of recurrence intervals of 2 yr, 5 yr, and 10 yr described by regional flood-frequency relations. Using data collected at gaging stations, we develop a relation between peak discharge and total-event sediment yield derived from hydrographs and sediment-rating curves. This third technique produces sediment yield estimates comparable to those of the regional data regression and Renard (1972) relations and may be a more robust technique for estimating sediment yield when streamflow data are available.

INTRODUCTION

Roughly 768 tributaries of the Colorado River drain the Grand Canyon in northern Arizona (fig. 1). Ranging in size from < 0.1 to 934 km^2, with a mean basin area of 16 km^2 (fig. 2), these ungaged tributaries have ephemeral flow, generating seasonal floods in summer and winter, and cut through bedrock that is predominantly sedimentary. Sediment data from these tributaries are virtually nonexistent, and data from the canyon in general are limited to those collected at gaging stations on the Colorado and its major tributaries (the Paria and Little Colorado Rivers, and Kanab and Havasu Creeks; fig. 1) (Garrett et al. 1993; Rote et al. 1997). However, the southern Colorado Plateau has a wealth of sediment-transport data that can be used to estimate sediment yield from ungaged tributaries. We used three methods to estimate streamflow sediment yield: (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 evaluate their appropriateness for estimating sediment yield in Grand Canyon.

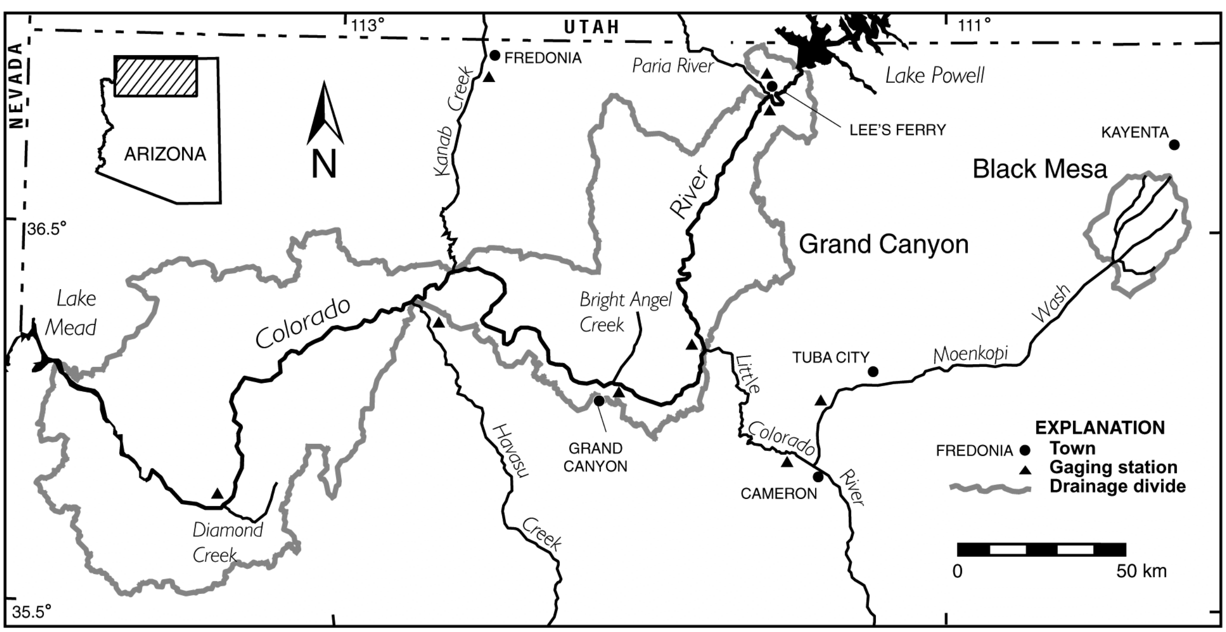

Figure 1. The Colorado River and major tributaries in northern Arizona.

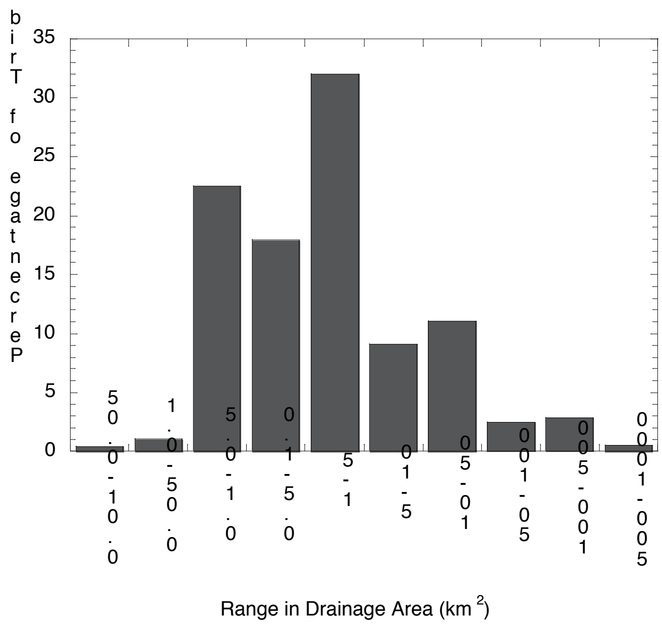

Figure 2. Histogram of drainage areas of ungaged tributaries in Grand Canyon.

ESTIMATING SEDIMENT YIELD

Regional Sediment-Yield Data: 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 1). These yields assume minimal long-term change in storage (Graf, 1987). On the basis of a range in drainage area most comparable with that of Grand Canyon tributaries, the most appropriate data are sedimentation data from 25 small reservoirs in northeastern Arizona (Fort Defiance region of the Navajo Indian Reservation; Hains et al. 1952). We combined this reservoir sedimentation data with the annual sediment yields from gaging stations in the region, excluding the mainstem Colorado River, and fit a power function to these data (fig. 3) to obtain

$$Q_s = 193 \cdot A^{1.04}, R^2 = 0.86, \qquad (1),$$

where Q_s = sediment yield (Mg/yr), A = drainage area (km^2), and n = 37. The high R^2 value suggests sediment data from the southern Colorado Plateau are readily modeled by a linear relation to drainage-basin area. Consequently, we use this relation interchangeably with the regional data in evaluating the other two estimation techniques.

Empirical Sediment-Yield Relations: We compared several extant empirical relations for estimating streamflow sediment yield (table 2). An implicit assumption in these approaches is that the percent of exposed bedrock in a drainage basin is not a factor in sediment yield. 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. The PSIAC method (Pacific Southwest Inter-Agency Committee, 1968) 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). The approaches by Howard and Dolan (1981) and Randle and Pemberton (1987) were developed specifically for Grand Canyon. Howard and Dolan (1981) assumed that ungaged tributaries yielded as much sediment per unit area as the gaged tributaries (table 2). Randle and Pemberton (1987) derived their estimate relating sediment yield to drainage area from reservoir sedimentation surveys of the western United States and adjusted it with data from the Paria and Little Colorado Rivers, and Kanab and Havasu Creeks.

Table 1. Measured sediment loads at selected gaging stations on the Colorado Plateau.

Gaging station name	Years of data (Water years)	Drainage area (km^2)	Sediment load (10^6 Mg/yr)	Sediment yield ($Mg\ yr^{-1} km^{-2}$)
*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.

Table 2. Estimates of sediment yield by streamflow from 219 ungaged tributaries of the Colorado River.

			A. Sediment†	
Source	**Original equation***	**Units**	**(10^6 Mg/yr)**	**($Mg\ yr^{-1}\ km^{-2}$)**
§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	0.14	42.6
Renard (1972)	$0.001846\ A^{-0.1187}$	ac-ft/ac/yr	0.67	204
Soil Conservation Service (1975)	PSIAC method	ac-ft/mi2/yr	13.5	4,110
Strand (1975)	$1130\ A^{0.77}$	m^3/yr	1.62	494
#Dendy and Bolton (1976)	$1280\ Q^{0.46} (1.43 - 0.26 \log A)$	tons/mi^2/yr	0.81	247
**Howard and Dolan (1981)	$780\ A$	Mg/km^2/yr	2.56	780
**Randle and Pemberton (1987)	$1750\ A^{-0.24}$	m^3/km^2/yr	2.4	731
Graf (1987)	$1200\ A^{1.0}$	m^3/yr	3.9	1,190

* A = drainage area km^2 if units are metric; otherwise in area units given.
† Sediment density is estimated as 1,200 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.

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

In order to limit the data collection necessary to evaluate the more complicated relations, we calculated sediment yield for a subset of Grand Canyon tributaries (n = 219) and compared the results. Estimates range through two orders of magnitude, from 43 to 4,110 Mg km^{-2} yr^{-1} (table 2) and most are significantly larger than measurements at gaging stations (table 1). Flaxman's (1972) approach produced the lowest sediment yield (43 Mg km^{-2} yr^{-1}) –

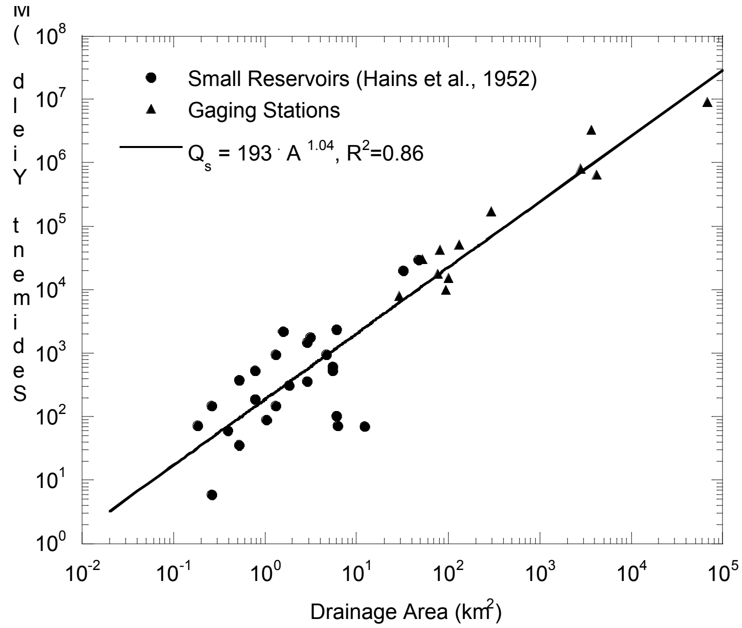

Figure 3. Sediment-yield data from small reservoirs (Hains and others, 1952) and gaging stations on the Colorado Plateau (n = 37).

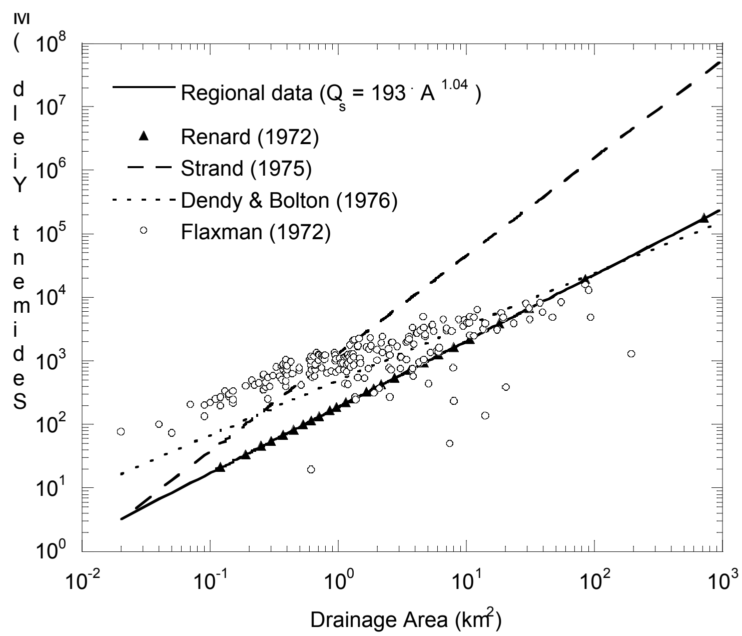

Figure 4. Estimates of streamflow sediment yield from empirical equations and the regional-data regression relation.

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underpredicting substantially for larger drainages in comparison to regional data (fig. 4) – while the PSIAC method produced the highest sediment yield (4,110 Mg km^{-2} yr^{-1}). Relations that produced estimates outside the range of regional gage data (Flaxman 1972, the PSIAC method, Howard and Dolan 1981, Randle and Pemberton 1987, and Graf 1987) were eliminated from further consideration.

Sediment yield was calculated for all ungaged Grand Canyon tributaries with each of the three remaining techniques and compared to regional gage data (fig. 4). The Strand (1972) equation consistently overpredicted sediment yield

Table 3. Estimated annual streamflow sediment yield from ungaged tributaries in Grand Canyon, Arizona.

Sediment-yield reach	Drainage area (km^2)	Sediment yield (Mg/yr) Data regression equation*	Renard (1972) equation†	Flood-frequency method*
Lake Powell- Paria River	321	64,800	76,400	45,200
Paria River - Little Colorado River	2,953	610,000	593,000	457,000
L. Colorado R. – Bright Angel Creek	494	97,700	127,000	82,300
Bright Angel – Kanab Creek	1,640	332,000	375,000	240,000
Kanab Creek – Havasu Creek	276	57,000	63,700	40,500
Havasu Creek – Diamond Creek	3,958	821,000	779,000	488,000
Diamond Creek – Lake Mead	3,236	669,000	633,000	397,000
Total	12,878	2,650,000	2,650,000	1,750,000

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

relative to regional data, the degree of overprediction increasing significantly with drainage area. The Dendy and Bolton (1976) equation overpredicted sediment yield as well, though to a lesser degree and did better with larger drainages than Strand (1972). However, the relation that best approximates the regional data is the Renard (1972) power function relating sediment yield to drainage area (fig. 4). The Renard (1972) equation, converted to SI units and assuming a sediment density of 1.2 Mg/m^3, is

$$Q_s = 351 \cdot A^{0.88}, \tag{2}$$

where Q_s = streamflow sediment yield (Mg/yr) and A = drainage area (km^2). Sediment yield calculations based on this equation are in close agreement with those from the regional-data regression, always within the same order of magnitude and differing by no more than 30% (Table 3).

The Flood-Frequency, Rating-Curve Technique: We developed a third method for estimating streamflow sediment yield based loosely on the work of Strand (1975) and Strand and Pemberton (1982). This technique uses local flood hydrographs as the link between regional flood-frequency relations and sediment rating curves. This method 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. 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 unreasonable assumption for most of the tributaries

Flood volumes and sediment-rating curves: Hydrographs for floods on Bright Angel Creek (fig. 1) collected between 1924 and 1972 are the only available data concerning the form of streamflow floods in small Grand Canyon tributaries. Although sediment data were collected at Bright Angel Creek between 1991 and 1993, they are of limited extent and possibly seasonally biased (Webb et al. 2000). Instead, we used sediment data collected at 8 gaging stations operated by the Peabody Coal Company on Black Mesa to calculate sediment rating curves (table 4). These gaging stations (table 1) 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 climate at Black Mesa is similar to that of Grand Canyon and the bedrock in both areas is mostly sedimentary. 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. Sediment-yield estimates based on these data may overestimate Grand Canyon sediment yield. The drainage areas of the Black Mesa tributaries are also more comparable to those of ungaged Grand Canyon tributaries than those of the larger gaged tributaries (fig. 1 and table 1).

Using hydrographs for 42 flood events in Bright Angel Creek, we applied each of the rating curves from Black Mesa to calculate five estimates of total sediment yield for each event. After separating base flow (0.4 to 1.0 m^3/s) from the runoff to calculate peak discharge for each event, we used linear regression to determine the relation between peak discharge and total sediment yield for each rating curve (table 5). The relation of sediment yield to peak

Table 4. Sediment rating 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 (m3/s)
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. Ratings are derived from unpublished data, Peabody Coal Company.

Table 5. Linear regression between peak discharge and sediment yield for 42 floods in Bright Angel Creek.

	Sediment rating curve used				
	Yellow Water #1	Yellow Water #2	Coal Mine #1	Coal Mine #2	Moenkopi #1
Coefficient (*a*)	1987	1258	1088	773	404
Exponent (*b*)	1.09	1.17	1.21	1.21	1.45
R^2	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.

Table 6. Regional regression equations from Roeske (1978) for streamflow flood.

Flood frequency region*	Recurrence interval(yrs)	Flood-frequency relation
1	2	$Q = 19\, A^{0.660}$
	5	$Q = 66.3\, A^{0.600}$
	10	$Q = 127\, A^{0.566}$
4	2	$Q = 1.35\, A^{0.491}\, (E/1{,}000)^{2.25}$
	5	$Q = 0.319\, A^{0.446}\, (E/1{,}000)^{3.60}$
	10	$Q = 0.143\, A^{0.423}\, (E/1{,}000)^{4.31}$

Q = peak discharge (ft^3/s); A = drainage area (mi^2); E = mean basin elevation (ft).
* Region 4 is east of the Colorado River and north of the Little Colorado River; the remainder of Grand Canyon falls within Region 1.

discharge took the form:

$$Q_e = a \cdot Q_p^{\,b}, \tag{3}$$

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 5). Of the eight relations, we elected to use that derived from Moenkopi Wash #1 because: 1) it had the highest R^2 (0.82), 2) it had the lowest coefficient and would produce the lowest sediment yield estimate as a counterbalance to potential overestimation of Grand Canyon sediment yield, and 3) the drainage area of Moenkopi Wash #1 (29.2 km^2) is closest to the mean area of ungaged tributaries in Grand Canyon (16 km^2).

Regional flood frequency: We evaluated the regional regression relations for flood frequency given by Thomas et al. (1997) for the southwestern United States, but found significant problems when applying them to the Grand Canyon region (Webb et al. 1997, 2000). Few small drainages in Grand Canyon have gaging records, and therefore these tributaries are poorly represented in the Thomas relations. Additionally, most of the data for these equations come from areas outside northern Arizona. 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 et al (1997). We therefore elected to use the regional-regression equations published by Roeske (1978) for calculating sediment yield in Grand Canyon (table 6).

Calculations of sediment yield: We linked flood-frequency discharge estimates to sediment yield-peak discharge relations using

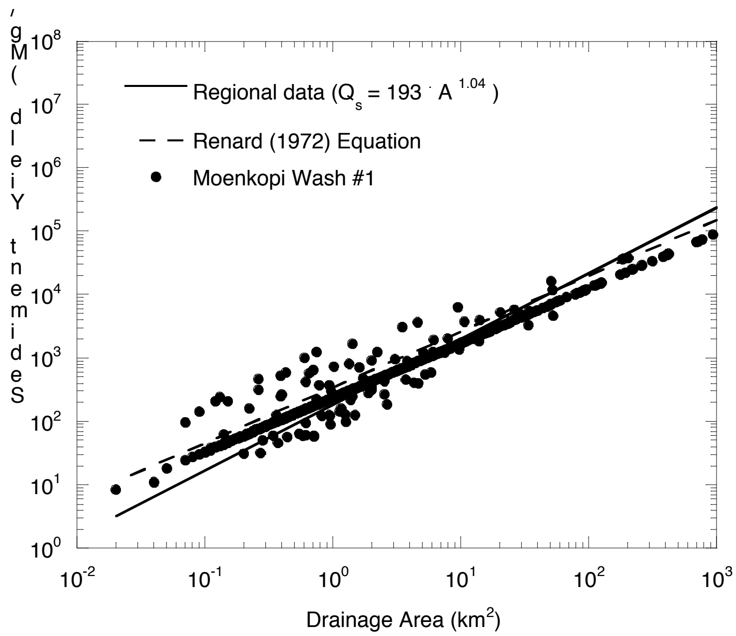

Figure 5. Streamflow sediment-yield estimates for 768 Grand Canyon tributaries calculated using the regional flood-frequency estimates of Roeske (1978) and sediment-rating data from Moenkopi Wash #1 compared to the regional-data regression and Renard (1972) equations.

$$Q_s = [1 \cdot f(Q_{10}) + 2 \cdot f(Q_5) + 5 \cdot f(Q_2)] / 10, \tag{4}$$

where Q_s is sediment yield in Mg/year, Q_t is the peak discharge of the *t* year flood in m^3/s (from Roeske 1978), and $f(Q_t)$ is the regression relating peak discharge to sediment yield in Mg/event (Q_e calculated for Moenkopi Wash #1). We assumed an expected value for the number of floods to occur in a decade which 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.

Sediment yield calculations based on the flood frequency-rating curve technique are in reasonable agreement with those from the regional-data regression (fig. 5) and with no more scatter than the original regional data (fig. 3). Estimates calculated by reach are lower than those from the regional-data regression and Renard relations (table 3), but still of the same order of magnitude and never vary by more than 40%.

CONCLUSIONS

All three techniques used to estimate sediment yield from small drainage basins in Grand Canyon agreed well with each other and regional data, suggesting they may all be useful in estimating sediment yield elsewhere on the southern Colorado Plateau. In evaluating eight empirical sediment-yield relations, complex multivariate methods, such as that of the PSIAC (1968) and Dendy and Bolton (1976), did not perform as well as simple power functions relating sediment yield to drainage basin area. This suggests that complex relations may not necessarily be more accurate in estimating sediment yield, at least on a regional scale. The new flood-frequency 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. It may be more robust than the others for estimating sediment yield where local streamflow data are available. Future testing of this technique in settings where sediment yields are known may bear this out. The flood-frequency technique depends on numerous untested 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.

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