INACCURACIES IN SEDIMENT BUDGETS ARISING FROM ESTIMATIONS OF TRIBUTARY SEDIMENT INPUTS: AN EXAMPLE FROM A MONITORING NETWORK ON THE SOUTHERN COLORADO PLATEAU

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Abstract Sediment budgets are an important tool for understanding how riverine ecosystems respond to perturbations. Changes in the quantity and grain-size distribution of sediment within river systems affect the channel morphology and related habitat resources. It is therefore important for resource managers to know if a channel reach is in a state of sediment accumulation, deficit or stasis. Many studies have estimated sediment loads from ungaged tributaries using regional sediment-yield equations or other similar techniques. While these approaches may be valid in regions where rainfall and geology are uniform over large areas, use of sediment-yield equations may lead to poor estimations of sediment loads in semi-arid climates, where rainfall events, contributing geology, and vegetation have large spatial variability.

Previous estimates of the annual sediment load from the ungaged tributaries to the Colorado River downstream from Glen Canyon Dam vary by an order of magnitude; this range in sediment loads has resulted in different researchers reaching opposite conclusions on the sign (accumulation or deficit) of the sediment budget in the Colorado River. To better estimate the supply of fine sediment (sand, silt, and clay) from these tributaries to the Colorado River, eight gages have been established on previously ungaged lesser tributaries in Glen, Marble, and Grand canyons. The remote locations of these streams and short duration of floods make it prohibitively expensive, if not impossible, to directly measure streamflow or to use conventional depth-integrating suspended-sediment samplers. Discharges are therefore calculated using a stage-discharge relation developed from a series of modeled flows and a stage record measured by a downward looking sonic ranging sensor. Flows are modeled using surveyed high-water marks, surveyed channel topography, and Z_0 bed roughness constrained by pebble counts. Suspended-sediment measurements are made with passive US U-59 samplers and, at some tributary gages, stage-triggered pump samplers. During floods with a sufficient number of suspended-sediment samples, loads are calculated by interpolating sediment concentrations between the physical samples. When few or no physical samples are collected for a given flood event, regression relations between discharge and sediment concentrations are used if the relations are statistically significant. For gages with no significant relation between discharge and sediment concentrations, mean sediment concentrations – averaged over the period of record – are used. Using these methods, suspended-silt-and-clay and suspended-sand loads transported past each of the lesser-tributary gages are calculated.

Results from this sediment-monitoring network show that previous estimates of annual sediment load from the tributaries were too high, and that the sediment budget for the Colorado River below Glen Canyon Dam is in greater deficit than previously concluded by most researchers. In addition, we found that floods of the same magnitude may have different source areas, resulting in large differences in sediment loads between equal magnitude flows. Because sediment loads do not necessarily correlate with drainage size, and cumulative sediment loads may vary by two orders of magnitude on an annual basis, using techniques such as sediment-yield equations to estimate sediment loads from ungaged tributaries may lead to large errors in sediment budgets.

INTRODUCTION

The calculation of accurate sediment budgets can be sensitive to the sediment supplied from ungaged tributaries. Studies have calculated sediment loads from ungaged tributaries using a number of methods, including: mass-balance calculations assuming quasi-equilibrium (Howard and Dolan 1981; Andrews, 1986), regional sediment-yield equations (Webb and et al., 2000), sediment-rating curves (Sutherland and Bryan, 1990) and peak discharge to total sediment-load relations (Rankl, 2002). The above methods can lead to errors when estimating annual sediment loads from semi-arid streams. Depending on the local geology, topography, and vegetation, floods in semi-arid regions can have large (10x) differences in sediment concentrations between equal magnitude flows as the result of locally intense rainfall events with footprints smaller than the receiving basin.

The Colorado River below Glen Canyon Dam is an example of a river reach where quantifying the supply of fine sediment from tributaries could be essential for calculating accurate sediment budgets. The Colorado River below Glen Canyon Dam is currently the focus of a major river restoration program (Campbell and others, 2010); one of the major goals of this program is the restoration of eddy sandbars in the Colorado River in Marble and Grand Canyons. Fine sediment is supplied to this reach from the Paria and Little Colorado Rivers as well as a number of smaller, herein referred to as lesser, tributaries. Sediment budgets calculated using estimates of cumulative sediment load from the lesser tributaries have been used to inform flow alternatives from Glen Canyon Dam with the objective of restoring sandbars (U.S. Department of the Interior, 1995). Over a factor of 5 variation exists in previous studies' estimates of the annual sediment load from the lesser tributaries to the Colorado River in Marble Canyon (BOR, 1956; BOR, 1958; Howard and Dolan, 1981; Randle and Pemberton, 1987; Webb et al., 2000). This large variation in estimated sediment load is large enough to have the effect of changing the sign of sediment budgets in the Colorado River in Marble and Grand canyons under certain conditions. The magnitude of the variation in these estimates and the fact that no direct measurements of lesser-tributary flood hydrographs or sediment transport were used in these estimates were the prime motivators of this study.

To better estimate the sediment supplied from the lesser tributaries to the Colorado River in Glen and Marble canyons, the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center established gages on previously ungaged lesser tributaries for measuring stage and suspended-sediment. This network of lesser-tributary gages was established in late 2000; most of the gages in the network now have over 13 years of data. At these gages, stage is recorded every 15 minutes during dry, or baseflow, periods and every minute during floods. Suspended-sediment measurements are made using US U-59 samplers (Edwards and Glysson, 1999), automatic-pump samplers, and rare dip samples. Channel topography and high-water marks are surveyed for subsequent flow modeling. High-water marks are modeled to determine flow; several sets of high-water marks are used to create a stage-discharge relation (Griffiths, 2010). This indirect method of determining discharge was chosen because of the remote location of the lesser-tributary gages and the short duration of floods. In this paper, we focus on the results from the ephemeral tributaries that discharge into the Colorado River in upper Marble Canyon. Upper Marble Canyon is herein defined as the reach of river from Lees Ferry to the formerly proposed Marble Canyon dam site at river mile 32.5 (by convention, river miles in Marble and Grand canyons begin at Lees Ferry and progress downstream).

PREVIOUS ESTIMATIONS OF LESSER-TRIBUTARY SEDIMENT SUPPLIES

A number of researchers have investigated the sediment supplied to the Colorado River from its lesser tributaries. The first studies were completed by the U.S. Department of the Interior, Bureau of Reclamation (BOR) in preparation for the proposed construction of Marble Canyon Dam (BOR, 1956; 1958). The initial 1956 BOR study estimated the mean-annual sediment load from the lesser tributaries using the area of ungaged tributaries and the sediment yield from the "roughly similar" San Juan River. This study concluded that the mean-annual sediment load from the lesser tributaries between the Paria River and the proposed dam site was approximately 2.8 million metric tons. A second study by the BOR (1958), based on field observations of geology, geomorphology, vegetation, and sedimentation in stock tanks, concluded that the mean-annual sediment load from the lesser tributaries was approximately 740,000 metric tons (including gravel). In 1981, Howard and Dolan (1981) estimated the mean-annual sediment load from all lesser tributaries upstream from the Grand Canyon gage (USGS 09402500 Colorado River near Grand Canyon, AZ) to be 34 % of the combined mean-annual load from the Paria and Little Colorado rivers, or ~4 million metric tons. Randle and Pemberton (1987) using a regional sediment-yield regression to calculate lesser-tributary sediment loads, estimated that the mean-annual sediment load from the lesser tributaries in Marble Canyon to be ~910,000 metric tons. Of this total, they estimated that the mean-annual sand load from these Marble Canyon tributaries was ~140,000 metric tons (i.e., 15% of the load was sand). Sediment yields are reported in units of mass per unit area-time, whereas annual or cumulative sediment loads (i.e., sediment supplies) are reported in units of mass. A similar regional sediment-yield regression approach was used by Webb et al. (2000), who, in addition, employed a flood-frequency rating-curve method and results from a reservoir-sedimentation study combined with a runoff model to calculate three estimates of mean-annual sediment load from the lesser tributaries; the mean-annual sediment load from all lesser tributaries in Marble Canyon was estimated to be 460,000-610,000 metric tons. Of this total, they calculated the mean-annual sand load (assumed to be 15-75% of total sediment) ranged from 70,000-460,000 metric tons.

The majority of the previous studies reported mean-annual sediment loads calculated on the basis of sediment-yield equations derived for drainages with substantially different geologic and climatic conditions. No direct measurements of sediment transport in the lesser tributaries were used. In addition, the time-averaged nature of the sediment loads reported by the previous studies make these mean-annual loads poorly suited for calculation of sediment budgets over shorter time frames.

In the sections below, we will investigate in more depth some of the methods used in the previous studies. The two BOR studies estimated sediment yields and sediment supplied to the upper Marble Canyon Reach. The remaining studies estimated sediment yields and resulting sediment supplies to longer reaches of the river than the upper Marble Canyon Reach. To allow comparison with the previous study results, and between previous studies, we converted yield values from the disparate studies using drainage area in combination with published bulk sediment density estimates to generate estimates of mean-annual sediment loads from the lesser tributaries to upper Marble Canyon (Table 1).

Table 1 Summary of previous estimations of summed lesser-tributary mean-annual sediment loads to the Colorado River corrected and apportioned to the upper Marble Canyon Reach.

Study	**Total sediment (metric tons)**	**Sand (metric tons)**
Reclamation (1956)	1,900,000	No value estimated
Reclamation (1958)	760,000[a]	No value estimated
Howard and Dolan (1981)	1,800,000	No value estimated
Randle and Pemberton (1987)	680,000	100,000[b]
Webb and others (2000)	520,000	78,000-390,000[c]

[a]Includes gravel
[b]Sand assumed to be 15% of total sediment
[c]Sand assumed to be 15-75% of total sediment

The study by BOR (1956) estimated a lesser-tributary sediment yield of 714 m^3/km^2-yr. This initial estimation of sediment yield in combination with the lesser-tributary area of upper Marble Canyon (2,319 km^2) from Webb et al. (2000) and the sediment density of 1,153 kg/m^3 used by Randle and Pemberton (1987) results in a mean-annual sediment load of ~1.9 million metric tons (Table 1). Because of errors made by BOR (1956) in determining the lesser-tributary area from the 1:500,000-scale map used, this mean-annual sediment load is less than the original study predicted. Because no grain-size distributions are reported by BOR (1956) for the lesser-tributary sediment load, no subdivision of predicted total sediment load into silt and clay supply and sand supply is possible.

The more-comprehensive BOR (1958) study conducted individual investigations in each of the "more-important" lesser tributaries and divided the lesser-tributary area between Glen Canyon Dam and the proposed Marble Canyon dam into 12 sediment-yield units. Correcting the BOR (1958) total drainage area by that reported in Webb et al. (2000) and using the Randle and Pemberton (1987) sediment density, the 1958 BOR study predicts the mean-annual sediment load from all upper Marble Canyon lesser tributaries of 760,000 metric tons of total sediment (Table 1).

Howard and Dolan (1981) estimated the sediment yield from the lesser tributaries to the Colorado River between Lees Ferry and the Grand Canyon gage (USGS 09402500 Colorado River near Grand Canyon, AZ) based on a pre-dam sediment mass balance and the assumption of the bathymetric changes observed at one cross section was representative of all geomorphic changes in this 140-km-long reach. By this approach, they estimated the sediment yield from the lesser tributaries to be approximately 34% of the combined annual sediment load from the Paria and Little Colorado Rivers, or ~780 metric tons/km^2-yr. This sediment yield in combination with the tributary drainage-basin areas from Webb et al. (2000) results in mean-annual sediment load from all upper Marble Canyon lesser tributaries of ~1.8 million metric tons (Table 1). As with BOR (1956, 1958), because no grain-size distributions are reported by Howard and Dolan (1981) for the lesser-tributary sediment yield, no subdivision of predicted total sediment load into silt and clay supply and sand loads is possible.

Applying the sediment yield from Marble Canyon (293 metric tons/km^2-yr) of Randle and Pemberton (1987) to the lesser-tributary area of upper Marble Canyon results in ~680,000 metric tons of sediment. Randle and Pemberton (1987) assumed sand comprised 15% of the total sediment, using this figure we calculate a mean-annual sand load from the lesser tributaries of ~100,000 metric tons.

Webb et al. (2000) used three methods for determining sediment yield from the lesser tributary areas. Because the results from the three methods were similar, they presented the results of the simplest method, the regional data regression. Using their sediment yield equation ($351 \cdot A^{0.88}$ where A is tributary drainage area in km^2) and the individual tributary drainage areas, we calculated the mean-annual sediment load from the lesser tributaries to upper Marble Canyon. In addition to the tributaries listed for Marble Canyon, they estimated an extra 120 km^2 of area that was not included in the list of tributaries. We divided this extra area by river miles and applied the resultant extra 62 km^2 to the upper Marble Canyon Reach. When determining sediment load from each tributary, we assumed this extra area was comprised of small drainages (1 km^2 each) and added the sediment loads to the total load for upper Marble Canyon. Using the Webb et al. (2000) methods, we thus calculated a mean-annual sediment load from the lesser tributaries of ~520,000 metric tons. Using their estimate of 15-75% sand results in ~78,000-390,000 metric tons of sand (Table 1).

LESSER-TRIBUTARY GAGES

There are currently eight gages on the lesser tributaries of the Colorado River in lower Glen, Marble, and Grand canyons where stage and suspended sediment are automatically measured (Figure 1). This monitoring network was established in 2000 and expanded in 2006 to include Bright Angel Creek (Griffiths et al., 2014). In this network, stage, suspended-silt and clay concentration, suspended-sand concentration, and suspended-sand grain-size measurements are made on lesser tributaries representing approximately 69% of the previously ungaged drainage area of upper Marble Canyon. All of the lesser-tributary gages, except for those in Water Holes Canyon and on Bright Angel Creek, monitor streams that drain into upper Marble Canyon. This paper will focus on the lesser tributaries that flow into upper Marble Canyon, putting aside the gages in Water Holes Canyon and on Bright Angel Creek.

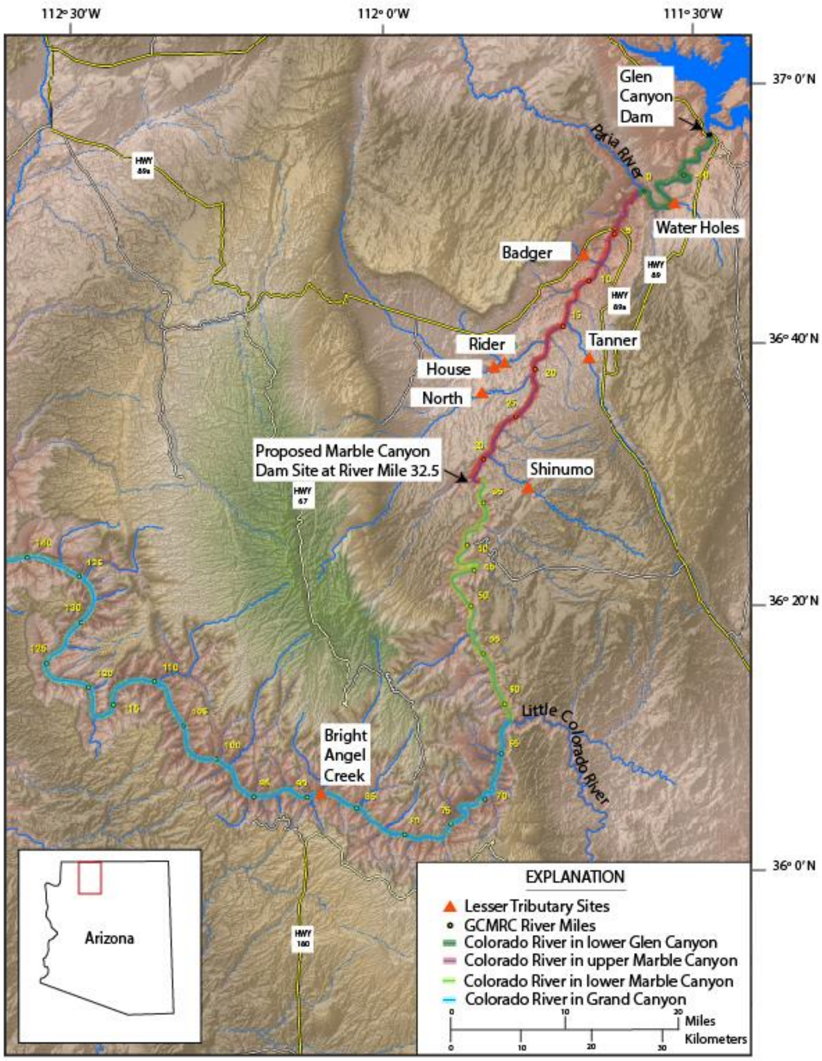

Figure 1 Digital elevation map showing the lesser-tributary gages. Lesser-tributary gages: Water Holes Canyon (Water Holes), Badger Creek (Badger), Tanner Wash (Tanner), House Rock Wash above Emmett Wash (House), House Rock Wash in Rider Canyon (Rider), North Canyon (North), Shinumo Wash (Shinumo), and Bright Angel Creek.

Geology of the lesser-tributary drainage basins can be broadly categorized into areas with higher potential fine-sediment yield associated with Mesozoic sandstones, and areas with lower potential fine-sediment yield associated with Paleozoic limestone. Four gages are located on higher potential fine-sediment yield lesser tributaries that drain into upper Marble Canyon: (1) Badger Creek, (2) Tanner Wash, (3) House Rock Wash above Emmett Wash (herein referred to as House Rock Wash), and (4) House Rock Wash in Rider Canyon (herein referred to as Rider Canyon). At the gage: the streambed of Badger Creek is composed of sand and gravel, the streambed of Tanner wash is composed of gravel and sand, the streambed of House Rock Wash is composed of sand and fine gravel, and the streambed of Rider Canyon is composed of patches of sand and gravel on bedrock. The House Rock Wash gage is located upstream, in the same drainage, as the Rider Canyon gage. The Rider Canyon gage has the most comprehensive suspended-sediment record of the lesser-tributary gages; at this gage, suspended-sediment measurements are made using arrays of US U-59 samplers and an automatic pump sampler.

North Canyon and Shinumo Wash drain areas that consist primarily of Paleozoic limestone and have lower potential fine-sediment yields. These two tributaries have streambeds that are almost exclusively angular limestone gravel with only minor amounts of interstitial sand. Vegetation at all the gages consists primarily of sparse, low-lying bushes and grasses, with little or no vegetation in the active channel.

METHODS

Discharge calculations The remote location of the lesser-tributary gages coupled with the extremely short duration of flash floods makes it difficult and expensive to measure the discharge of water directly. Calculation of discharge at the lesser-tributary monitoring sites therefore requires the development of a stage-discharge relation constrained by modeled peak discharges from multiple floods. Peak discharges are modeled using the USGS National Research Program multi-dimensional surface water modeling system – now named international river interface cooperative – and the "quasi-three-dimensional flow and sediment transport with morphological evolution of channels solver" (McDonald et al., 2005). The approach used is to:

(1) Select a suitable reach for modeling and complete a base topographic survey. A suitable channel reach is stable and relatively straight, with simple channel geometry that will result in an easier flow-modeling process. Survey the position of the stage sensor and any suspended-sediment sampler intakes. Survey cross sections every 2-3 meters along the channel, depending on channel complexity, and generate a topographic map and model grid of the stream channel from survey data.
(2) Survey multiple sets of high-water marks within the reach corresponding to floods with different peak stages. A wide range of high-water marks allows the development of a comprehensive stage-discharge relation.
(3) Perform successive 2-D model runs varying the discharge and Z_0 (Z_0 roughness values are constrained by pebble count data) to minimize the root-mean-square error between the surveyed high-water marks and the modeled water surface.
(4) Attempt to hold the established Z_0 constant in the model, and model the discharge associated with different high-water marks to develop stage-discharge relations (Griffiths et al., 2010).
(5) Only allow Z_0 to increase with increasing peak flood stage if there is physical evidence that the roughness characteristics of the bed changes with increasing stage, as described below.

The Nikuradse (1933) Z_0 bed roughness parameter is used for flow modeling. This roughness parameter was chosen instead of the more commonly used Manning's *n* because, unlike the Manning's *n* roughness parameter, Z_0 does not depend on stage and only depends on the characteristics of the streambed. As discharge increases in gravel-bedded rivers Z_0 should remain constant unless the gravel bed becomes fully mobile or rougher areas of the streambed and banks become inundated. As either vegetated or formerly dry rougher areas of the streambed, banks, and canyon walls become inundated and are added to the model grid, Z_0 may increase. For an immobile gravel bed, Z_0 is approximately equal to $0.1 \cdot D_{84}$ (Whiting and Dietrich, 1989; Wiberg and Smith, 1991), where D_{84} is the 84th percentile grain size of the gravel. As the gravel bed becomes fully mobile, Z_0 increases to approximately equal $0.5 \cdot D_{84}$ (Pitlick, 1992)

Modeled flows are combined with corresponding recorded stages to develop a stage-discharge relation for the gage. This stage-discharge relation is used for all subsequent floods unless major changes in the channel geometry or hydraulic control are observed. If large channel changes occur, a new stage discharge relation must be developed using the steps above. Where an insufficient number or diversity of flood peaks have been modeled to develop a stage-discharge relation, any high-water marks observed during maintenance visits to the gage are flagged for later survey. The stage-discharge relation and stage record are used to calculate the discharge record for each gage.

Sediment-transport calculations At each lesser-tributary gage, cumulative sediment load is calculated using the discharge record and a combination of physical-sample sediment-concentration data and averaged sediment concentrations or a regression relationship developed between log-transformed discharge and log-transformed sediment concentrations. Logarithmic transformation is used to reduce heteroscedasticity in the data. Samples collected by the US U-59s or the automatic pump samplers are analyzed for silt and clay concentration, sand concentration, and sand grain-size distribution. On the basis of analyses conducted on the Paria River (a similarly steep, sandy river, with similarly high sediment concentrations), the sediment concentrations measured in these "point" samples are assumed to be representative of the sediment concentrations in the entire cross section. The automatic pump samplers record the date and time the samples were collected. The US U-59 samples are assigned a date and time of sampling based on the date they were recovered, the preceding hydrograph, and the surveyed elevations of the sampler intakes. Once the date and time of collection is known for each of the samples and the laboratory analyses are completed, an F-test is preformed to determine if any significant dependence of log-transformed concentration on log-transformed discharge is present (Figure 2). Because of the large variability in suspended-sediment concentrations observed during individual flood events and between different floods, many of the gages do not exhibit significant "stable" relations between discharge and silt and clay concentration and between discharge and sand concentration. However, most sites do show a significant positive relation between discharge and suspended-sand D_{50}.

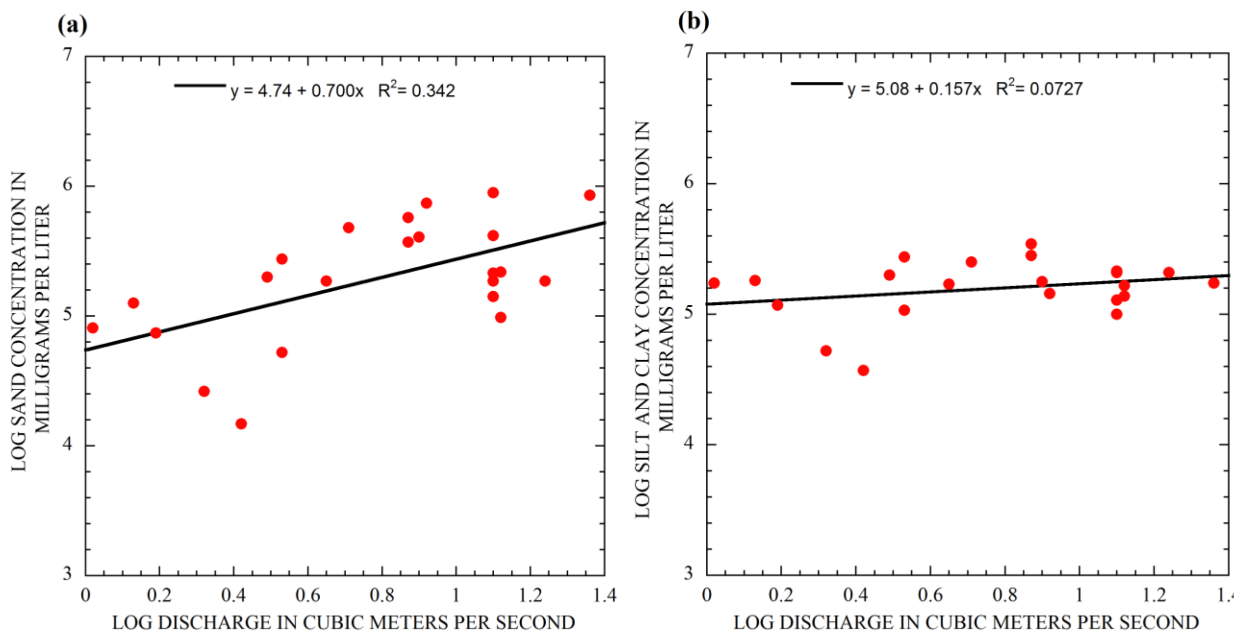

Figure 2 Log-log plots of concentration of sand (a) and silt and clay (b) vs discharge for the Badger Creek gage. Results from F-tests indicate that the linear fit is significant for the relation between log-transformed discharge and log-transformed sand concentration ($p < 0.05$), but not for the relation between log-transformed discharge and log-transformed silt and clay concentration.

For many of the lesser tributaries, suspended-sediment concentration does not correlate well with discharge. Using a F-test, log-transformed suspended silt and clay concentrations were significantly related ($p < 0.05$) to log-transformed discharge in only the Shimumo Wash drainage, while log-transformed sand concentrations are significantly related to log-transformed discharge in two of the five drainages (Badger Creek and Shimumo Wash). Poor correlation between discharge and suspended-sediment concentration is independent of sampling method; at the Rider Canyon gage, all sampling methods yield similar poor correlations between log-transformed discharge and suspended-sand concentration (Figure 3).

Sediment concentration and discharge are combined to calculate instantaneous loads; these loads are then integrated over the entire hydrograph to calculate the cumulative loads of suspended-sediment transported past each of the lesser-tributary gages. If samples were collected during a flood event, the concentrations from those samples are used for a half hour window surrounding the sample collection time. If no samples were collected during a flood, or not collected within a half hour of a calculated discharge, mean sediment sample concentrations from the entire dataset at that gage are used; gages with significant discharge-concentration relations use these relations in the place of mean concentrations. Silt and clay loads and sand loads are calculated using the same techniques.

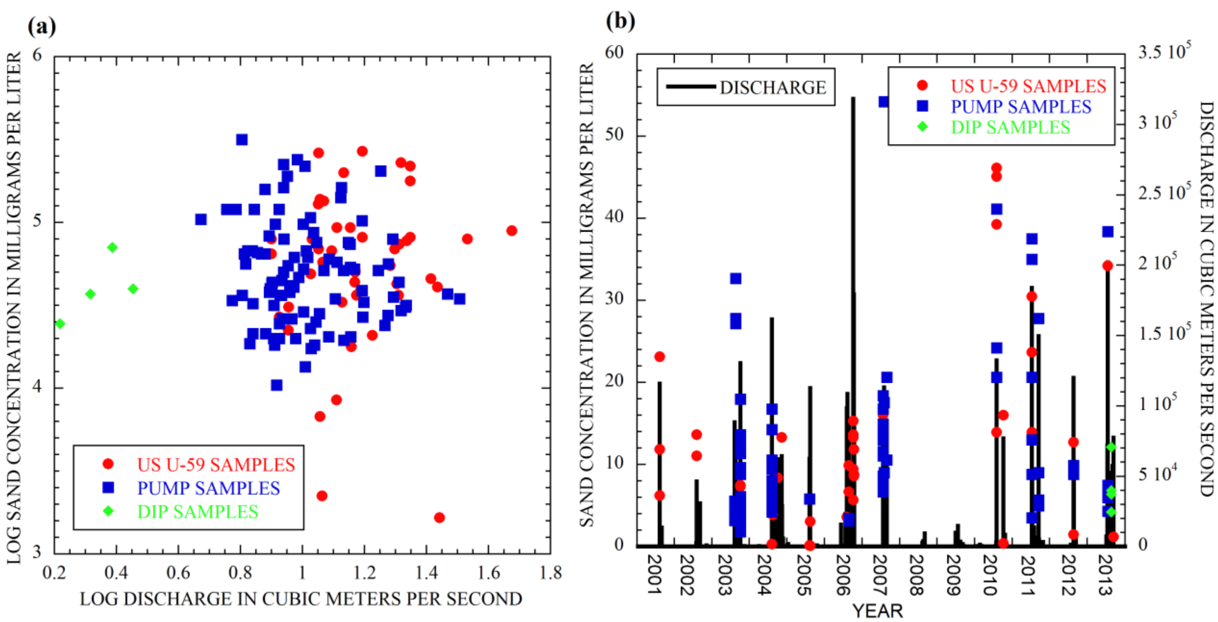

Figure 3 Log-log plot of sand concentration vs discharge for the Rider Canyon gage showing the three sampling methods (a), sand concentration and discharge for the entire period of study (b).

RESULTS AND DISCUSSION

<u>Results from this study</u> We estimate total sediment load from the lesser tributaries to the Colorado River in upper Marble Canyon by applying the mean-annual measured cumulative loads of the gaged tributaries, 69% of the total lesser-tributary area of upper Marble Canyon, to the remaining ungaged 31%. The ungaged area is divided into potentially higher and lower sediment yields based on drainage basin geology and similarity to other, gaged, lesser tributaries. Using this classification, only 25% of the higher-potential-yield tributaries remain ungaged; sediment yield from this ungaged area is estimated based on the annual yield of the three gaged higher-potential-yield tributaries. Ungaged tributaries draining the lower-potential-yield area represent 40% of the total lower-potential-yield tributaries; the sediment yield from this area is estimated from the annual yield of the lower-potential-yield tributaries.

Over the 13 years of this study, annual sediment load from the lesser tributaries to the Colorado River in upper Marble Canyon was found to vary two orders of magnitude from ~1,800 to 340,000 metric tons of sand and from ~2,900 to 370,000 metric tons of silt and clay (Table 2). The mean-annual sand and silt-and-clay loads in the lesser tributaries were ~72,000 metric tons of sand and ~96,000 metric tons of silt and clay. This is equivalent to ~10% of the measured mean-annual sand load and ~8% of measured mean-annual silt-and-clay load in the Paria River over the same period (Table 2). Although the lesser tributary mean-annual sand load is 10% of the Paria River, the annual sand load of the lesser tributaries as a percent of the Paria River sand load ranges from ~1.6-49% during individual years.

The vast majority of the sediment entering Marble Canyon from the lesser tributaries is supplied from the 57% of the tributary area with higher potential sediment yield. The three gaged higher-potential-yield tributaries, Badger Creek, Rider Canyon, and Tanner Wash, contribute approximately 73% of the total sand and 65% of the total silt and clay to the upper Marble Canyon Reach.

Table 2 Measured annual sediment loads in metric tons (t) from the higher- and lower-potential-sediment-yield lesser tributaries to the Colorado River, the summed annual lesser-tributary sediment loads to upper Marble Canyon including estimates from the remaining ungaged area, and the measured Paria River annual sediment loads.

Year	Higher-Yield Tributaries		Lower-Yield Tributaries		Upper Marble Canyon		Paria River	
	Sand (t)	Silt (t)	Sand (t)	Silt (t)	Sand (t)	Silt (t)	Sand (t)	Silt (t)
2001	8,400	8,000	0	0	11,000	11,000	88,700	399,000
2002	28,000	28,000	62	720	38,000	38,000	78,100	468,000
2003	19,000	30,000	380	3,600	26,000	48,000	341,000	780,000
2004	47,000	59,000	970	6,200	64,000	89,000	676,000	1,530,000
2005	54,000	54,000	3,900	32,000	79,000	130,000	976,000	1,280,000
2006	260,000	270,000	350	5,200	340,000	370,000	1,590,000	2,080,000
2007	57,000	67,000	32	1,100	76,000	90,000	829,000	1,580,000
2008	8,400	7,400	27	550	11,000	11,000	305,000	685,000
2009	1,400	2,100	3	34	1,800	2,900	116,000	520,000
2010	72,000	63,000	310	500,467	9,700	89,000	1,460,000	2,170,000
2011	35,000	35,000	500	3,700	47,000	53,000	144,000	325,000
2012	13,000	22,000	170	1,400	17,000	32,000	706,000	1,270,000
2013	76,000	98,000	12,000	34,000	120,000	190,000	1,950,000	2,150,000
Mean	**52,000**	**58,000**	**1,400**	**710**	**72,000**	**96,000**	**712,000**	**1,170,000**

Annual sediment loads from the lesser tributaries vary greatly between drainages and from year to year (Table 2, Figure 3). Drainages have diverse geology and topography, storm cells that produce locally heavy rain may have a footprint much smaller than the size of the receiving drainage basin. While regional precipitation events do occur, precipitation events are typically more spatially variable with many higher-discharge events recorded in one tributary not present in the discharge record of other, nearby, tributaries (Figure 3a). In addition, a tributary may experience several large floods within days followed by years of quiescence. Over the course of this study, three of the gaged tributaries, Tanner Wash, Shinumo Wash, and North Canyon, have cumulative discharges that are approximately the same; however, the observed sediment loads, as well as the timing of events, differ dramatically (Figure 3). Both North Canyon and Shinumo Wash contributed very little sediment (combined less than 2% of the total sand and approximately 8% of the silt and clay), while Tanner Wash alone contributed approximately 28% of the sand and 18% of the silt and clay.

The ratio of suspended sand to suspended silt and clay varies considerably even among drainages of similar geology. Higher-potential-yield tributaries average approximately 47% sand and 53% silt and clay while the lower-potential-yield tributaries average only 17% sand. Because the higher-potential-yield tributaries contribute much more sediment than do the other tributaries, sand comprises, on average, approximately 45% of the sediment supplied to the entire Marble Canyon Reach by the lesser tributaries. Sediment yield varies within drainages as well as between different tributaries. A drainage representing approximately 25% of the total drainage area enters between the House Rock Wash gage and the Rider Canyon gage (these gages are located on the same drainage, with House Rock Wash being the upstream gage). This drainage, which is similar to Badger Creek in geology and topographic relief, is responsible for approximately 53% of the sand passing the Rider Canyon gage, but only 22% of the silt and clay.

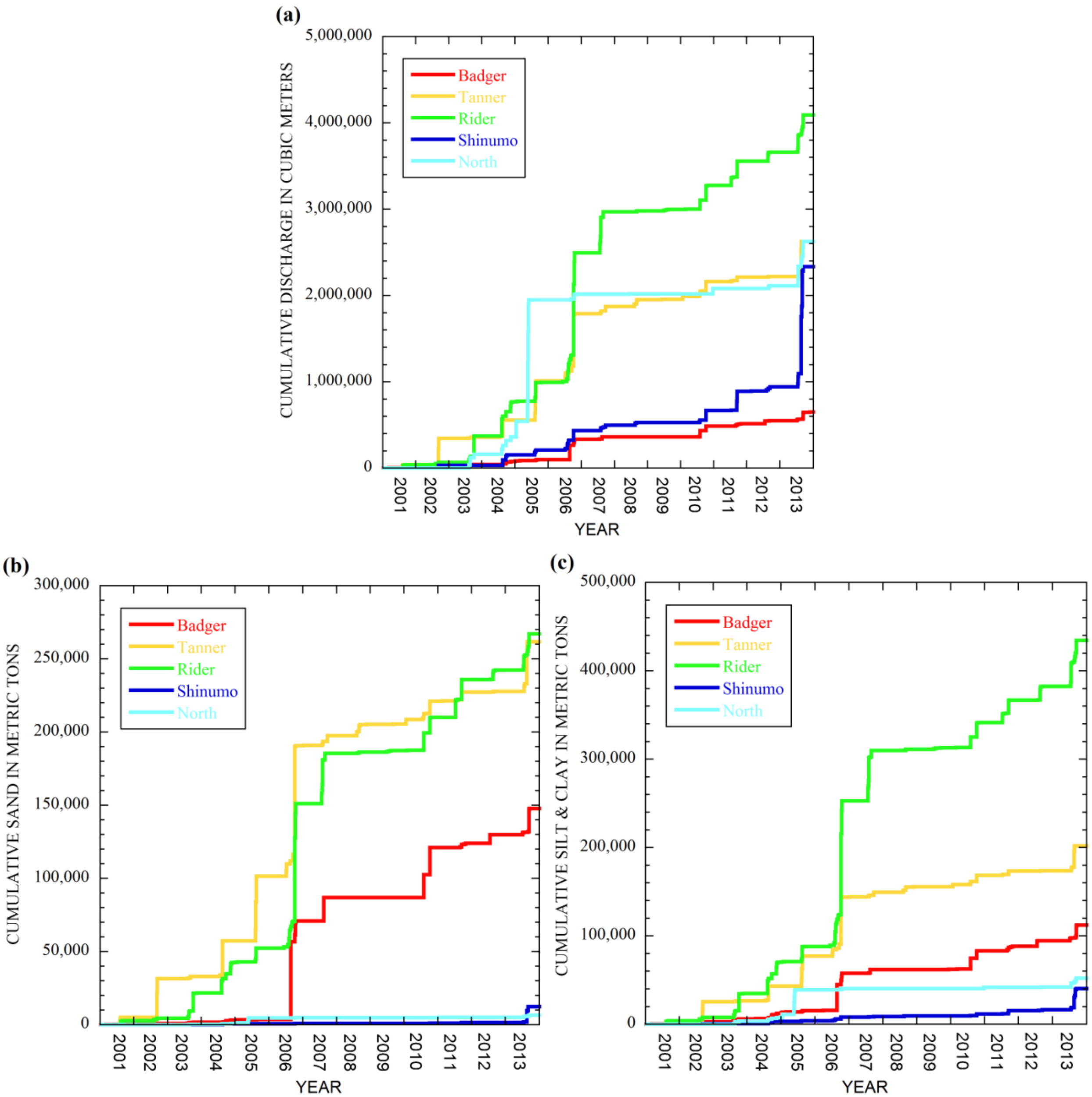

Figure 3 Cumulative water discharges in cubic meters (a) sand loads in metric tons (b) and silt and clay loads in metric tons (c) for the gaged lesser tributaries in upper Marble Canyon.

Comparison with previous work The results from this study show that previous studies all over-estimated the sediment supply from the lesser tributaries to the Colorado River in Marble Canyon (Table 1, Table 2). Two of the previous studies, BOR (1956) and Howard and Dolan (1981), overestimated the quantity of total sediment entering from the lesser tributaries by an order of magnitude. The other three previous studies estimated mean-annual lesser-tributary sediment loads ranging from ~520,000 to 760,000 metric tons. Our study measured a mean-annual lesser-tributary sediment supply of ~170,000 metric tons, a factor of 3.1-4.5 lower than the previous estimates. Previous studies also greatly overestimated the amount of lesser-tributary sand supplied to the Colorado River in upper Marble Canyon. Only the low-end estimates of lesser-tributary sand load from Webb et al. (2000) seemingly agree with our measurements of lesser-tributary sand load; this apparent agreement is, however, misleading as Webb et al.'s (2000) low-end estimates assumed that only 15% of the total sediment load was sand. Our suspended-sediment measurements show that this estimate of percent sand is too low, the measured value is actually much larger at ~45% sand. If Webb et al. (2000) had used a more-correct higher percentage of sand, their lowest estimate of lesser-tributary sand supply would have been roughly 3.3 times larger than the values calculated in our study.

The differences in lesser tributaries sediment loads between previous studies and our study can be attributed to previous studies not using direct measurements of stage, discharge, or sediment concentrations, but relying on relations from drainage basins that do not accurately reflect the local geology, climate and vegetation. Additionally, previous studies, using older established sediment-yield relations, are based on data that do not reflect current climatic conditions. Lastly, previous studies present mean-annual results that do not capture the year-to-year variation in sediment loads measured in our study.

SUMMARY

Relying on indirect methods to estimate the cumulative sediment load from ungaged tributaries and close sediment budgets may result in substantial errors in these budgets. This study found that previous, indirect, methods that used no actual measurements of sediment transport greatly overestimated the amount of sand and the amount of silt and clay supplied by the lesser tributaries to the Colorado River in upper Marble Canyon. Because large variation exists in annual tributary sediment loads, additional error will be introduced into shorter-term sediment budgets (with durations of several years or less) even when measured mean-annual lesser-tributary sediment loads are used in these budgets; sediment supply to the Colorado River in upper Marble Canyon from the lesser tributaries was found to vary over a factor of 100 on an annual basis. For sediment budgets that vary greatly as a function of the sediment supplied from tributaries, direct measurement of the sediment loads in these tributaries may be necessary to accurately close sediment budgets, and provide valid recommendations to resource managers.

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