Measurements of sediment loads in small, ungaged, basins may be required to accurately close sediment budgets: an example from a monitoring network on the southern Colorado Plateau

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EP43B-0845

1. Introduction

•Sediment budgets for river reaches of concern can hinge on the input of sediment from small ungaged tributaries.

•Studies have calculated input from ungaged tributaries using a number of methods, some examples are: mass balance assuming quasi-equilibrium (Howard and Dolan 1981; Andrews, 1986), sediment-yield equations (Webb and others, 1991) sediment-rating curves (Sutherland and Bryan, 1990) and peak discharge to total sediment-load relations (Rankl, 2004).

•Problems with the above methods can lead to errors in estimating the sediment yield from semi-arid ephemeral streams.

- ➢ Rain fall events have large spatial and temporal variability.
- ➢ Flow events of the same magnitude may have different source areas resulting in large differences in sediment concentrations between equal magnitude flows.
- ➢ Differences in the local geology can result in large (10x) differences in sediment yield.

•To better constrain the sediment input from small tributaries to the Colorado River in Marble and Glen canyons the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center established monitoring sites on previously ungaged small tributaries (fig. 1).

- ➢ Stage is recorded every 15 minutes during dry periods and every minute during flood events.
- ➢ Sediment samples are collected using point samples, US U-59s, ISCO pump samplers, and dips.
- ➢ 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; available at: http://acwi.gov/sos/pubs/2ndJFIC/Contents/P40_Griffiths_paper.pdf).

The purposes of this study are: (1) to describe the methods used in calculating sediment loads for the small tributaries, (2) to examine several examples of these methods used at gaging statinos on House Rock Wash above Emmett Wash (House), House Rock Wash in Rider Canyon (Rider), and Shinumo Wash (Shinumo), and (3) compare previous estimates of sediment yield to those found in this study.

2. Study Sites

- Drainage basin areas range from 47 km^2 (Badger) to 770 km^2 (House/Rider).
- Gaging stations have been installed on tributaries representing approximately 53% of the previously ungaged area of Glen Canyon and 54% of Marble Canyon.
  - ➢ Badger area = 1.6%
  - ➢ House/Rider area = 26%
  - ➢ Shinumo area = 6.3%
- Geology varies between Mesozoic sandstones with high sediment yield to Paleozoic limestone with lower sediment yield.
  - ➢ House/Rider drainage basin and the Badger drainage basin are dominated by Mesozoic sandstones (high sediment yield).
  - ➢ Shinumo drainage basin is dominated by Paleozoic limestone (lower sediment yield).

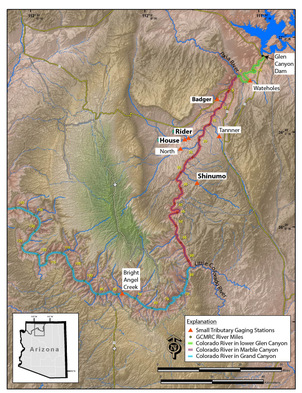

Figure 1 Digital elevation map showing the small tributary stage and suspended-sediment gaging stations. Stations: Water Holes Canyon (Water), Badger Creek (Badger), Tanner Wash (Tanner), House Rock Wash (House), Rider Canyon (Rider), North Canyon (North), Shinumo Wash (Shinumo), and Bright Angel Creek.

3. Methods

(A) Model high-water mark flows.

- Survey channel reach and generate a topographic map.
- Survey multiple high-water lines from floods.
- Perform successive 2-D model runs (using iRIC) varying the discharge and Z_0 (Z_0 roughness values are constrained by pebble count data) to minimize the root-mean-square (RMS) error between the surveyed high-water marks and the modeled water surface (fig. 2).
- Use the Z_0 value to model multiple high-water marks.

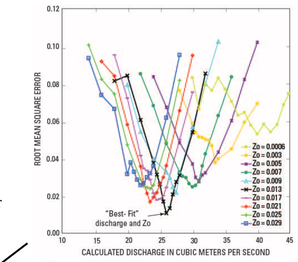

Figure 2 Model results for the House station

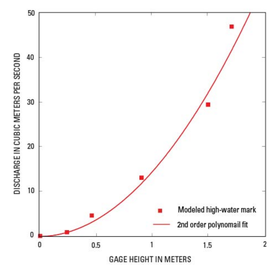

Figure 3 Stage discharge relation for the Badger station

(B) Create stage discharge relation for each station:

- Match modeled flows with measured stage (fig. 3).
- Fit a trend line forced though 0.

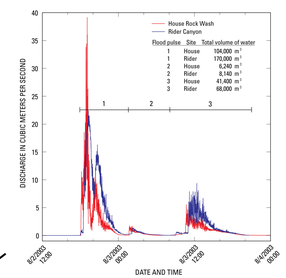

Figure 4 Example floods in House and Rider

(C) Calculate the discharge record for each site

- Edit the stage record to remove obviously bad points.
- Create a bed-elevation file; bed elevation often changes slightly during flow events
- Calculate discharge and compare with other gaging stations, if possible (fig. 4).

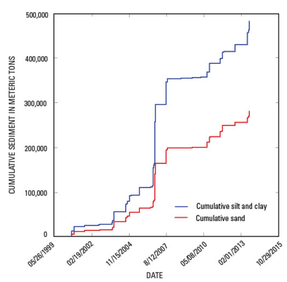

Figure 5 Cumulative sediment load transported past the Rider station for 10+ years

(D) Calculate the instantaneous and cumulative sediment loads (fig. 5)

- Assign a date and time to US U-59 samples based on the stage record and surveyed height.
- Evaluate sediment and discharge data for trends.
- Calculate sediment loads, this study uses sediment concentration data from samples collected within half hour of stage measurement, if no samples were collected during this time average sediment sample values are used.

4. Results and Discussion

- Suspended-sediment concentration data does not correlate well with discharge for these drainages (fig. 6)
  - ➢ Drainages have diverse geology and topography, storm cells that produce local heavy rain events may have a significantly smaller footprint than the size of the receiving drainage basin.
  - ➢ Flow periods are episodic, several large floods may occur within days followed by years of inactivity
  - • The suspended-sediment samples collected with the US U-59 point sampler compares well with samples collected with an automated pump sampler (fig. 6).
  - ➢ Samples collected from similar gradient and sediment-concentration streams where suspended sand and silt and clay are well mixed in the cross section (Paria and Little Colorado rivers) have shown that automated pump samples and dip samples are equivalent to traditional depth-integrated samples.
  - • Sediment input from the small tributaries varies greatly between drainages and from year to year (figs. 7 & 8).

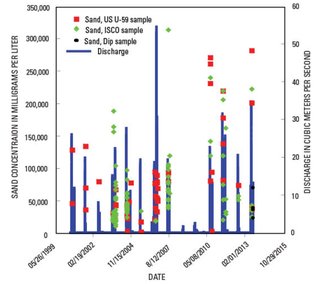

Figure 6 Discharge record for Rider with associated suspended-sediment samples

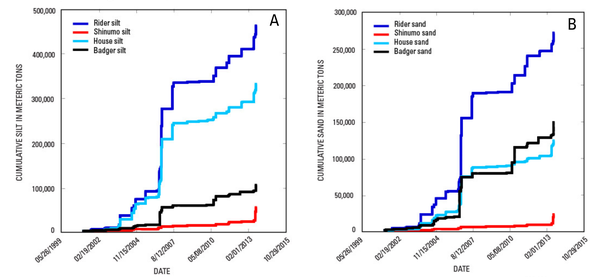

Figure 7 Cumulative sediment input, silt and clay (A), sand (B)

- The ratio of suspended-sediment silt and clay to suspended sand varies considerably even among drainages of similar geology (fig. 7).
  - ➢ Between the House gaging station and the Rider gaging station (these stations are located on the same drainage, with House being the upstream gage) a drainage representing approximately 25% of the total drainage area enters. This drainage is responsible for approximately 50% of the sand passing the Rider station.

- The annual sand and silt and clay input from the small tributaries can vary greatly year to year (fig. 8).
  - ➢ Annual sediment input was found to vary two orders of magnitude, from an annual total suspended sediment input of 5,500 mt to over 690,000 mt (fig. 8 and Table 1).
  - • The geology of a basin exerts great control on the quantity of sediment exported.
  - ➢ The Shinumo and Badger drainage basins have similar climate and topography, however Badger, which drains predominately Mesozoic sandstones, transports much more sediment than the larger Shimuno, which drains predominately Paleozoic limestone.
  - • The results from this study show that previous estimates of sediment input from small tributaries to the Colorado River in Marble Canyon over-estimated their contribution (Table 1).

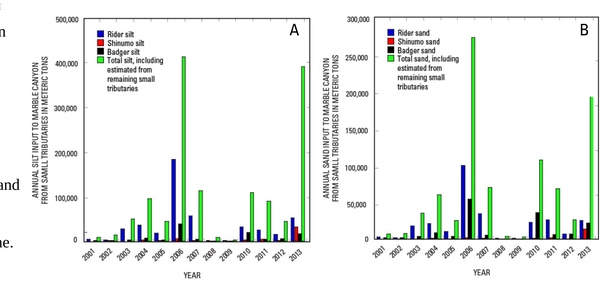

Figure 8 Annual sediment input, silt and clay (A), sand (B)

Study	Sand (mt)	Silt (mt)	Total sediment (mt)	Method	Notes
USBR Marble Canyon Dam Site Study (1958)	-	-	940300*	Observation of geology, geomorphology, vegetation and tanks	*This figure includes all sediment, not just suspended. Original study from 0-32 mile, extrapolated
Howard and Dolan (1981)	-	-	2291528	0.34*paria+LCR suspended-sediment yield (776 t/km^2)	Originals study from 0-87 mile, used yield equation for Marble Canyon calculations
Randle and Pemberton (1987)	136107	771273	907380	Drainage Area and Regional sediment yield (semiarid US)	Sand assumed to be 15% of total sediment
Webb and others (2000)	92000-458000	-	610000	Regional Sediment yield regression (193*A^1.04) in Mg/yr	Sand assumed to be 15-75% of total sediment
	89000-445000	-	593000	Renard, reservoir sediment data & stochastic runoff model	Sand assumed to be 15-75% of total sediment
	69000-343000	-	457000	Flood frequency rating-curve method	Sand assumed to be 15-75% of total sediment
Griffiths and Topping (2013)	2150-274000	8200-417000	5500-691342	Flow and sediment gaging (yearly)	Range of sediment input found during the 12 years of study
	67600	107000	175000	Flow and sediment gaging (averaged)	Average result for the 12 years of study, sand found to be approximately 39% or total sediment

Table 1 Summary results from this and previous studies on the sediment input from small tributaries to the Colorado River in Marble Canyon

5. Summary

- **Sediment delivery to the Colorado River in Marble Canyon from the small tributaries can vary 100x on an annual basis.**
- **Sediment yield does not necessary correlate with drainage size, local geology is a strong controlling factor.**
- **Previous, indirect, methods tended to greatly overestimate how much sand and silt and clay was contributed by the small tributaries.**
- **Measuring the sediment yield from small tributaries may be necessary to accurately close sediment mass-balances.**

Provisional Data – do not cite

Dec 2013