THE USE OF THE MULTI-DIMENSIONAL SURFACE-WATER MODELING SYSTEM (MD_SWMS) IN CALCULATING DISCHARGE AND SEDIMENT TRANSPORT IN REMOTE EPHEMERAL STREAMS

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Abstract Construction and operation of Glen Canyon Dam has greatly reduced the sediment supply to the Colorado River in Grand Canyon National Park, with almost all of the sand and finer sediment now being supplied by two main tributaries: the Paria and Little Colorado Rivers. Other smaller ephemeral tributaries may collectively be a lesser, but still important, additional source of sand and finer sediment. However, the sediment supply from the smaller tributaries is currently poorly constrained. Calculating discharge, and the resultant sediment transport, for these remote ephemeral streams can be challenging; most significant run-off events are short-duration events (lasting minutes to hours) related to thunderstorms. The remote location of the streams and the short duration of the floods make it prohibitively expensive, if not impossible, to directly measure the discharge of water. Discharge of water during floods is therefore modeled using the U.S. Geological Survey National Research Program Multi-Dimensional Surface Water Modeling System (MD_SWMS) developed by McDonald and others (2005, 2006).

The U.S. Geological Survey Grand Canyon Monitoring and Research Center has established eight monitoring sites on previously ungaged tributaries of the Colorado River downstream from Glen Canyon Dam. Monitoring sites typically consist of a downward-looking stage sensor and passive suspended-sediment samplers. Two of the sites also have automatic pump samplers to collect suspended-sediment samples during floods. At each of the monitoring sites, channel topography and high-water marks for different peak flows have been surveyed. The approach used to calculate discharge for the surveyed high-water marks is to: (1) generate a topographic map of the stream channel from survey data, (2) enter a “best guess” flood discharge and Z_0 roughness parameter (based on the bed-sediment grain-size distribution) for the first model run, (3) perform successive model runs varying the discharge and Z_0 to minimize the root-mean-square error between the surveyed high-water marks and the modeled water surface and (4) hold the established Z_0 constant in the model (Z_0 scales with the bed-sediment grain-size distribution and does not depend on stage like Manning’s *n* does), and model the discharge for different high-water marks to develop stage-discharge relations. Using the stage sensor and suspended-sediment data from each site, total sediment transport can then be determined. This paper presents the methods used in calculating stage-discharge relations and examines several examples. The methods developed herein can be used at other remote locations where information on discharge and sediment loads is needed.

INTRODUCTION

Closure of the Glen Canyon Dam gates in 1963 cut off approximately 95% of the natural supply of sand and finer sediment at the upstream boundary of Grand Canyon National Park. The reduced sediment supply affects native species, archeological-site preservation, and recreation. Sand and finer sediment are now supplied seasonally to the Colorado River in Grand Canyon National Park mainly from the Paria and Little Colorado Rivers, as well as from a number of smaller (that is, lesser) tributaries (Topping et al., 2000; Webb et al., 2000). Sediment inputs from both the Paria and Little Colorado Rivers are computed using the geomorphically coupled flow and sediment-transport model of Topping (1997) in combination with suspended-sediment data collected in these tributaries. This leaves the lesser tributaries as the only major unquantified part of the sediment supply to the Colorado River in Grand Canyon National Park.

Beginning in 2000, the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center (GCMRC) established monitoring sites on previously ungaged lesser tributaries for the purpose of measuring stage and collecting suspended-sediment data. Calculating discharge and sediment input from these ephemeral lesser tributaries is difficult because of both the remote location of the sites and the short duration of floods. This combination makes it prohibitively expensive, if not impossible, to directly measure discharge. Because of the complicated channels and super elevation of the water surface found at some study sites, a 1-dimensional modeling approach cannot be accurately used to represent the water surface during a flood. Therefore, discharge of water during floods is simulated numerically using the quasi-three-dimensional FaSTMECH (Flow and Sediment Transport with Morphologic Evolution of CHannels) model within the USGS National Research Program’s graphical user interface MD_SWMS (Multi-Dimensional Surface Water Modeling System) developed by McDonald and others (2005, 2006). Sediment loads in these lesser tributaries are then calculated using measured suspended-sediment concentrations and 1-minute stage data coupled with stage-discharge relationships developed using MD_SWMS.

The purposes of this paper are: (1) to describe the methods used in calculating stage-discharge relations, and ultimately sediment loads, in the lesser tributaries, and (2) to examine several examples of these methods used at monitoring sites on Bright Angel Creek, House Rock Wash above Emmett Wash, and House Rock Wash in Rider Canyon. This paper draws these examples from a larger and more exhaustive study; it is not intended to be comprehensive but rather to provide only a few examples of the methods employed.

LESSER TRIBUTARY SITES

There are currently eight stage and suspended-sediment monitoring sites located on the lesser tributaries of the Colorado River in lower Glen, Marble and Grand Canyons (Fig.1), with the primary focus being the tributaries of the Colorado River in Marble Canyon. Stage, suspended-silt and clay concentration, suspended-sand concentration, and suspended-sand grain size are currently monitored on lesser tributaries that drain approximately 56% of the previously ungaged drainage area of Marble Canyon. All monitored lesser tributaries except for Bright Angel Creek and Water Holes Canyon drain into Marble Canyon.

Lesser tributary stage and suspended-sediment monitoring sites have two main components: a downward-looking ultrasonic Campbell Scientific SR-50[1] stage sensor, and several arrays of passive U-59 samplers[2]. ISCO automatic pump samplers are also deployed at the Bright Angel Creek and House Rock Wash in Rider Canyon monitoring sites. Stage is measured and recorded at a site-specific 15-minute or 1-hour interval during background baseflow or zero-flow conditions and every minute during flood conditions.

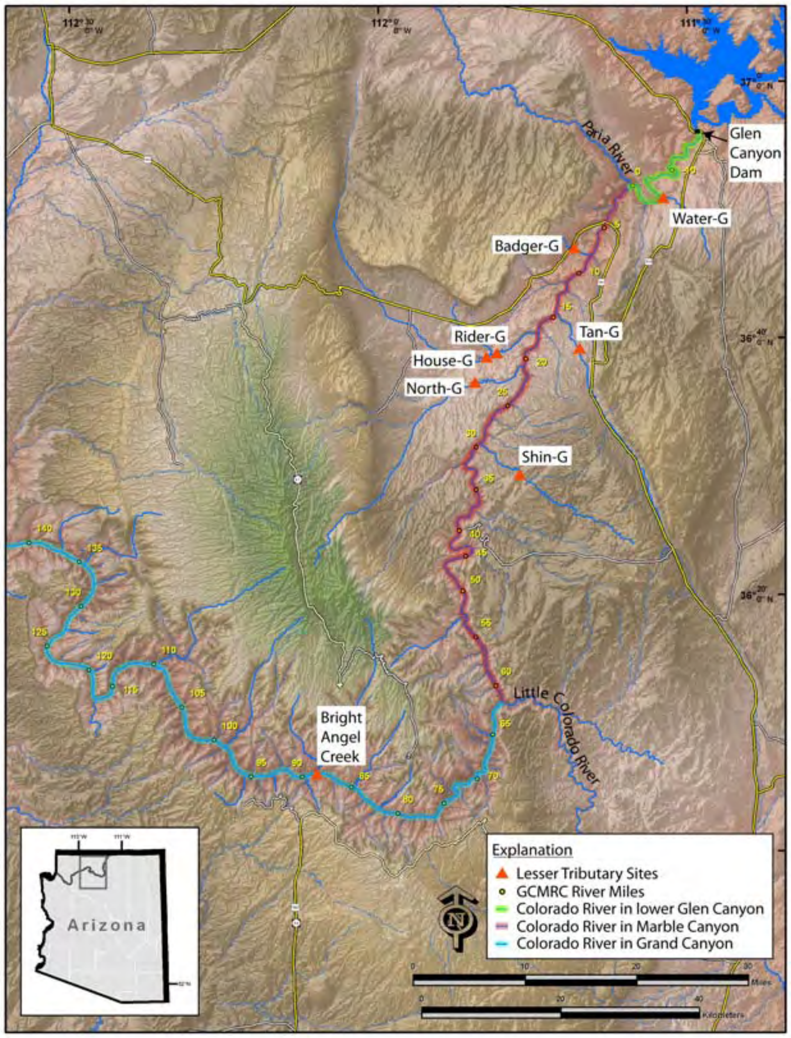

Figure 1 Digital elevation map showing the lesser tributary stage and suspended-sediment monitoring sites. Lesser tributary suspended-sediment monitoring sites: Water Holes Canyon (Water-G), Badger Creek (Badger-G), Tanner Wash (Tan-G), House Rock Wash above Emmett Wash (House-G), House Rock Wash in Rider Canyon (Rider-G), North Canyon (North-G), Shinumo Wash (Shin-G), and Bright Angel Creek.

[1] Use of brand and firm names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.
[2] U-59 single-stage samplers described in Edwards and Glysson (1999).

The three lesser tributary monitoring sites examined in detail are located on Bright Angel Creek and at two sites on House Rock Wash (above Emmett Wash and in Rider Canyon). Bright Angel Creek is a steep, cobble-dominated stream with an average baseflow of about 0.54 m^3/s. Bright Angel Creek has a historical stream-gaging record from 1923 through 1993 (with substantial gaps after 1974) that provides hydrologic context for the other short-record sites. The bed of House Rock Wash above Emmett Wash (herein referred to as House Rock Wash) is dominated by sand and fine gravel. The bed of House Rock Wash in Rider Canyon (herein referred to as Rider Canyon) is composed of patches of sand on bedrock. The Rider Canyon site has the most comprehensive suspended-sediment record of the lesser tributary monitoring sites; at this site, suspended-sediment samples are collected with both an array of U-59 samplers and an ISCO automatic pump sampler. Unlike Bright Angel Creek, House Rock wash has zero baseflow. Vegetation at the sites (except for Bright Angel Creek) consists primarily of sparse, low lying, bushes. The vegetation at the Bright Angel Creek site consists of sparse grasses and sedges along the channel, and small willow and other brush on the upper channel banks.

METHODS

Calculation of discharge, and ultimately sediment transport, at the lesser-tributary monitoring sites requires the development of a stage-discharge relation constrained by modeled peak discharges from multiple floods. Because only the peak discharge of each flood is modeled, and not the entire flood hydrograph, a steady-state model is used. The FaSTMECH model, a quasi-three-dimensional model, was used within the MD_SMWS graphical user interface program to model discharge. Surveyed inputs to the model are: (1) high-resolution stream channel data (an interval of 1-4 surveyed cross-sections per channel width through the length of reach was used), and (2) high-water marks from multiple floods. Z_0 is chosen for this modeling exercise over other types of roughness parameters because: (1) the roughness characteristics of the wetted bed do not change greatly between the various flood stages, and (2) Z_0 does not vary with stage and is related to the characteristics of the bed sediment, channel form, and vegetation.

To determine the best value of Z_0, a modeling approach is employed to find the value for Z_0 that minimizes the root-mean-square (RMS) error between the surveyed high-water marks and the model-predicted water-surface elevations among all surveyed floods. Because the model performs better (with lower RMS errors) at higher discharge, the final chosen Z_0 is biased toward the value of Z_0 that minimizes RMS error between the surveyed high-water marks and the model-predicted water-surface elevations during higher-discharge floods. Where possible, this best-value Z_0 is validated by comparison to estimates of Z_0 based on the bed-sediment grain-size distribution. After the best value of Z_0 is determined by this error-minimization approach, stage-discharge relations are developed for the sites using the modeled discharges and measured peak stages during the floods. Discharge and sediment transport past each site are then calculated using the developed stage-discharge relation, stage record, and suspended-sediment-concentration data. Further details of the data-collection and modeling methods used are provided below.

To minimize the difficulty of multi-dimensional flow modeling, the location of each lesser-tributary monitoring site was selected based on minimal channel complexity. The straightest and simplest channel segments of each tributary were selected for each monitoring site to minimize the complexity of the model, and thus the time required for modeling. Although the geometries of the selected channel segments were the simplest available, some of these channel segments were too complicated to be accurately modeled using a 1-dimensional model, hence the selection of the FaSTMECH model to ensure consistency in methods among all monitoring sites. Upon site selection and equipment installation at each monitoring site, channel and overbank topography, and visible high-water marks from floods pre-dating site installation were surveyed with total stations and GPS. The survey lengths of channels range between 100-300 meters, approximately 10-30 times the average channel width. The locations of the SR-50 stage sensors and the intakes for the U-59 and automatic-pump suspended-sediment samplers were also surveyed. Following floods at each monitoring site, new high-water marks were identified, marked, and later surveyed. Channel-bed and bank survey data were also collected in conjunction with the high-water-mark surveys to ensure that the channel shape and slope had not been substantially altered during these floods.

At sites where the bed of the channel was largely composed of gravel, initial Z_0 values were calculated using pebble-count data from each modeled reach. Where the bed at the site was largely composed of sand or bedrock, the initial Z_0 was estimated. Pebble counts were conducted using the Wolman (1954) method. Because most of the gravel that constitutes the bed are likely to be either immobile or only in marginal transport during the floods modeled, initial Z_0 values were set equal to 10% of the pebble-count D_{84} value based on the work of Whiting and Dietrich (1989), Wiberg and Smith (1991), and Pitlick (1992).

The surveyed channel topography and Z_0 values were used to model the peak-flood discharge associated with each set of high-water marks. An accurate representation of the channel topography is critical to calculate the correct discharge associated with each set of high-water marks. Significant attention was given to the development of the topographic surface. At each site, cross-sections, which overlapped the measured high-water marks, were measured at an interval of 1-4 cross-sections per channel width through the channel reach. In addition, significant topography features such as boulders and ledges were surveyed. Where necessary to create an accurate continuous surface suitable for projecting on to the model grid, breaklines and interpolations were used between measured points. Editing the topography ensured that surveyed features such as large boulders or cliff faces were projected onto the model grid accurately

To simulate flow through a channel, FaSTMECH requires at a minimum: stage at the downstream end of the model grid, discharge, roughness (Z_0), and the lateral-eddy-viscosity coefficient. A series of model runs were completed while systematically varying the discharge (this mainly shifted the water surface vertically) and Z_0 (this mainly adjusted the water-surface slope) to minimize the RMS error between the surveyed high-water marks and the model-predicted water-surface elevations. For the purpose of determining the best-value Z_0 to hold constant over the full range of modeled peak-flood discharges, a weighted average of the Z_0 values that resulted in the lowest RMS errors among the various floods was used (all sites examined in this paper have two sets of surveyed high-water marks). Because the model performed better (with lower RMS errors) in the higher-discharge cases with an estimated Z_0 that was associated with a more prominent minima in RMS error, this weighted average was biased toward the value of the Z_0 that minimized the RMS error between the surveyed high-water marks and the model-predicted water-surface elevations during higher-discharge floods. The improved performance of the model at higher discharges is likely the result of topographic details; during lower floods, topographic details affect a greater percent change on the model than they would during higher floods. Once the best-value Z_0 was determined, this value was used as the roughness parameter in all subsequent discharge models at a given site. After all sets of high-water marks at a site were modeled, a stage-discharge relation was calculated and the discharge record for the site computed.

The more-commonly used roughness parameter for estimating peak discharges during floods, and the parameter previously used by the USGS to model floods in Bright Angel Creek, is Manning's *n*. Thus, to place the model results from this study into a broader and historical context, Manning's *n* values were calculated from the model results and compared to values of *n* both found in the literature and previously used for Bright Angel Creek. Rearrangement of the standard Manning discharge formula to back-calculate *n* yields:

$$n = \frac{A}{Q} \cdot R_h^{\,2/3} \cdot S^{1/2} \,, \qquad (1)$$

where A = the cross-sectional area of flow (m^2), Q = the discharge (m^3/s), R_h = the hydraulic radius (m), and S = the slope of the water surface. For each flood event, four cross-sections were used to calculate Manning's *n*; the average value for the four cross-sections is reported.

At each monitoring site, sediment transport was calculated using the developed stage record and an average sediment concentration. Owing to the large variability in suspended-sediment concentration and grain size during individual floods and between different floods that arises from sediment-supply effects, no stable relations between discharge and concentration (for silt and clay or for sand only) could be developed for the lesser tributary sites.

RESULTS AND DISCUSSION

Models were created for two flow stages at each of the three example sites investigated in this paper. The measured D_{84} (the grain size for which 84% of the clasts are smaller in size), model results and calculated Manning's *n* for each modeled flow are presented in Table 1.

Table 1 Summary of physical and computed site information.

Site name	**Stage[a] (m)**	**Bed D_{84} (m)**	**Z_0 (m)**	**Modeled Flow (m^3/s)**	**Water surface slope**	**Manning's *n***
Bright Angel Creek	749.40	0.224	0.031	0.54	0.029	0.195
	750.09[b]	0.224	0.031	16.8	0.029	0.054
House Rock Wash	1391.08[b]	0.060	0.013	10.6	0.005	0.034
	1391.36	0.060	0.013	26.0	0.006	0.036
Rider Canyon	1358.08[b]	na[c]	0.006	6.3	0.006	0.032
	1358.79	na[c]	0.006	26.0	0.004	0.028

[a] Relative to North American Vertical Datum of 1988

[b] Current stage sensor was not in place, stage taken from high-water mark surveys

[c] Channel bed consists predominately of bed rock and sand

Bright Angel Creek Because the Bright Angel Creek site has non-zero baseflow, Z_0 can be estimated here by a third approach, in addition to the two approaches described above. This third approach to estimating Z_0 is to minimize the RMS error between the modeled and surveyed water surface during a measured baseflow discharge. Flows modeled for Bright Angel Creek include 0.54 m^3/s, the normal baseflow for the creek, and one flood event. Using the measured baseflow discharge with the surveyed water surface for this flow, the best-fit Z_0 value was found to be 0.031 m (Table 1). This value is only slightly larger than the value of Z_0 = 0.022 m determined from the pebble-count approach, and is almost identical to the value of Z_0 = 0.035 m determined from applying the error-minimization approach to the flood event. Over the 0.013-m range of variation between these different values of Z_0, the modeled discharge that best fit the flood high-water marks only varied by 12 to 14%. Therefore, the Z_0 value of 0.031 m was used to model the flood associated with the surveyed high-water marks; the best-fit peak discharge for this flood was found to be 16.8 m^3/s.

Manning's *n* values were calculated for four cross-sections taken from the model results; the Manning's *n* values for the four cross-sections were then averaged. This yielded a Manning's *n* of 0.195 for the 0.54 m^3/s flow and 0.054 for the 16.8 m^3/s flow. The high calculated Manning's *n* value of 0.195 for the 0.54 m^3/s flow results from the wide shallow flow and very rough bed (D_{84} = 0.224 m). The calculated Manning's *n* value of 0.054 for the 16.8 m^3/s flow is consistent with values for similar streams (Chow, 1959; Barnes, 1967) as well as the value used by the USGS (0.055) for calculating peak-flood discharges for this reach on August 5, 1948, and August 5, 1957.

A USGS gaging station, located approximately 35 meters upstream from the current SR-50 site, operated from 1933 to 1968. Plotting the model-predicted discharges against stage-discharge relations from the 1950s (relations plotted relative to the various stages associated with a discharge of 0.54 m^3/s) shows reasonable agreement between the modern and 1957 stage-discharge relations (Fig. 2). While high flows in 1936 (120 m^3/s) and 1966 (110 m^3/s) substantially altered the Bright Angel Creek channel (Cooley, et al., 1977), the records from the 1950s show that the channel was relatively stable during this time and similar to the modern channel in this reach. Analysis of cross-sections from the flood of August 5, 1957 shows that the water surface slope (0.032) during this flood is similar to the modern water-surface slope in this same reach (0.029). In addition, surveyed cross-sections and photographs from 1957 show a channel that is remarkably similar to the modern channel. Until additional modern floods can be modeled, the form of the historical stage-discharge relation that was used from October 1, 1956, to August 5, 1957, will therefore be used in conjunction with the model results to constrain the modern stage-discharge relation at this site.

To accurately predict discharge over the entire stage range, two 2^{nd} order polynomials were fit to the October 1, 1956 to August 5, 1957 stage-discharge record. Because small rock dams built by hikers often alter the baseflow stage record, the lower-part of the stage-discharge relation in Figure 2B is adjusted over time using the "shifting control method" (Rantz, S.E. et al., 1982). A similar approach is used for the other lesser tributary sites to correct for small changes in bed elevation.

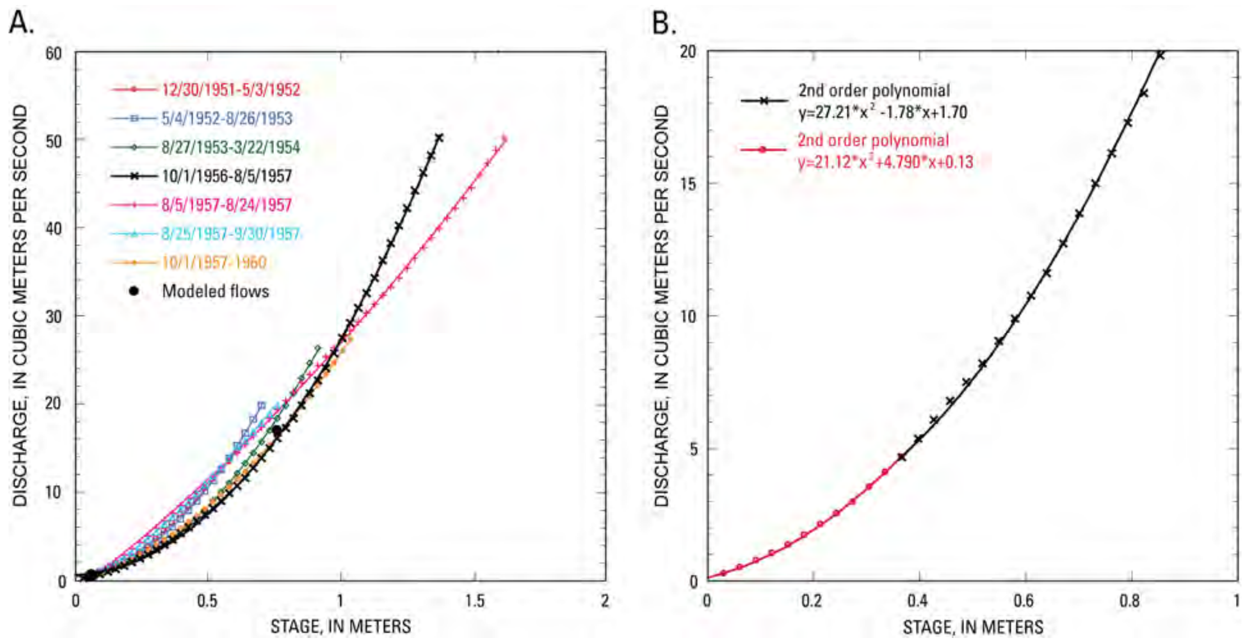

Figure 2 Stage-discharge relations for Bright Angel Creek. (A) Modern stage-discharge data from the two modeled flows compared with historic stage-discharge relations (from years where the relation extended beyond 14 m^3/s). Stage-discharge relations were shifted to be equal at the stage associated with a discharge of 0.54 m^3/s. (B) Stage-discharge relation from October 1, 1956 to August 5, 1957 fitted with two 2^{nd} order polynomials forced to match at a discharge of 5 m^3/s. Relation has been shifted to be in the same local datum as the SR-50 stage sensor.

House Rock Wash Peak-flood discharge associated with two sets of high-water marks were modeled for House Rock Wash, with corresponding flows determined to be 10.6 m^3/s and 26.0 m^3/s by the error-minimization approach for determining the best value of Z_0 (Fig. 3). Because the bed of the channel at this site is composed of sediment that is likely to be mobile during these flood events, the pebble count estimation of Z_0 (0.006 m) is less than half the error-minimization Z_0 value of 0.013 m. This difference is likely a result of sediment-transport-induced roughness, channel-bank roughness, and vegetation roughness, and is consistent with Pitlick (1992).

Manning's n values calculated from the model results were n = 0.034 for the 10.6 m^3/s flood and n = 0.036 for the 26.0 m^3/s flood. These calculated Manning's n values are consistent with values for this type of channel (Chow, 1959; Barnes, 1967).

A stage-discharge relation was calculated for the House Rock Wash site using the two modeled flow events, the average zero-flow bed stage, and a discharge estimated for a stage 0.10 m above the zero-flow stage. Because the low-flow channel is relatively steep and smooth, discharge for the zero-flow plus 0.10 m stage was estimated, assuming a Froude number for this flow equal to 1 (critical flow), as:

$$Q = A \cdot \sqrt{g \frac{A}{B}}, \qquad (2)$$

where Q is the discharge (m^3/s), A is the cross-sectional area (m^2), g is acceleration due to gravity (m/s^2), and B is the width of the water surface (m).

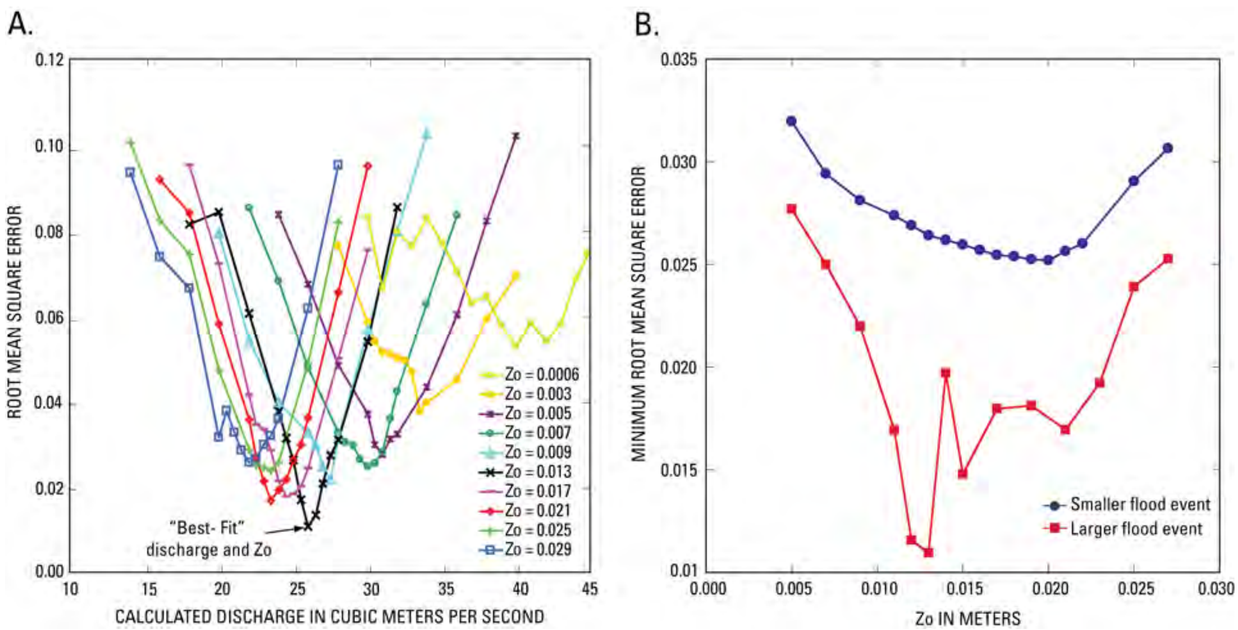

Figure 3 Model results for House Rock Wash showing the relation between Z_0, discharge, and RMS error between the surveyed high-water marks and the model-predicted water-surface elevations. (A) RMS error as a function of model-predicted discharge for a range of Z_0 values. In this case (the larger of the two floods on House Rock Wash—likely 26 m^3/s peak discharge), error is minimized with a Z_0 of 0.013 m. (B) Minimum RMS error as a function of a range of "best-fit" Z_0 values for the larger (likely 26 m^3/s peak discharge) and smaller (likely 10.6 m^3/s peak discharge) flood events on House Rock Wash. As discussed in the text, the RMS error is generally lower at higher modeled discharges, and the minima in RMS error are much more pronounced. Thus, the larger-flood minimum-RMS-error Z_0 of 0.013 m was chosen as the error-minimization Z_0 to hold constant when modeling discharge at this site. A choice of the smaller-flood minimum-RMS-error Z_0 of 0.020 m as the Z_0 to hold constant when modeling discharge at this site, however, would result in only a -9% difference in peak discharge for the larger flood event.

The elevation of the bed at this and other lesser-tributary sites varies only slightly, usually much less than 0.10 m, after floods. These types of small bed-elevation changes do not greatly change the shape or slope of the channel, and therefore do not affect the stage-discharge relation at higher discharges. Thus, to compensate for these small changes in bed elevation, the shifting-control method is used to adjust the stage-discharge relation at stages within 0.10 m of the average zero-flow stage.

Rider Canyon Peak-flood discharge associated with two sets of high-water marks were also modeled for Rider Canyon, the corresponding flows were determined to be 6.3 m^3/s and 26.0 m^3/s by the error-minimization approach for determining the best value of Z_0. By this approach,

Z_0 was determined to be 0.006; because the bed at this site is composed of patches of sand on bedrock, Z_0 could not be estimated based on the bed-sediment grain-size distribution. Manning's *n* values were calculated from the model results for four cross-sections, which were then averaged to yield a Manning's *n* of 0.032 for the 6.3 m^3/s flood and 0.028 for the 26.0 m^3/s flood. These calculated Manning's *n* values are consistent with values for this type of channel (Chow, 1959; Barnes, 1967).

Two 2nd order polynomials, one for discharges greater than 6.3 m^3/s and one for discharges less than 6.3 m^3/s, were fit to the stage-discharge data using the two modeled peak-flood discharges, the average zero-flow bed stage, and the discharge estimated using equation (4) for the zero-flow plus 0.10 m stage. Using this stage-discharge relation and the stage record, the discharge record was computed. Comparison of the Rider Canyon discharge record with the discharge record from House Rock Wash (located approximately 1.5 km upstream) shows flood-peak attenuation between the two sites as well as more water passing the Rider Canyon site (Fig. 4). The larger volume of water passing the Rider Canyon site is the likely result of water being supplied by Emmett Wash, which enters between the two sites.

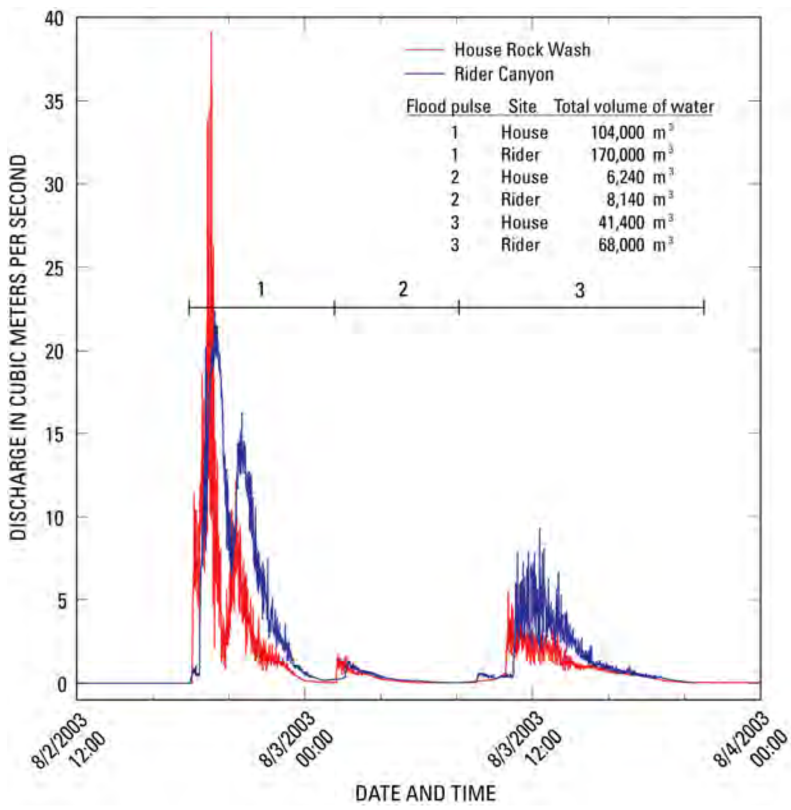

Figure 4 Comparison of several flood events passing the House Rock Wash and Rider Canyon sites.

The floods shown in Figure 4 represent the majority of the discharge past the House Rock Wash and Rider Canyon monitoring sites for the year 2003. During 2003, there were only two other large flood events, with peak discharges of 15.2 and 11.4 m^3/s, both of which were of shorter duration. Based on the average suspended-sand concentration and average suspended-silt and clay concentration among all samples collected at the Rider Canyon site, the floods shown in Figure 4 transported approximately 13,500 metric tons of sand and 23,000 metric tons of silt and clay into the Colorado River.

SUMMARY

Using the quasi-three-dimensional model (FaSTMECH) in MD_SWMS, stage-discharge relations can be constructed at remote sites on ephemeral streams, where discharge measurements are extremely difficult and impractical to obtain. Stage-discharge relations are developed by generating a topographic map of the stream channel and modeling a number of flood events with different peak discharges. The approach used to model the flood events is to: (1) enter a "best guess" flood discharge and Z_0 roughness parameter for the first model run, (2) perform successive model runs varying the discharge and Z_0 to minimize the root-mean-square error between modeled and measured high-water marks, and (3) hold the "best-fit" Z_0 constant to model the peak-flood discharges associated with the sets of high-water marks. The stage-discharge relations developed from these methods can be used in conjunction with stage and suspended-sediment data to compute sediment loads. Prior to this study, only relatively crude estimates of the importance of the lesser tributaries in lower Glen, Marble, and Grand Canyons tributaries as a source of sediment for the Colorado River existed. The enhanced ability to calculate sediment loads in the lesser tributaries made possible by this study will therefore provide much-needed information into the relative importance of these tributaries in supplying sediment to the Colorado River in Grand Canyon National Park. Furthermore, the methods developed herein can easily be used to accurately compute discharge and sediment loads at other remote locations where information on discharge and sediment loads is needed.

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