WATER RESOURCES RESEARCH, VOL. 42, W11411, doi:10.1029/2005WR004847, 2006

Click Here for Full Article

Debris flow deposition and reworking by the Colorado River in Grand Canyon, Arizona

Brian J. Yanites,[1] Robert H. Webb,[2] Peter G. Griffiths,[2] and Christopher S. Magirl[2]

Received 30 December 2005; revised 15 June 2006; accepted 26 July 2006; published 18 November 2006.

[1] Flow regulation by large dams affects downstream flow competence and channel maintenance. Debris flows from 740 tributaries in Grand Canyon, Arizona, transport coarse-grained sediment onto debris fans adjacent to the Colorado River. These debris fans constrict the river to form rapids and are reworked during river flows that entrain particles and transport them downstream. Beginning in 1963, flood control operations of Glen Canyon Dam limited the potential for reworking of aggraded debris fans. We analyzed change in debris fans at the mouths of 75-Mile and Monument Creeks using photogrammetry of aerial photography taken from 1965 to 2000 and supplemented with ground surveys performed from 1987 to 2005. Our results quantify the debris fan aggradation that resulted from debris flows from 1984 to 2003. Volume, area, and river constriction increased at both debris fans. Profiles of the two debris fans show that net aggradation occurred in the middle of debris fans at stages above maximum dam releases, and surface shape shifted from concave to convex. Dam releases above power plant capacity partially reworked both debris fans, although reworking removed much less sediment than what was added by debris flow deposition. Large dam releases would be required to create additional reworking to limit the rate of debris fan aggradation in Grand Canyon.

Citation: Yanites, B. J., R. H. Webb, P. G. Griffiths, and C. S. Magirl (2006), Debris flow deposition and reworking by the Colorado River in Grand Canyon, Arizona, *Water Resour. Res.*, *42*, W11411, doi:10.1029/2005WR004847.

1. Introduction

[2] Thresholds of erosion in landscape evolution studies have been shown to greatly influence the rate of erosion in various environments [*Snyder et al.*, 2003; *Tucker*, 2004; *Kirkby*, 1994; *Talling*, 2000]. In many cases, these studies are concerned with long-term rates of fluvial or hillslope erosion and ignore recent anthropogenic influences on the system, which may be much more significant in terms of rate of change. Construction and operation of dams has changed hydrological conditions along rivers downstream [*Collier et al.*, 1996], thereby disrupting any steady or quasi-steady state that the fluvial system may have had with the surrounding topography. For large rivers, such as the Changjiang (Yangtze) in China, flow regulation has significantly reduced sediment transport, which is expected to cause large-scale erosion problems downstream and in its delta [*Yang et al.*, 2006].

[3] One of the greatest changes instituted by flood control operations on major rivers is a decreased river competence, which potentially leads to increased rates of aggradation of coarse sediment that affects channel maintenance. By measuring changes in rates of aggradation or degradation influenced by flow conditions in the river, the sensitivity of the system to changes in the flow variability can be assessed. This has important implications in regulated rivers, such as the Colorado River through Grand Canyon (Figure 1), where dam operations have altered the river's state from a highly variable discharge with large spring floods and low winter flows to a fluvial systems that varies diurnally, not seasonally, with greatly reduced amplitude (Figure 2). Examples of a transient landscape, such as ones caused by flow regulation, can demonstrate the dependence on a system's ability to produce conditions that exceed a transport threshold.

[4] Debris flows are an important sediment transport process in river canyons of the Colorado Plateau [*Webb et al.*, 2000, 2004; *Larsen et al.*, 2004; *Grams and Schmidt*, 2002] and elsewhere [*Whipple and Dunne*, 1992; *David-Novak et al.*, 2004]. Distributed along 444 km of river between the Paria River and the Grand Wash Cliffs, 740 debris flow producing tributaries of the Colorado River drain 12,000 km^2 of steep terrain in Grand Canyon [*Webb et al.*, 1989; *Griffiths et al.*, 2004]. These tributaries produce debris flows which are typically more than 80% sediment by weight with individual particles ranging from fine clays to boulders, some of which have a b axis diameter greater than 2 m. Debris flows deposit their poorly sorted sediment load onto a debris fan and into the channel, constricting the Colorado River until its flows rework coarse-grain deposits to remove or reposition boulders and finer particles [*Webb et al.*, 1999b; *Pizzuto et al.*, 1999]. When submerged, the remaining boulders are subject to dissolution and corrasion by lesser river flows, which is a much slower process.

[5] The large boulders deposited in the river by debris flows form the core of rapids that shape the longitudinal

[1]Department of Geological Sciences, University of Colorado, Boulder, Colorado, USA.
[2]U.S. Geological Survey, Tucson, Arizona, USA.

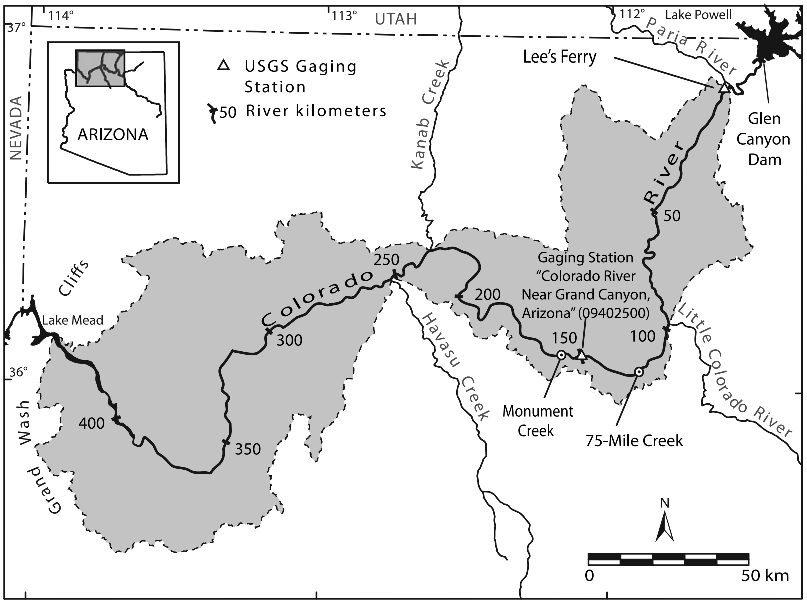

Figure 1. Map of the Colorado River in Grand Canyon, Arizona. Shaded area represents the drainage area of the Colorado River between the Paria River and Grand Wash Cliffs, excluding the Little Colorado River, Kanab Creek, and Havasu Creek. Canyon rims are denoted by the dashed line.

water surface profile [*Hanks and Webb*, 2006] and locally control the geomorphic framework of the Colorado River in Grand Canyon [*Howard and Dolan*, 1981; *Webb*, 1996], creating fan-eddy complexes conducive to deposition of sandbars [*Schmidt and Graf*, 1990; *Schmidt and Rubin*, 1995]. Despite reworking during floods, the riverbed has risen at tributary confluences during the Holocene [*Webb et al.*, 1999a; *Hanks and Webb*, 2006] and historically [*Magirl et al.*, 2005] owing to debris flow deposition. Rapids account for most of the vertical fall of the river in Grand Canyon; in 2000, 66% of the drop occurred in 9% of the modern river's length [*Magirl et al.*, 2005], which is significantly higher than the previously reported 50% drop in 9% of the length estimated using 1923 data [*Leopold*, 1969].

[6] Following *Howard and Dolan* [1981], *Magirl et al.* [2005] suggested, but could not demonstrate, that the 20th century increase in the fall through rapids in Grand Canyon was related to operations of Glen Canyon Dam, which was completed in 1963. Because no canyon-length data exist for the status of rapids in 1963, the question of the effect of Glen Canyon Dam on aggradation in rapids remains unresolved. A better understanding of annual variations of debris fan morphology is critical to understanding the effects of dam operations on reworking processes in the Grand Canyon river corridor and will contribute to a broader understanding of the short- and long-term impacts human activity can have on channel morphology.

[7] In this study, we combine ground surveys with photogrammetric analyses of high-frequency, small-scale aerial photography to quantify topographic changes on two debris fans for the period 1965–2005. These debris fans, at the mouths of 75-Mile Creek and Monument Creek

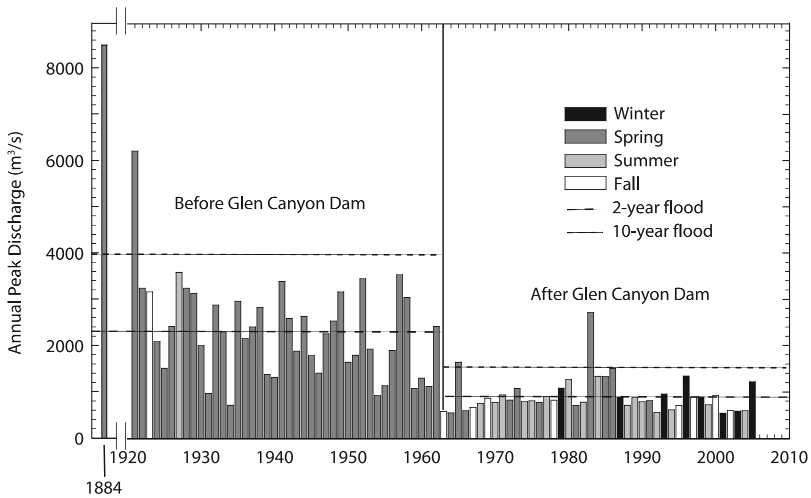

Figure 2. Annual peak flood series for the Colorado River near Grand Canyon, Arizona (USGS gauging station 09402500; see Figure 1) showing discharges for the 2- and 10-year floods before and after operations of Glen Canyon Dam.

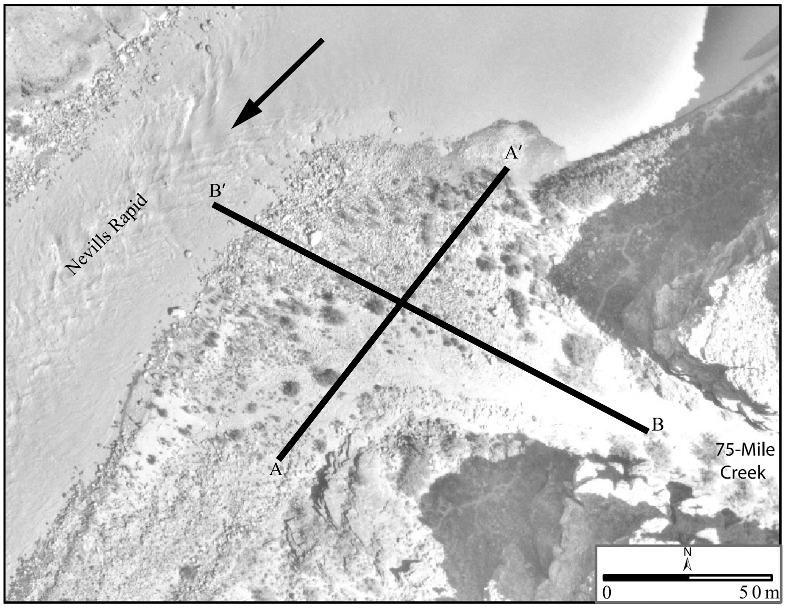

Figure 3. Aerial photograph of 75-Mile Creek taken 2 September 1996. Locations of profiles for Figure 6 are shown as A-A′ and B-B′. Direction of river flow is indicated by the arrow.

(Figure 1), were chosen for their relatively frequent debris flow occurrence [*Webb et al.*, 1988; *Melis et al.*, 1994]. Using high-resolution photogrammetric techniques, we document changes over four decades and annual changes from 1984 to 2000 that reflect the net effects of debris flow deposition and river reworking in Grand Canyon. This paper contributes a unique data set of topographical changes of debris fans during a transient response to a new hydrological flow regime imposed by Glen Canyon Dam operations.

2. Background

[8] Beginning in 1963, operations of Glen Canyon Dam altered the flow regime of the Colorado River through the Grand Canyon (Figure 1). Before flow regulation, annual peak discharges averaged 2650 m^3/s and were as large as 5900 m^3/s [*O'Connor et al.*, 1994; *Topping et al.*, 2003]. Flows of this magnitude can entrain most particles present in debris flow deposits, in some cases leaving winnowed, reworked accumulations of boulders >1 m b axis diameter [*Melis*, 1997]. After dam operations began, the average annual peak discharge decreased to 932 m^3/s (Figure 2), which has decreased the amount of reworking of new debris flow deposits [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1999b]. Many researchers have shown that flow regulation by Glen Canyon Dam reduced the 2- and 10-year floods by 38 and 40%, respectively [*Howard and Dolan*, 1981; *Schmidt and Graf*, 1990; *Webb et al.*, 1999c; *Topping et al.*, 2003].

[9] The largest flood in the postdam era peaked at 2720 m^3/s in 1983 and resulted in significant reworking of the Crystal Creek debris fan [*Kieffer*, 1985; *Webb et al.*, 1989]. Annual peak discharges of 1340–1520 m^3/s occurred in 1984, 1985, and 1986 (Figure 2). In March 1996, dam outlet works were used to produce a flood release that had a peak discharge of 1350 m^3/s and lasted 7 days. *Webb et al.* [1999b] showed that debris fan reworking during the 1996 flood was a function of both local stream power and the elapsed time between debris flow emplacement and the flood. Regulated flow continued on the river until November 2004, when another controlled flood with a peak discharge of 1220 m^3/s was released to benefit the downstream ecosystem.

[10] Debris flow monitoring in Grand Canyon began in 1986 at Monument Creek [*Webb et al.*, 1988]. The methods used to document dimensional changes include ground surveys of debris fans aggraded between 1984 and 2003 and two-dimensional photogrammetric analyses of aerial photography [*Webb et al.*, 1999b]. Although the point accuracy of ground surveys is high (<1 cm), the topographic roughness created by debris flow deposition of poorly sorted sediments, combined with limited spatial acquisition of points during ground surveys, suggests that other methods of producing digital terrain models may be useful for debris fan monitoring. Abundant aerial photography, taken annually between 1984 and 2000 and supplemented with light detection and ranging (lidar) in 2000, can be used to document changes in debris fan dimensions. High-resolution photogrammetric analyses have sufficient accuracy to estimate geomorphic changes [*Lane et al.*, 2000]. In addition, photogrammetry can be used to produce topographic models of debris fans for years that ground surveys were not conducted, extending the retrospective topographic data back to the initial small-scale aerial photography taken in 1965.

3. Geomorphic Setting

3.1. The 75-Mile Creek

[11] The channel of 75-Mile Creek, 122 km downstream from Lee's Ferry, empties onto a large debris fan that controls Nevills Rapid (Figure 3). While a significant rapid, Nevills Rapid has a fall of 4.78 m but is not as imposing as other rapids nearby [*Stevens*, 1983]. Since the start of debris flow monitoring in 1986, we observed four debris flows at 75-Mile Creek (August 1987, September 1990, August 2001, and August 2003). As determined from repeat pho-

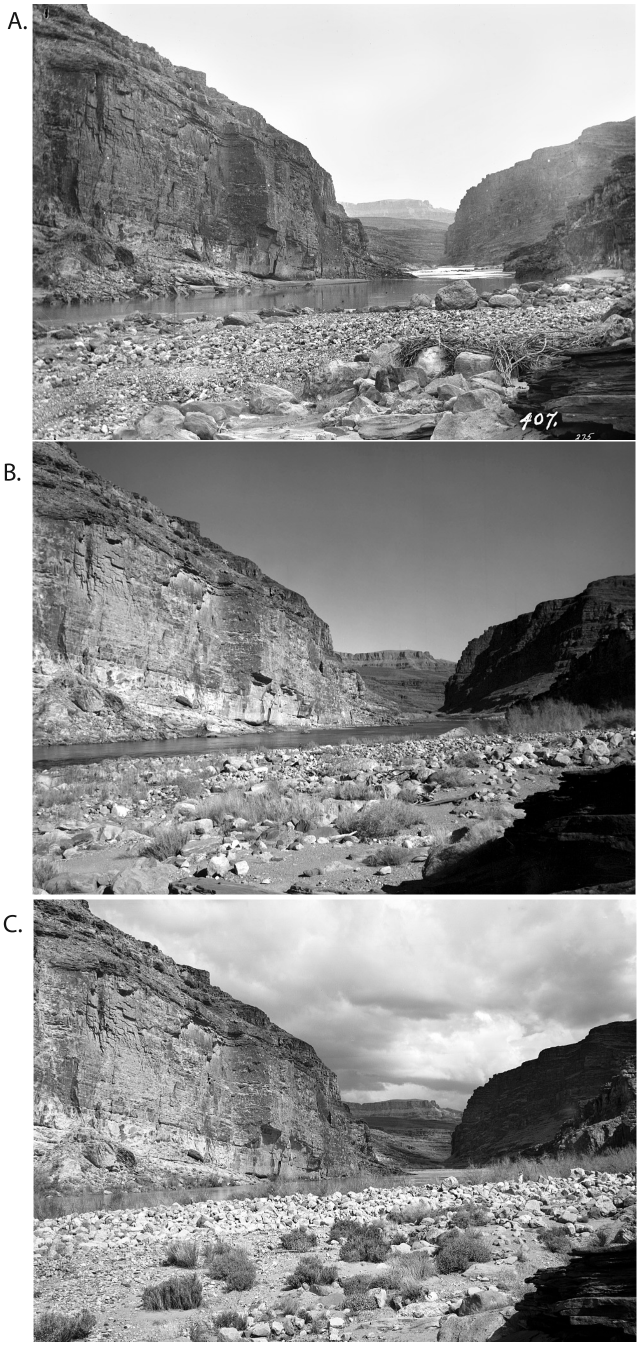

Figure 4. Photographs of the mouth of 75-Mile Creek at Nevills Rapid (RM 75.5), showing aggradation of the debris fan from 1890 to 2005. The views are upstream and taken from river left. (a) From 25 January 1890. This view, the first image of the debris fan, shows that a debris flow occurred shortly before the photographer arrived at the site. The boulder at right center is 4 m in b axis diameter. Discharge in the river is about 141 m^3/s. (R. B. Stanton 407, courtesy of the National Archives and Records Administration). (b) From 27 January 1990. The debris flow of August 1987 nearly covered the large boulder at right center. Discharge in the river is about 141 m^3/s (R. Hopkins). (c) From 6 March 2005. Debris flows in 1990, 2001, and 2003 caused significant aggradation of the debris fan, obscuring the view of the large boulder. Discharge in the river is about 566 m^3/s (S. Young, stake 1445).

tography, at least one other debris flow occurred between 1890 and 1960 [*Melis et al.*, 1994]. The basin has a total relief of 1531 m and drains 11.47 km^2. Recent debris flows were initiated on the south, footwall side of this fault-controlled drainage. A long bar extending 500 m downstream from the fan is composed of intact and reworked Holocene debris flow deposits. The median diameter of the 1987 debris flow deposits was 128 mm [*Melis et al.*, 1994].

[12] The earliest ground photograph documenting conditions on the 75-Mile Creek debris fan was taken in 1890, and subsequent matches (Figure 4; for color versions of recent photographs, see auxiliary material[1], Figure S1) reveal that considerable aggradation has occurred in the last 115 years. Riparian vegetation has increased on both sides of the active area of deposition, and this vegetation affects photogrammetric reconstruction of debris fan volume (see below). A total of 23 sets of aerial photographs between 1935 and 2000 are available for photogrammetric analyses of the 75-Mile Creek debris fan (Table 1). The 1935 photographs did not have overlap, and the lack of stereographic coverage precludes their use in development of orthophotographs (see section 3.2).

3.2. Monument Creek

[13] Monument Creek, which forms Granite Rapid (Figures 5a and 5b), drains 9.73 km^2 of steep terrain with a maximum relief of 1413 m and enters the Colorado River 151 km downstream from Lee's Ferry. A more formidable navigational obstacle than Nevills Rapid, Granite Rapid falls 5.24 m and is one of the largest drops in Grand Canyon. Five debris flows have reached the Colorado River at Monument Creek in the last 40 years (1966–1967, July 1984, July 1996, August 2001, and August 2003). Other streamflow floods deposited fine-grained sediments and scoured new channels through the debris fan in the late 1990s, altering its shape.

[14] Previous work has described flow through Granite Rapid [*Kieffer*, 1987] and changes in the debris fan that resulted from the 1984 debris flow [*Webb et al.*, 1988, 1989]. Particle size analyses of the 1984 deposits indicated a median particle diameter of 24 mm; reworked deposits had a median particle diameter of 720 mm [*Webb et al.*, 1988]. A large island consisting of reworked debris flow deposits occurs approximately 100 m downstream from the fan; this island, which is separated from the rapid by a pool, is exposed at discharges lower than $\sim$1000 m^3/s. Higher debris flow deposits on the downstream margin of the debris fan are of Holocene age.

[15] A total of 23 sets of aerial photographs are available for Granite Rapid from 1935 to 2000 (Table 1). As in the case of 75-Mile Creek, the 1935 photographs were not used because they lacked sufficient overlap for stereographic coverage. The earliest ground photographs of the mouth of Monument Creek, taken in 1872, have been repeatedly matched [*Stephens and Shoemaker*, 1987, pp. 238–239], and the combined views (Figure 6; for color versions of recent photographs, see auxiliary material, Figure S3) show significant aggradation has taken place on the debris fan. By 1968, debris flow deposition had already constricted the river channel significantly. Aggradation of the surface by

[1]Auxiliary materials are available in the HTML. doi:10.1029/2005WR004847.

Table 1. Aerial Photography Used to Analyze Changes at 75-Mile and Monument Creeks

Aerial Photograph Date[a]	Estimated Discharge, m^3/s	Scale	Pixel Resolution, cm	RMSE, pixels	RMSE of Z (m) for Check Points
75-Mile Creek					
1935[b]	~170	–	–	–	–
5/14/1965	680–792	1:12000	19.05	–	–
6/17/1973	76–396	1:14400	22.86	–	–
7/11/1980	708	1:3600	–	–	–
6/8/1982	354	1:37000	–	–	–
6/24/1982	425	1:37000	–	–	–
10/22/1984	144–227	1:3000	4.76	0.6100	0.311
6/7/1985	993	1:4800	–	–	–
5/28/1988	320	1:4800	7.62	0.7610	0.2572
10/8/1989	142	1:6000	9.53	0.6009	0.3680
6/3/1990	142	1:4800	7.62	–	–
6/30/1991	142	1:4800	7.62	–	–
6/30/1992	227	1:4800	7.62	0.6727	0.3236
5/31/1993	227	1:4800	7.62	0.3971	0.2979
5/30/1994	227	1:4800	7.62	0.6743	0.3135
5/29/1995	227	1:4800	7.62	0.5101	0.1931
3/24/1996	227	1:4800	7.62	0.7003	0.3919
4/6/1996	227	1:4800	7.62	0.4789	0.3074
9/2/1996	227	1:4800	7.62	0.7078	0.3907
9/1/1997	227	1:4800	7.62	0.6712	0.2716
9/6/1998	439	1:4800	7.62	0.8603	0.3581
9/5/1999	439	1:4800	7.62	0.9460	0.3048
7/2/2000	227	1:4800	10.00	0.7707	0.3902
Monument Creek					
1935[b]	~170	–	–	–	–
5/14/1965	680–792	1:12000	19.05	–	–
6/17/1973	76–396	1:14400	22.86	–	–
6/8/1982	354	1:37000	–	–	–
6/14/1982	340	1:37000	–	–	–
10/22/1984	144–227	1:3000	4.76	0.7764	0.2429
6/7/1985	1019	1:4800	–	–	–
6/14/1986	227	1:4800	–	–	–
5/25/1988	320	1:4800	7.62	–	–
10/7/1989	142	1:6000	9.53	0.9232	0.3166
6/3/1990	142	1:4800	7.62	0.6818	0.2423
6/30/1991	142	1:4800	7.62	0.5246	0.3878
10/12/1992	227	1:4800	7.62	0.5739	0.2859
5/31/1993	227	1:4800	7.62	0.4742	0.3448
5/30/1994	227	1:4800	7.62	0.7394	0.2287
5/29/1995	227	1:4800	7.62	0.4213	0.3855
3/25/1996	227	1:4800	7.62	0.8002	0.2922
4/6/1996	227	1:4800	7.62	0.9175	0.3388
9/2/1996	227	1:4800	7.62	0.9412	0.3666
9/1/1997	227	1:4800	7.62	0.5336	0.2644
9/6/1998	439	1:4800	7.62	0.8570	0.3828
9/5/1999	439	1:4800	7.62	0.6781	0.2689
7/2/2000	227	1:4800	10.00	0.9076	0.3350

[a]Read 5/14/1965 as 14 May 1965.
[b]Not used in the photogrammetric analyses because the views do not have significant overlap.

debris flows and the increase in riparian vegetation has nearly blocked any view of the river from this camera station by 2005. As with the debris fan at 75-Mile Creek, the increase in riparian vegetation at Monument Creek is substantial and affects the photogrammetric analyses.

4. Methods

[16] We used a combination of ground surveys and photogrammetric analyses of historical aerial photography to document changes in the debris fans at the mouths of 75-Mile and Monument Creeks. Previous studies have shown that photogrammetry of small-scale aerial photography is an effective tool in extracting morphological information from digital terrain models (DTMs) [*Brasington et al.*, 2003; *Lane et al.*, 2000]. Our approach was to combine ground surveys conducted from 1986 to 2005 with analog and digital imagery, mostly from the Grand Canyon Monitoring and Research Center (GCMRC) in Flagstaff, Arizona. *Lane et al.* [2003] showed that photogrammetric techniques may produce more reliable volume estimates than ground surveys because photogrammetric techniques produce high-density spatial data even though the precision from point to point may be lower. In our analyses, the photogrammetric technique produced up to 20,000 three-dimensional points, significantly more than the typical <750 points obtained during conventional ground survey.

4.1. Ground Survey and Image Acquisition

[17] Debris flow monitoring in Grand Canyon [*Melis et al.*, 1994; *Webb et al.*, 2000, 2005] resulted in surveys of the debris fans at 75-Mile and Monument Creeks at various

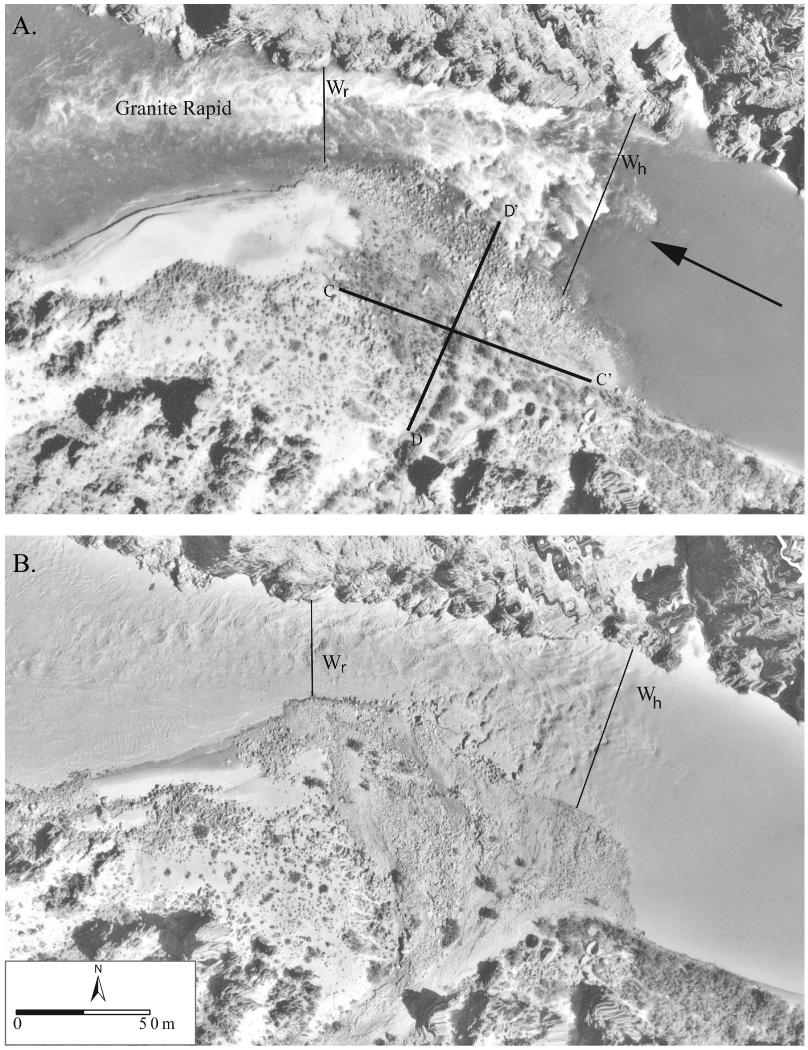

Figure 5. Comparison of aerial photographs for Monument Creek showing aggradation on the debris fan from the 1996 debris flow. (a) From 6 April 1996. Lines representing the maximum constriction (W_r) and constriction at the head of the rapid (W_h) are shown. Thicker lines represent profiles C-C′ and D-D′. The arrow indicates flow direction. (b) From 2 September 1996. The maximum constriction (W_r) has not changed, but constriction at the head of the rapid (W_h) has increased, and the distribution of new debris flow deposits is apparent.

times from 1986 to 2005 (Table 2). Some of these surveys did not include enough coverage to produce a water surface profile fully through the rapid. For 75-Mile Creek, surveys of the water surface profile through Nevills Rapid were completed in October 2003 and March 2005; similarly, profiles of Granite Rapid were surveyed in March 1999, October 2001, March 2003, and March 2005 (Table 2). In March 2005, the surveys at 75-Mile Creek and Monument Creek had 739 points and 607 points, respectively. Because of the cyclic diurnal nature of releases from Glen Canyon Dam, any survey measurements relative to the water surface need to be normalized to allow direct comparison with other points within a survey or from points from a different survey. For each water surface survey point, the time of survey was noted and tied to discharge values reported at the nearest Grand Canyon gauge. Thus knowing the discharge for a measured survey point, values of each water surface elevation were normalized to a standard 227 m3/s from the stage-discharge relationship predicted using a step-backwater model constructed for the Colorado River in Grand Canyon (C.S. Magirl, U.S. Geological Survey, unpublished data, 2005). Though the precision, or accuracy, of the predicted stage-discharge relationships cannot be independently determined at 75-Mile or Monument Creek, comparison of the stage-discharge relationships with known stage-discharge sites elsewhere in Grand Canyon show a correction error no greater than 0.17 m (J.E. Hazel Jr., Northern Arizona University, personal communication, 2005). These normalized water surface profiles were compared to each other and to a water surface profile constructed from lidar data collected in May 2000 [*Magirl et al.*, 2005]. The values reported for each water surface profile are relative to an ellipsoid surface (NAVD 88).

[18] From 1984 to 2000, stereographic aerial photographs had been taken at least annually at similar discharge, typically from 142 to 227 m^3/s (Table 1). Several other sets

Figure 6. Photographs of the debris fan at the mouth of Monument Creek and Granite Rapid showing aggradation from 1872 to 2005. The views are upstream and taken from river left. (a) From 1 September 1872. This view shows a high river discharge of 1700–2300 m^3/s (J. K. Hillers 871, courtesy of the National Archives and Records Administration). (b) From 16 September 1968. This view shows a wide rocky rapid before the debris flows from 1984 through 2001. A debris flow occurred a short time before this photograph was taken. Discharge in the river is about 221 m^3/s (H. Stephens). (c) From 30 January 1990. This view shows the net effects of the 1984 debris flow and reworking by high flows from 1984 through 1986. The sandbar apparent in Figures 6a and 6b has been eliminated. Discharge in the river is about 141 m^3/s (T. Brownold). (d) From 8 March 2005. This view shows the net effects of debris flows in 1996, 2001, and 2003 and reworking by the river flood of 1175 m^3/s in 2004. The newly established vegetation affects the volume model. Discharge in the river is about 566 m^3/s (B. Quayle, stake 1462).

of photographs were taken before 1984 at higher discharges than after 1984 and generally are of larger scale. Photographs were taken with metric film cameras or, beginning in 2000, with a variety of digital frame and metric cameras. Photograph diapositives were digitized using an Epson Expression 1640XL scanner at a resolution of 1600 dpi (15.875 μm). Previous studies have shown this resolution provides the optimal balance between retention of information and noise levels [*Davis et al.*, 2002]. All images, whether gray scale, color, or color infrared, were scanned in gray scale; image balance processing maximized debris fan texture while maintaining acceptable noise levels for photogrammetric analysis.

4.2. Photogrammetric Model

[19] Photogrammetric models were created using the Leica Photogrammetry Suite (LPS) associated with ERDAS Imagine 8.7 image-processing software. Processed stereo-

Table 2. Ground Surveys of 75-Mile and Monument Creeks Made From 1986 to 2005

Date of Survey	Water Surface Profile?	Daily Discharge,[a] m^3/s
	75-Mile Creek	
10/22/87	no	245
5/9/92	yes	306
10/30/03	yes	242
3/6/05	yes	427
	Monument Creek	
3/25/86	no	767
3/13/99	yes	399
10/30/01	yes	297
5/16/02	yes	308
3/25/03	yes	385
11/02/03	yes	241
3/08/05	yes	410

[a]Uncertainty in the discharge at the time of survey may be as high as 170 m^3/s for some dates with strongly fluctuating flows.

pairs were imported into a block file. The LPS software uses a bundle-block adjustment that simultaneously produces solutions for all images in the file utilizing an iterative least squares adjustment, which solves for the unknown parameters while minimizing error of the input data [*ERDAS*, 2001]. The exterior orientation parameters (i.e., location of the camera during exposure) were calculated using this procedure.

[20] Interior orientation parameters available from the aerial camera's calibration included calibrated focal length, position of fiducial marks, and radial distortion values. Establishment of numerous, well-distributed ground control points (GCPs), which are distinguishable features that help establish the relation among the ground, camera/sensor, and image, were acquired from lidar collected in March 2000 at a constant discharge of 227 m^3/s [*Davis et al.*, 2002]. The lidar data provided the geospatial data needed to locate GCPs (15–20 in most cases) and check points that were used to test the accuracy of the photogrammetric models. GCPs were allowed to deviate slightly from the inputted values (0.1 m), which is within the range of error reported by *Davis et al.* [2002] for lidar points.

[21] Tie points (40–100 per block file) were used to establish the relative orientation between the two-dimensional photographs using an automated tie point generation function within the LPS. Triangulation was performed on the model using the bundle-block adjustment method explained above and in more detail by *ERDAS* [2001]. Triangulation results were accepted if the root-mean-square error (RMSE) of the independent check points was less than 0.40 m (Table 1). Using an automatic extraction tool, DTMs were created in the form of three-dimensional shapefiles. Optimized point collection parameters were determined by following the methods outlined by *Gooch and Chandler* [1999] and were set to improve the quality of matches.

4.3. Data Postprocessing

[22] Topographic data generated using the photogrammetric analyses were postprocessed to remove all points within the river, readily identified trees and shrubs, and any other features that were not part of the debris flow deposits. For each pixel match, a correlation coefficient, r, was calculated between 5 pixel by 5 pixel windows used in the matching procedure [*ERDAS*, 2001]. The quality of each point (generated by a pixel match) was designated within the categories of excellent, good, fair, poor, and suspicious. A point was designated excellent if $r \geq 0.90$, good if $0.80 \leq r < 0.90$, or fair or poor if $r < 0.80$; fair and poor matches were rejected. In addition, each point elevation was compared to the average elevation of points within a 0.5 by 0.5 m window, and the difference of the average elevation and point elevation was compared to the standard deviation of the neighboring extracted elevation values outside that window; if the difference was greater than 3σ, the point was deemed suspicious and was removed [*ERDAS*, 2001]. Finally, preliminary triangular-integrated networks (TINs) were produced and overlain on orthorectified images to check for visually obvious inaccuracies, such as anomalous elevation spikes on smooth sandbars and depressions on debris fans deeper than the river level, that were not otherwise detected.

4.4. Morphological Derivatives

[23] The shapefiles extracted from each set of aerial photographs were used to create TINs with no data smoothing. For consistency among volumetric calculations and to provide absolute interannual comparisons, a base plane elevation, or a horizontal plane of constant elevation underlying the debris fan, was established at 785 and 714 m for 75-Mile Creek and Monument Creek, respectively. These elevations are somewhat arbitrary in that they were selected to ensure that all elevation data would lie above the respective planes to avoid negative space in the volume calculations; therefore the volume data presented later is not an absolute volume since the bottom boundary condition for these debris fans is unknown. The edges of the debris fan were delineated using 1992 and 1999 survey data for 75-Mile Creek and Monument Creek, respectively. These boundaries were adjusted for years in which debris flow deposits extended beyond the previously defined boundary. Debris fan boundaries varied because slight variations in stage or debris fan morphology have a large effect by exposing or covering boulders resolvable in the imagery.

[24] Profiles of debris fan surfaces approximately parallel and perpendicular to the river (Figures 3 and 5) were produced for the earliest and more recent surface models as well as years before and after each known debris flow. Quantifying pre-1984 surface conditions is difficult owing to the limited number of years with stereographic aerial photography, the low resolution of the available imagery, and the variable discharge of the Colorado River at the time of the overflights. Despite these problems, debris fan area and river constriction could be extracted from these early photographs.

[25] Previous studies of river constriction by debris fans quantified the maximum constriction of the river through the rapid [*Kieffer*, 1985; *Schmidt and Graf*, 1990; *Webb et al.*, 1999b]. We estimated percent constriction (C_w) using

$$C_w = 100\left\{1 - \left[2W_r(W_u + W_d)^{-1}\right]\right\}, \quad (1)$$

where W_r is the width of the river at the narrowest section through the rapid, W_u is the width upstream of the rapid, and W_d is the width downstream of the rapid. We also used a second method developed to account for the effects of the July 1996 debris flow at Monument Creek (Figure 4). Because most of the deposition during this event occurred upstream from the narrowest point of the rapid and was therefore undetected by equation (1), we estimated an average constriction, C_a, by incorporating an area/length ratio of the rapid and the upstream and downstream stretches of river using

$$C_a = 100 \cdot \left\{1 - \left[(A_r/L_r) \cdot (A_{ud}/L_{ud})^{-1}\right]\right\}, \qquad (2)$$

where A_r and L_r are the area and length of the rapid, respectively, and A_{ud} and L_{ud} are the average area and length of the upstream and downstream reaches associated with the rapid. This method integrates the width along the entire debris fan as well as in the pools upstream and downstream and reflects net change along the entire fan-eddy complex instead of just at the narrowest constriction.

4.5. Discharge Correction

[26] For some surface models collected at discharges less than or greater than 227 m^3/s, a significant amount of the debris fan was either exposed or submerged. To allow interannual comparison of volumes, we normalized the area of the fan to the average of the photographs taken at 227 m^3/s. For higher discharges, we conservatively assumed that the submerged surface was just below water level, and the volume was then calculated using the base plane selected for each debris fan. Corrections were made for the 1998 and 1999 photographs, which were flown at a steady discharge of 439 m^3/s, and the 2005 survey of Monument Creek. Between 1989 and 1991 (Table 1), aerial photographs were taken at a discharge of 141 m^3/s, and the 1984 photographs were taken at discharges ranging between 144 and 227 m^3/s, exposing additional debris fan surface. By using the previously defined base planes, we evaluated change in the debris fans above the 227 m^3/s stage.

4.6. Quality Assessment of Digital Terrain Models

[27] Acceptance of DTMs requires a rigorous analysis of qualitative and quantitative tests [*Cooper and Cross*, 1988; *Pyle et al.*, 1997; *Butler and Chandler*, 1998]. Distortion of orthophotographs produced using the extracted DTMs provides an initial qualitative assessment. Sections with distortion suggest a poor surface model, whereas little or no distortion indicates an acceptable model. Resultant TINs were overlain on orthophotographs and assessed on relative representation of surface features, such as sandbars, river banks, incised channels, old debris flow terraces, and active surfaces.

[28] Three methods were used to quantify the overall performance of the photogrammetric analyses: (1) the precision, or the internal expectance, of the bundle adjustment model used to evaluate the quality of the pixel-matching algorithm; (2) the accuracy, or comparison, of photogrammetric results to independent check points; and (3) the reliability, or measure of the reproducibility, of surface models extracted from separate stereopairs of the same overflight. The least squares adjustment, which measures stereomatching precision, calculates the RMSE between the predicted and the actual pixel-matching location; all RMSEs were less than 1 pixel (Table 1). The accuracy of each DTM was analyzed based on the RMSE calculated for at least 5 independent check points in each photogrammetric model, which assessed the ability to predict real coordinate values. We rejected DTMs with a RMSE > 0.3919 m for the vertical (z) component of check points (Table 1); the mean RMSE was 0.3136 ± 0.055 m, which shows a consistent accuracy. Reliability was assessed using DTMs produced from 1999 images of the Monument Creek debris fan; a linear regression of 41 random points yielded $r^2 = 0.98$, which shows highly correlated fan surfaces and reflects the reproducibility of our procedure.

[29] In these tests, residuals were found to have random orientation. With no detectable systematic error in the DTMs and assuming a Gaussian error distribution [*Lane et al.*, 2003], the derived volumes appear to be accurate. Using an RMSE of 0.5 pixels and a pixel size of 7.6 cm, the error is ±3.8 cm per pixel; for an entire debris fan, the error in area is approximately ±15 m^2 and ±0.2%, or much less than the uncertainty caused by variability in discharge. *Webb et al.* [1999b] reported an implied accuracy of ±50 m^2 in area, underscoring our improvement in accuracy over their two-dimensional photogrammetric analyses. We assumed that the uncertainty in vertical thickness of volume can be represented by ±1 median particle diameter, which yields an error in volume of approximately ±1000 m^3. Because of the high-quality surface models and high point density, our results likely have greater accuracy than previous debris fan volumes reported for Grand Canyon [e.g., *Melis et al.*, 1994].

5. Results

[30] As indicated by the repeat photography (Figures 4 and 6), both debris fans significantly aggraded over the period of aerial photography and direct survey. Between 1984 and 2005, the volume of the 75-Mile Creek debris fan increased by more than 10,000 m^3; likewise, the Monument Creek debris fan increased almost 8000 m^3 (Table 3 and Figure 7). Not unexpectedly, the largest volume increases were recorded in aerial photograph intervals when debris flows are known to have occurred; the largest decreases followed high river discharges that reworked the distal margins of debris fans. Both fans gradually increased in volume between June 1992 and March 1996, a period of no debris flow activity and normal dam releases. In subsequent years, debris fan volumes were relatively stable.

5.1. Changes in the Debris Fan at 75-Mile Creek

[31] The area of the 75-Mile Creek debris fan was smallest in 1965 and 1973 (Figure 7b and Table 3), but high river discharge during the aerial photography (Table 1) reduces the certainty of this conclusion. The 1984 aerial photographs provided the initial volume estimate for this debris fan (Table 3). A debris flow in August 1987 increased the fan volume by about 4200 m^3, and a second debris flow in 1990 caused an increase of nearly 9800 m^3, a value similar to the previous estimate of 12,000 m^3 [*Melis et al.*, 1994]. A peak discharge of 966 m^3/s in January 1993 (Figure 2) reworked the distal margin of this debris fan, causing a volume decrease of ∼2900 m^3. A gradual increase totaling just over 5200 m^3 occurred between May 1993 and March 1996 and probably reflects the net effects of sand deposition on the debris fan margins and growth of riparian vegetation.

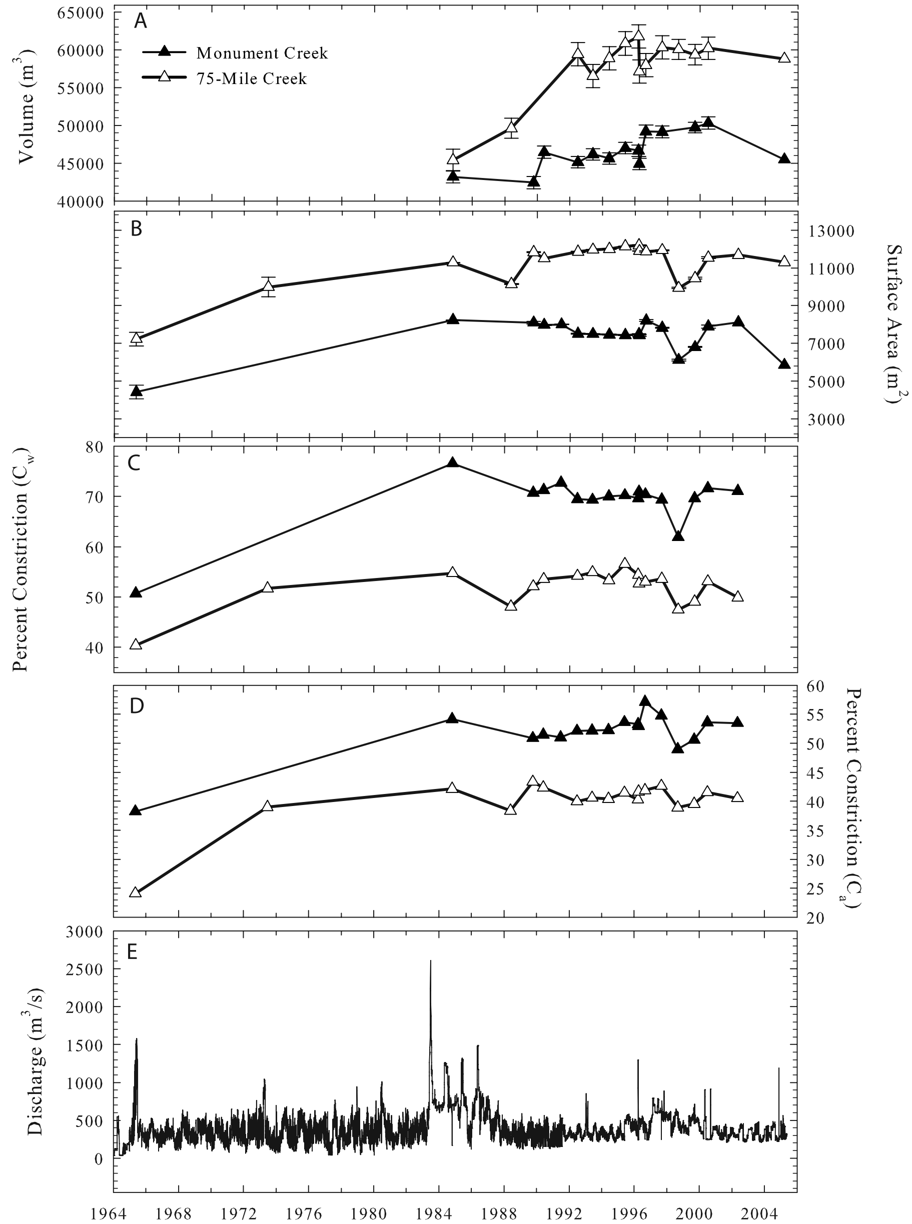

Figure 7. Changes in the debris fans at the mouths of 75-Mile Canyon (open triangles) and Monument Creek (solid triangles) from 1965 through 2005. (a) Volume changes from 1984 to 2005. (b) Surface area changes from 1965 through 2005. (c) Percent constriction (C_w, equation (1)) changes from 1965 through 2000. (d) Percent constriction (C_a, equation (2)). (e) Average daily discharge for the Colorado River near Grand Canyon, Arizona (USGS gauging station 09402500).

The 1996 flood removed about 4600 m^3 from the debris fan (Figure 7a), and the volume again increased slightly between 1996 and 1999, a period when there were no floods. Volume increases were probably a result of sand deposition and riparian vegetation that was unable to be resolved in the aerial photographs. Debris flows in August 2001 and 2003 and the large dam release in November 2004 did not greatly affect the debris fan volume which measured 58,800 m^3 in the March 2005 survey.

[32] Between 1965 and 1990, the surface area of the debris fan at 75-Mile Creek increased from about 7200 to 11,300 m^2 (Figure 7b); after 1990, the area fluctuated between 10,000 to 12,000 m^2. A slight increase proportional to discharge occurred from 1992 to 1996 (Figure 7b). The significant decreases in surface area recorded for 1998, 1999, and 2005 likely reflect the high discharge during aerial photography overflights or ground surveys, which also affected the estimated constriction (Figures 7c and 7d).

[33] Profiles extracted from the surface models reveal significant increases in surface elevation at 75-Mile Creek (Figure 8). For profiles A-A′ and B-B′ (Figures 8a and 8b), the 1984 surface is considerably lower than later surfaces, especially when the uncertainty in the elevation estimates is considered. The 1988 profiles show the aggradation of the 1987 debris flow; similarly, the 1992 profiles show aggradation created by the 1991 event. These profiles quantify the aggradation documented in repeat photographs (Figure 4) [see also *Webb*, 1996] as well as a shift in the

Table 3. Areas, Volumes, and Constrictions for 75-Mile and Monument Creeks

Aerial Photograph Date	Volume	Surface Area	Maximum Constriction C_w	Average Constriction C_a
75-Mile Creek				
5/14/1965	–	7222	40.38	24.08
6/17/1973	–	9982	51.69	38.99
10/22/1984	45395	11281	54.72	42.11
5/28/1988	49620	10137	48.08	38.36
10/8/1989	–	11831	52.09	43.34
6/3/1990	–	11493	53.53	42.35
6/30/1991	–	–	–	–
6/30/1992	59400	11845	54.18	39.96
5/31/1993	56536	11963	54.91	40.59
5/30/1994	58866	12000	53.32	40.41
5/29/1995	60832	12136	56.56	41.47
3/25/1996	61750	12190	54.40	40.27
4/6/1996	57130	11883	52.69	41.65
9/2/1996	57980	11863	53.00	41.87
9/1/1997	60304	11937	53.62	42.65
9/6/1998	60045	10292	47.51	38.91
9/5/1999	59347	10451	49.06	39.55
7/2/2000	60201	11539	53.10	41.51
5/2/2002	–	11674	49.90	40.50
3/6/2005	58794	11297	–	–
Monument Creek				
5/14/1965	–	4411	50.70	38.22
6/17/1973	–	–	–	–
10/22/1984	43211	8226	76.53	54.15
5/28/1988	–	–	–	–
10/8/1989	42442	8090	70.74	50.86
6/3/1990	46458	7968	71.25	51.48
6/30/1991	–	7996	72.72	51.02
6/30/1992	45126	7504	69.41	52.12
5/31/1993	46175	7492	69.29	52.17
5/30/1994	45637	7456	69.95	52.26
5/29/1995	46997	7423	70.20	53.64
3/25/1996	46668	7479	69.65	53.28
4/6/1996	44913	7421	70.93	52.95
9/2/1996	49205	8205	70.37	57.14
9/1/1997	49133	7818	69.37	54.79
9/6/1998	–	6110	61.90	48.97
9/5/1999	51561	6979	69.60	50.61
7/2/2000	50324	7887	71.59	53.58
5/2/2002	–	8108	71.07	53.17
3/6/2005	51002	5854	–	–

shape of the debris fan. The A-A′ profiles reveal a more convex curvature in the cross-fan profile, and the B-B′ profiles show that the largest increase in volume is near the geometric center of the debris fan.

[34] Figure 9a shows water surface profiles surveyed at Nevills Rapid in October 2003, after the 2001 and 2003 debris flows, and March 2005, five months after the November 2004 river flood. The 2000 water surface profile constructed from lidar data [*Magirl et al.*, 2005] is provided for comparison. The elevation of the pool at the head of the rapid rose by approximately 0.2 m between 2000 and 2003 in response to the debris flows, a relatively modest response in comparison to the change measured at other rapids in Grand Canyon; elevation increases at the head of Grand Canyon rapids can exceed 1 m, even for small debris flows [*Magirl et al.*, 2005]. Much of the aggradation on the debris fan occurred near the center of Nevills Rapid, minimizing the impact in the backwater pool upstream from the rapid. Figure 9a shows that the water surface profile became more convex from 170 to 220 m downstream in the rapid, which shows approximately where aggradation had its largest effects on the rapid. On the basis of the March 2005 survey, the 2004 flood reworked the distal end of the newly aggraded debris fan, and those sediments appear to have been removed from the rapid without reducing the elevation at the head of the rapid. Presumably, a larger flood is needed to return the water surface profile to its pre-2003 state.

5.2. Changes in the Debris Fan at Monument Creek

[35] As with 75-Mile Creek, our estimates of volume change in the Monument Creek debris fan begin in 1984. Volumetric changes caused by the 1966–1967 and 1984 debris flows, the latter of which occurred about 2 months before the 1984 photographs were taken, could not be estimated owing to either lack of imagery or poor DTMs. Analysis of the 1984 photographs produced a volume of 43,200 m^3 (Figure 7a); *Webb et al.* [1988] used survey data and ground evidence to estimate that 8500 m^3 was contributed by the 1984 debris flow and that 4200 m^3 remained on the debris fan after reworking from August 1984 to March 1986. In 1989, this debris fan had a volume of about 42,400 m^3, which suggests that most of the reworking

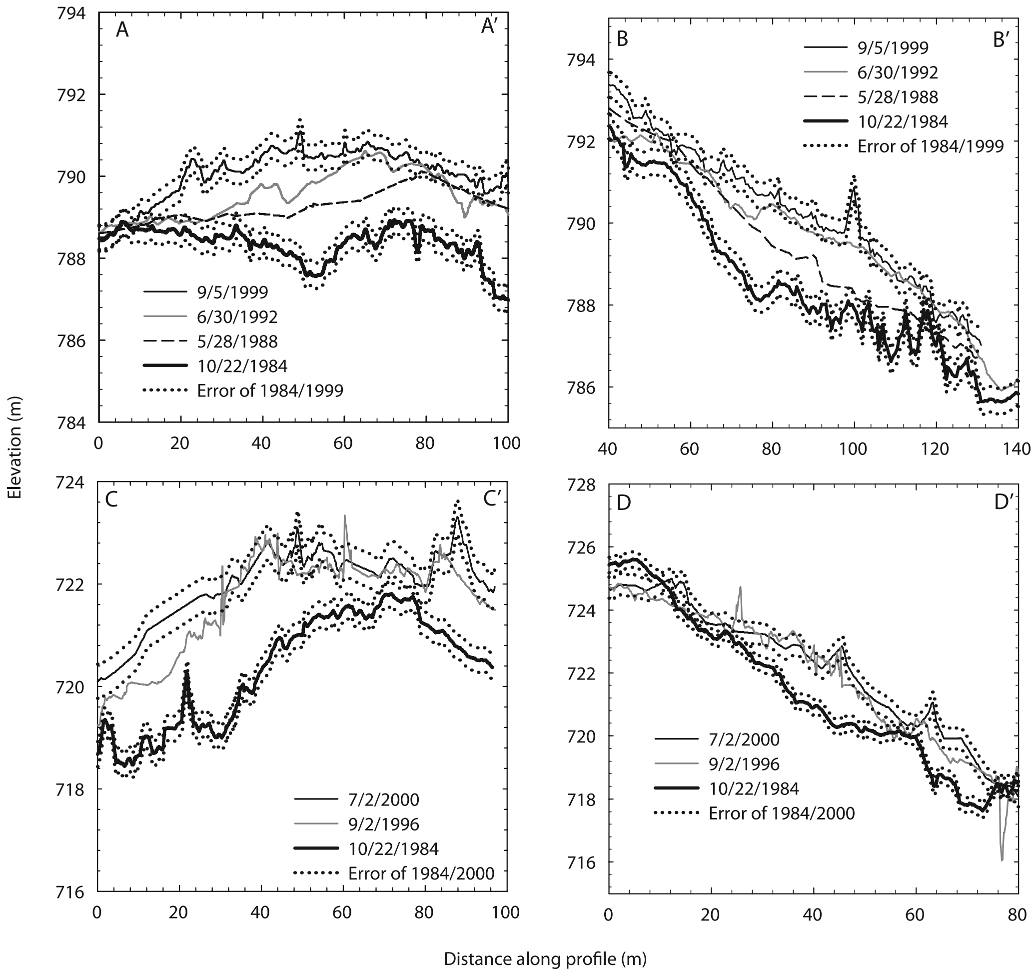

Figure 8. Profiles showing aggradation of debris fans at 75-Mile Creek from 1984 to 1999 and Monument Creek from 1984 to 2000. Uncertainty bands for 1984 and 1999 or 2000 appear as dotted lines. (a) Profiles extracted from the topographic model of the debris fan at 75-Mile Creek on line A-A′ (Figure 3). (b) Profiles extracted from the 75-Mile Creek topographic model on line B-B′. (c) Profiles from the Monument Creek topographic model on line C-C′ (Figure 5). (d) Profiles from the Monument Creek topographic model at D-D′. See auxiliary material, Figures S2 and S4, for representative DEMs and whole fan elevation changes for the two sites.

occurred immediately following the August 1984 debris flow and before the October 1984 aerial photography.

[36] Between June 1990 and March 1996, debris fan volume gradually increased at Monument Creek during a period of low dam releases (Figure 7a), mirroring our results for 75-Mile Creek. Reworking from the 1996 controlled flood decreased the volume by about 1800 m^3. In July 1996, a debris flow aggraded the Monument Creek debris fan by 4300 m^3 (Figure 7a), after which the debris fan volume again increased until 1999, in part because a series of streamflow floods from Monument Creek deposited sand and rearranged larger particles on the surface of the debris fan. The volume obtained from ground survey in March 2005 reflects the net effect of the 2001 and 2003 debris flows and reworking by the November 2004 controlled flood. This data indicates that debris flows in August 2001 and 2003, in addition to significant reworking by the 2004 flood, resulted in a net increase of less than 2000 m^3 following the 1996 debris flow (Figure 7a).

[37] Surface area changes were more significant at Monument Creek than at 75-Mile Creek (Figure 7b). Changes from 1965 to 1984 probably reflects a combination of the discharge difference at the time of the aerial photography and the 1984 debris flow. The 1996 debris flow increased the area by 800 m^2, most of which occurred in the upstream stream pool (Figure 5). The decreases in area between 1996 and 1999 likely were the result of streamflow floods from Monument Creek in the late 1990s, and the decrease before the 2005 survey was the net result of the 2003 debris flow and the 2004 flood in the Colorado River.

[38] Except for the change from 1965 to 1984, constriction ratios for Granite Rapid (Figures 7c and 7d) appear to be relatively insensitive to the interactions of tributary and river. The highest value of C_w was in 1984 and may show the effect of the 1984 debris flow; for C_a, the highest value followed the 1996 debris flow. The constriction ratios show variable effects of the 1996 debris flow on the river; the more conventional C_w measured virtually no change in river constriction but C_a increased by more than 4%. The

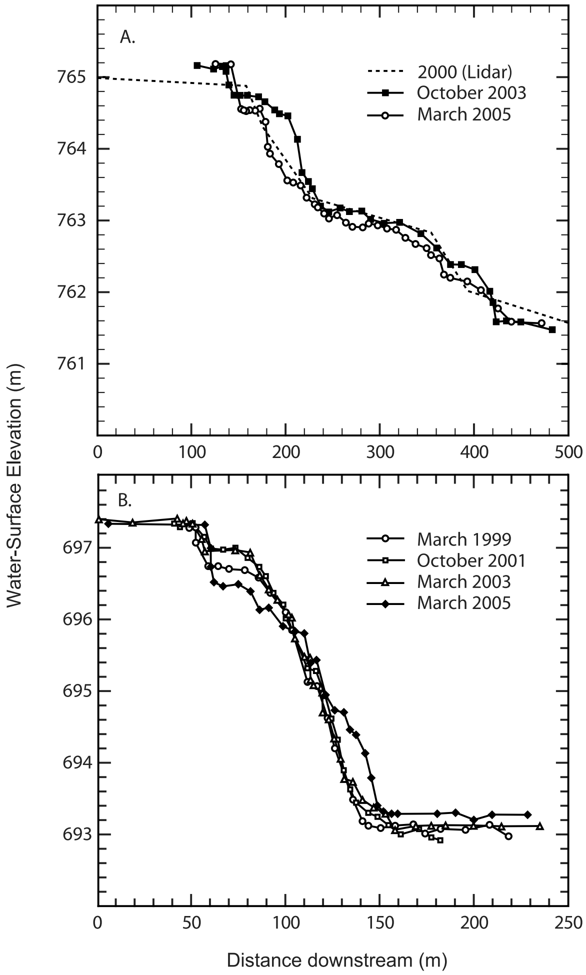

Figure 9. Water surface elevation profiles constructed from field surveys at Nevills Rapid (75-Mile Creek) and Granite Rapid (Monument Creek). (a) Surveys of Nevills Rapid measured in October 2003 and March 2005. The profile measured in May 2000 was constructed from aerial lidar data [*Magirl et al.*, 2005] and is included for comparison. (b) Four surveys measured at Monument Creek in March 1999, October 2001, March 2003, and March 2005. All profiles were normalized to a standard 227 m^3/s discharge using a one-dimensional flow model (C. S. Magirl, U.S. Geological Survey, unpublished data, 2005).

constriction ratios mirror the change in area, which suggests that the late 1990s streamflow floods from Monument Creek had a large effect on both the debris fan and its interaction with the river.

[39] The surface profiles at Monument Creek further illustrate debris fan aggradation. The 1984 profile reveals a surface that is significantly lower than the more recent surfaces for both transects (Figures 8c and 8d), a finding verified by the repeat photography (Figure 6). Further comparisons reveal a more convex curvature for modern surfaces along the D-D′ transect. The surface profiles do not show the effects of the 2001 and 2003 debris flows.

[40] Figure 9b shows the net effect of debris flow aggradation and reworking on Granite Rapid. Water surface profiles measured in March 1999, October 2001, March 2003, and March 2005, which span the 2001 and 2003 debris flows and the 2004 flood, show that the elevation at the head of the rapid was essentially unaffected. *Magirl et al.* [2005] found this to be a long-term trend; they reported a drop of 0.4 m at the head of Granite Rapid between 1923 and 2000. A convexity in the water surface profile at 60–100 m downstream (Figure 9b) was formed by the 2001 debris flow and persisted through the 2003 debris flow. The 2004 flood reworked the debris fan, removing the convexity and altering the water surface profile in this section to below its 1999 elevation. A new convexity appeared in the 2005 water surface profile at 120 to 150 m, in the lower half of the rapid, and this probably represents boulders that were pushed only part way down the rapid. In 2005, we observed that the tailwaves of the rapid spanned the downstream pool, suggesting that the fan-eddy complex at Granite Rapid had deteriorated into a completely fast water reach.

6. Discussion and Conclusions

[41] Using photogrammetric analyses of aerial photography combined with ground surveys, we quantified changes in the area and volumes of debris fans of 75-Mile and Monument Creeks in Grand Canyon from 1965 to 2005 and the effects of changes in Nevills and Granite Rapids, respectively, on the Colorado River. The debris fans at 75-Mile and Monument Creeks had four and five debris flows, respectively, that reached the river following the start of flow regulation in 1963, and aggradation of debris flow deposits are easily quantified owning to sufficient high-quality aerial photography available for 1984–2000. From 1984 to 2005, debris flows increased debris fan volumes, which also increased gradually owing to deposition of river sand, deposition during tributary streamflow floods, and growth of riparian vegetation. Volumes were reduced by reworking Colorado River floods in 1996 and 2004 (Figure 7). Our results do not completely measure the total sediment delivery of debris flows because matrix dewatering delivers fine-grained sediments to the river during the event and some reworking occurs immediately following deposition [*Webb et al.*, 1988, 1999b; *Larsen et al.*, 2004]; the aerial photographs were taken at least one month after any debris flow and thus only show net deposition.

[42] Reworking by typical dam releases, as documented with the aerial photography and ground surveys, did not significantly reduce debris fan volumes, surface area, or river constriction, and reworking by the intentionally released floods was less than the amount of deposition on the fans. The history of these two debris fans indicates that river reworking by the regulated Colorado River is insufficient to offset debris flow aggradation given the release history of Glen Canyon Dam from 1984 to 2005. Others have suggested that dam operations reduce the potential for reworking [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1989; *Magirl et al.*, 2005], particularly at stages exceeded by predam floods. Because of the coarseness of debris flow deposits, significant stream power is necessary to entrain and transport large particles [*Pizzuto et al.*, 1999]. The interaction of debris fans and river hydraulics is driven by the size and amount of material deposited adjacent to or in the river. Increases in river constriction increase stream power [*Webb et al.*, 1999b] and therefore its reworking ability as long as the surface has not been armored by

previous flows. The evidence presented in this paper confirms that a decrease in the river's reworking potential contributes to debris fan aggradation, particularly those parts of debris fans at a stage higher than is reached by typical dam releases.

[43] Previous researchers have suggested that the change in flood regime brought about by operations of Glen Canyon Dam affects the morphology of coarse-particle deposits downstream in Grand Canyon [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 2000]. In a dynamic river system such as the Colorado River, hydrologic alterations such as flood control operations will induce geomorphic changes at a rate dependent on many variables including the magnitude of hydrologic change, the processes at work, and landform characteristics, notably the particle size distribution. For example, sandbars along the Colorado River in Grand Canyon have already undergone a system-wide reduction in response to the decrease in available sediment and changes in the flow regime [*Howard and Dolan*, 1981; *Schmidt and Graf*, 1990; *Schmidt et al.*, 1995; *Wright et al.*, 2005]. Sufficient time may not have elapsed to document a system-wide change in debris fan morphology, although our work and previous studies [*Melis et al.*, 1994; *Webb et al.*, 1999a; *Magirl et al.*, 2005] have suggested that the morphology of at least some debris fans has responded to the change in the flow regime.

[44] The gradual increase in debris fan volume estimated for periods without debris flow aggradation or significant reworking likely reflects visual smoothing of the debris fans from a number of interactive processes, including plant growth (Figures 4 and 6) and fine-grained sediment deposition in topographic lows (note sand infilling in Figures 3 and 5). Streamflow floods occur annually in tributaries of the Colorado River and may contribute fine-grained sediments that enable topographic smoothing. Plant establishment and growth enhances sediment trapping from both fluvial sources, Colorado River and tributary, and eolian sources. In addition, our photogrammetric analyses are less accurate on smooth surfaces, such as sandbars, that lack visual markers. A better understanding of post debris flow changes would help improve the accuracy of photogrammetric monitoring in Grand Canyon. Although no systematic error was detected in the photogrammetric models, we cannot reject the hypothesis that random noise could be responsible for some volume increase, but the fact that similar trends were simultaneously observed for both debris fans suggests this source of error is minimal.

[45] Although it is possible that debris flow deposition increased debris fan area between 1965 and 1984, higher river stage during the 1965 aerial photography limits our confidence in the amount of change spanning the period of Glen Canyon Dam operations. The nearly 800 m^2 increase in area resulting from the 1996 debris flow at Monument Creek, which was mostly confined to the upstream pool, was the largest we observed. Surface area at both debris fans was relatively stable because bedrock limits the depositional area on the upstream side and older, higher debris flow terraces limit deposition on the downstream side of the debris fans. Therefore any increase in surface area occurs mostly at the expense of the river by constricting flow, which then increases stream power and reworking potential. Because the surface of the debris flow is unconfined, vertical aggradation in the most apparent response we observed.

[46] Our results of river constriction are consistent with those of *Webb et al.* [1999b], who found that percent constriction is sensitive to reworking by dam releases. Nonetheless, the area/length method of determining river constriction (equation (2)) is more sensitive and better reflects overall changes on debris fans, particularly if aggradation occurs elsewhere than the narrowest cross section of the rapid. Although maximum constriction may better reflect potential stream power, it does not provide a realistic estimate of change in debris fans.

[47] Increases in debris fan elevation and profile may represent the most significant long-term effects of flow regulation. Profiles made before recent debris flow aggradation depict a concave downslope profile that may be a relict of predam reworking. Postevent profiles are convex and are unlikely to be reworked by dam releases because of their high stage. In the postdam era, most debris fan reworking occurs along the water/debris fan interface as bank collapse [*Webb et al.*, 1999b], leaving intact most of the original upslope deposit. Before flow regulation, floods with high stages would overtop the debris fan, entraining surface particles and winnowing most particles <1 m b axis diameter from the deposit [*Melis*, 1997]. Only that part of the debris fan closest to the regulated river exhibits the winnowed, concave form of the predam debris fan.

[48] Our data demonstrates that the form and size of coarse-grained deposits along fluvial systems dominated by debris flows depend on the system's ability to reach a threshold condition of particle transport. Although this assumption appears simple in environments such as Grand Canyon, its demonstration, especially in timescales detected by historical data, in natural systems remains elusive. Monitoring and previous work in Grand Canyon have produced robust data sets that include instantaneous discharge, historical debris flows, grain size of debris fans, sediment budget analysis, and historical sedimentation records in Lake Mead. The contribution of topographical data of debris fans from photogrammetry provide an additional data set that can be used in investigations of delivery, storage, and reworking of sediment resources in a regulated river that has experienced a change in the hydrological conditions.

[49] Although future rates of aggradation of these debris fans can only be guessed, it is probable that debris fans at other tributary junctions that have not experienced significant debris flows in the postdam era will aggrade when debris flows inevitably occur, particularly if the current flow regime of the Colorado River is continued. To promote greater river reworking downstream of Glen Canyon Dam, more frequent high-magnitude dam releases would be required to promote greater amounts of coarse-particle entrainment. Considering the benefits of channel maintenance and mitigation of potentially hazardous conditions to whitewater recreationalists, management of flow regulation should consider the impacts of debris flow aggradation when scheduling controlled flood releases.

[50] **Acknowledgments.** We thank Stephanie Wyse of the Grand Canyon Monitoring and Research Center for providing the aerial photographs used in our analyses. We thank the numerous individuals who helped with field work in Grand Canyon during the period of this study. All

repeat photographs are courtesy of the Desert Laboratory Collection of Repeat Photography, Tucson, Arizona; we thank Diane Boyer of the U.S. Geological Survey for preparing the digital imagery. We thank Jeffrey Gartner of the U.S. Geological Survey, Jack Schmidt of Utah State University, and two anonymous reviewers for critically examining this manuscript. Use of trade names does not imply endorsement by the U.S. Geological Survey.

References

Brasington, J., J. Langham, and B. Rumsby (2003), Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport, *Geomorphology*, *53*, 299–316.

Butler, J. B., and J. H. Chandler (1998), Assessment of DEM quality for characterizing surface roughness using close range digital photogrammetry, *Photogramm. Rec.*, *16*(92), 271–291.

Collier, M., R. H. Webb, and J. C. Schmidt (1996), Dams and rivers: A primer on the downstream effects of dams, *U.S. Geol. Surv. Circ.*, *1126*, 94 pp.

Cooper, M. A. R., and P. A. Cross (1988), Statistical concepts and their application in photogrammetry and surveying, *Photogramm. Rec.*, *12*(71), 637–663.

David-Novak, H. B., E. Morin, and Y. Enzel (2004), Modern extreme storms and the rainfall thresholds for initiating debris flows on the hyperarid western escarpment of the Dead Sea, Israel, *Geol. Soc. Am. Bull.*, *116*, 718–728.

Davis, P. A., M. R. Rosiek, and D. M. Galuszka (2002), Evaluation of airborne image data and lidar main stem data for monitoring physical resources within the Colorado River ecosystem, *U.S. Geol. Surv. Open File Rep., 02–470*, 65 pp.

ERDAS (2001), Imagine OrthoBASE user's guide, Atlanta, Ga.

Gooch, M. J., and J. H. Chandler (1999), Accuracy assessment of digital elevation models generated using the ERDAS Imagine OrthoMAX digital photogrammetric system, *Photogramm. Rec.*, *16*(93), 519–531.

Grams, P. E., and J. C. Schmidt (2002), Streamflow regulation and multilevel flood plain formation: Channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah, *Geomorphology*, *44*, 337–360.

Griffiths, P. G., R. H. Webb, and T. S. Melis (2004), Frequency and initiation of debris flows in Grand Canyon, Arizona, *J. Geophys. Res.*, *109*, F04002, doi:10.1029/2003JF000077.

Hanks, T. C., and R. H. Webb (2006), Effects of tributary debris on the longitudinal profile of the Colorado River in Grand Canyon, *J. Geophys. Res.*, *111*, F02020, doi:10.1029/2004JF000257.

Howard, A., and R. Dolan (1981), Geomorphology of the Colorado River in Grand Canyon, *J. Geol.*, *89*, 269–297.

Kieffer, S. W. (1985), The 1983 hydraulic jump in Crystal Rapid—Implications for river-running and geomorphic evolution in the Grand Canyon, *J. Geol.*, *93*, 385–406.

Kieffer, S. W. (1987), The rapids and waves of the Colorado River, Grand Canyon, Arizona, *U.S. Geol. Surv. Open File Rep., 87–096*, 69 pp.

Kirkby, M. J. (1994), Thresholds and instability in stream head hollows: A model of magnitude and frequency for wash processes, in *Process Models and Theoretical Geomorphology*, edited by M. J. Kirby, pp. 295–314, John Wiley, Hoboken, N. J.

Lane, S. N., T. D. James, and M. D. Crowell (2000), Application of digital photogrammetry to complex topography for geomorphological research, *Photogramm. Rec.*, *16*(95), 793–821.

Lane, S. N., R. M. Westaway, and D. M. Hicks (2003), Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing, *Earth Surf. Processes Landforms*, *28*(3), 249–271.

Larsen, I. J., J. C. Schmidt, and J. A. Martin (2004), Debris-fan reworking during low-magnitude floods in the Green River canyons of the eastern Uinta Mountains, Colorado and Utah, *Geology*, *32*(4), 309–312, doi:10.1130/G20235.1.

Leopold, L. B. (1969), The rapids and the pools—Grand Canyon, in *The Colorado River Region and John Wesley Powell*, *U.S. Geol. Surv. Prof. Pap.*, *669*, 131–145.

Magirl, C. S., R. H. Webb, and P. G. Griffiths (2005), Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000, *Water Resour. Res.*, *41*, W05021, doi:10.1029/2003WR002519.

Melis, T. S. (1997), Geomorphology of debris flows and alluvial fans in Grand Canyon National Park and their influences on the Colorado River below Glen Canyon Dam, Arizona, Ph.D. dissertation, 490 pp., Univ. of Ariz., Tucson.

Melis, T. S., R. H. Webb, P. G. Griffiths, and T. J. Wise (1994), Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 94–4214*, 285 pp.

O'Connor, J. E., L. L. Ely, E. E. Wohl, L. E. Stevens, T. S. Melis, V. S. Kale, and V. R. Baker (1994), A 4500-year record of large floods on the Colorado River in the Grand Canyon, Arizona, *J. Geol.*, *102*, 1–9.

Pizzuto, J. E., R. H. Webb, P. G. Griffiths, J. G. Elliott, and T. S. Melis (1999), Entrainment and transport of cobbles and boulders from debris fans, in *The Controlled Flood in Grand Canyon: Scientific Experiment and Management Demonstration*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 53–70, AGU, Washington, D. C.

Pyle, C. J., K. S. Richards, and J. H. Chandler (1997), Digital photogrammetric monitoring of river bank erosion, *Photogramm. Rec.*, *15*(89), 753–763.

Schmidt, J. C., and J. B. Graf (1990), Aggradation and degradation of alluvial sand deposits, 1965–1986, Colorado River, Grand Canyon National Park, Arizona, *U.S. Geol. Surv. Prof., 1493*.

Schmidt, J. C., and D. M. Rubin (1995), Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, in *Natural and Anthropogenic Influences in Fluvial Geomorphology*, *Geophys. Monogr. Ser.*, edited by J. E. Costa et al., vol. 89, pp. 177–195, AGU, Washington, D. C.

Schmidt, J. C., P. E. Grams, and R. H. Webb (1995), Comparison of the magnitude of erosion along two large regulated rivers, *Water Res. Bull.*, *31*(4), 617–631.

Snyder, N. P., K. X. Whipple, G. E. Tucker, and D. J. Merritts (2003), Importance of a stochastic distribution of floods and erosion thresholds in the bedrock river incision problem, *J. Geophys. Res.*, *108*(B3), 2117, doi:10.1029/2001JB001655.

Stephens, H. G., and E. M. Shoemaker (1987), *In the Footsteps of John Wesley Powell*, 286 pp., Johnson Books, Boulder, Colo.

Stevens, L. (1983), *The Colorado River in Grand Canyon: A Guide*, 115 pp., Red Lake Books, Flagstaff, Ariz.

Talling, P. J. (2000), Self-organization of river networks to threshold states, *Water Resour. Res.*, *36*, 1119–1128.

Topping, D. J., J. C. Schmidt, and L. E. Vierra Jr. (2003), Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000, *U.S. Geol. Surv. Prof. Pap.*, *1677*.

Tucker, G. E. (2004), Drainage basin sensitivity to tectonic and climatic forcing: Implications of a stochastic model for the role of entrainment and erosion thresholds, *Earth Surf. Processes Landforms*, *29*, 185–205.

Webb, R. H. (1996), *Grand Canyon: A Century of Environmental Change*, 290 pp., Univ. of Ariz. Press, Tucson.

Webb, R. H., P. T. Pringle, S. L. Reneau, and G. R. Rink (1988), Monument Creek debris flow, 1984—Implications for formation of rapids on the Colorado River in Grand Canyon National Park, *Geology*, *16*, 50–54.

Webb, R. H., P. T. Pringle, and G. R. Rink (1989), Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona, *U.S. Geol. Surv. Prof. Pap.*, *1492*, 39 pp.

Webb, R. H., T. S. Melis, P. G. Griffiths, J. G. Elliott, T. E. Cerling, R. J. Poreda, T. W. Wise, and J. E. Pizzuto (1999a), Lava Falls Rapid in Grand Canyon, effects of late Holocene debris flows on the Colorado River, *U.S. Geol. Surv. Prof. Pap.*, *1591*, 91 pp.

Webb, R. H., T. S. Melis, P. G. Griffiths, and J. G. Elliott (1999b), Reworking of aggraded debris fans, in *The Controlled Flood in Grand Canyon: Scientific Experiment and Management Demonstration*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 37–51, AGU, Washington, D. C.

Webb, R. H., D. L. Wegner, E. D. Andrews, R. A. Valdez, and D. T. Patten (1999c), Downstream effects of Glen Canyon Dam on the Colorado River in Grand Canyon: A review, in *The Controlled Flood in Grand Canyon: Scientific Experiment and Management Demonstration*, *Geophys. Monogr. Ser.*, vol. 110, edited by R. H. Webb et al., pp. 1–21, AGU, Washington, D. C.

Webb, R. H., P. G. Griffiths, T. S. Melis, and D. R. Hartley (2000), Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 00–4055*, 67 pp.

Webb, R. H., J. Belnap, and J. Weisheit (2004), *Cataract Canyon: A Human and Environmental History*, 268 pp., Univ. of Utah Press, Salt Lake City.

Webb, R. H., P. G. Griffiths, C. S. Magirl, and T. C. Hanks (2005), Debris flows in Grand Canyon and the rapids of the Colorado River, in *The State of the Colorado River Ecosystem in Grand Canyon*, edited by S. P. Gloss, J. E. Lovich, and T. S. Melis, *U.S. Geol. Surv. Circ.*, *1282*, 119–132.

Whipple, K. X., and T. Dunne (1992), The influence of debris-flow rheology on fan morphology, Owens Valley, California, *Geol. Soc. Am. Bull.*, *104*, 887–900.

Wright, S. A., T. S. Melis, D. J. Topping, and D. M. Rubin (2005), Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, in *The State of the Colorado River Ecosystem in Grand Canyon*, edited by S. P. Gloss, J. E. Lovich, and T. S. Melis, *U.S. Geol. Surv. Circ.*, *1282*, 17–31.

Yang, Z., H. Wang, Y. Saito, J. D. Milliman, K. Xu, S. Qiao, and G. Shi (2006), Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam, *Water Resour. Res.*, *42*, W04407, doi:10.1029/2005WR003970.

P. G. Griffiths, C. S. Magirl, and R. H. Webb, U.S. Geological Survey, 520 North Park Avenue, Tucson, AZ 85719, USA.

B. J. Yanites, Department of Geological Sciences, Campus Box 399, 2200 Colorado Avenue, Boulder, CO 80309-0399, USA. (brian.yanites@colorado.edu)