Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000

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[1] In 1923, a U.S. Geological Survey expedition surveyed the water surface profile of the Colorado River through Grand Canyon with theodolite and stadia rod. In 2000, lidar overflights collected topographic data centered on the river corridor, allowing construction of a new water surface profile and detection of change in the profile since 1923. By registering the surveys with respect to each other on the basis of 11 locations that were independently determined to have been unchanged between 1923 and 2000, 80 rapids were directly compared for change between 1923 and 2000. The average change for all measured rapids was +0.26 m, indicating net aggradation of the coarse-grained alluvium forming the rapids throughout Grand Canyon. In addition, comparison of the two water surface profiles showed enhanced pool-and-rapid morphology. While 50% of the total drop of the river occurred in just 9% of the river distance in 1923, that value increased to 66% by 2000.

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1. Introduction

[2] Flowing through northwestern Arizona, the Colorado River in Grand Canyon (Figure 1) has long, flat sections of quiet water separated by steep, turbulent rapids. Periodic debris flows originating in tributaries build debris fans at tributary mouths and deposit large boulders into the river [*Cooley et al.*, 1977; *Webb et al.*, 1989; *Melis et al.*, 1994]. The Colorado River, confined by bedrock walls, pools upstream of the accumulated debris fans before descending as rapids over the fans, commonly plunging into downstream pools formed behind debris fans or boulder bars even further downstream. When viewed in profile, the water surface is stepped, termed by *Leopold* [1969] as the pool-and-rapid morphology. In this study, the term rapid is used to describe any short reach of river (typically 100 to 400 m in length) in which the water is choked to critical flow, descends down a relatively steep slope, and produces breaking waves which span the width of the channel.

[3] The longitudinal configuration of pools and rapids results from the dynamic interplay between the addition of coarse-grained alluvium from tributaries and the subsequent removal, or reworking, of that material by main stem Colorado River floods [*Kieffer*, 1985; *Webb et al.*, 1999a]. Reworking consists of both entrainment of smaller particles and the jostling of the largest particles until they settle into a stable matrix. Most reworking occurs during the rising stage of a flood, and by reducing the stream power of a rapid, reworking can lower the water surface elevation at the head of a rapid several centimeters in a matter of hours [*Webb et al.*, 1999a]. Repeat photography shows that the largest particles in a debris fan matrix reworked by a flood of given discharge remain stable for at least a century unless subjected to a larger flood [*Webb*, 1996; *Webb et al.*, 1999c]. For stable debris fans, corrasion continues to remove material through ablation at the surface of individual boulders. Though not measured on the Colorado River, the rate of corrasion is probably several orders of magnitude less than the rate of change due to reworking.

[4] The rates of both reworking and corrasion are strong functions of flood regime. Before Glen Canyon Dam, the mean annual peak discharge of the Colorado River was 2645 m^3/s (1921–1961 [*Schmidt and Graf*, 1990]). The largest flood during the period of record at the U.S. Geological Survey (USGS) streamflow gauging station at Lees Ferry was 4800 m^3/s in 1921; a larger flood in 1884 was estimated to be 5900 m^3/s [*O'Connor et al.*, 1994; *Topping et al.*, 2003]. After closure of the dam in 1963, peak flows were reduced (Figure 2) with a mean annual peak discharge (1963–1996) of 920 m^3/s [*Webb et al.*, 1999b]. *Howard and Dolan* [1981] proposed that the reduction in flood peaks (and erosive potential) following the closure of Glen Canyon Dam would lead to accumulation of debris at tributary junctions, therefore increasing the severity and quantity of rapids on the Colorado River in Grand Canyon. The current study compares the modern water surface profile of the Colorado River, surveyed in March 2000, with a 1923 USGS survey of the river corridor, measuring general trends of aggradation in the river corridor. The study also produces a new set of geomorphic statistics associated with this 2000 profile.

[5] Though most data in this report are presented in metric units, position along the river corridor is reported in river miles relative to the gaging station on the Colorado River at Lees Ferry (River Mile 0; RM 0). This convention, established by the *USGS* [1924], is the standard nomenclature for describing locations along the river. Indeed, many official place names are derived from river mile position (e.g., 60-Mile Canyon, 75-Mile Creek, 205-Mile Rapid).

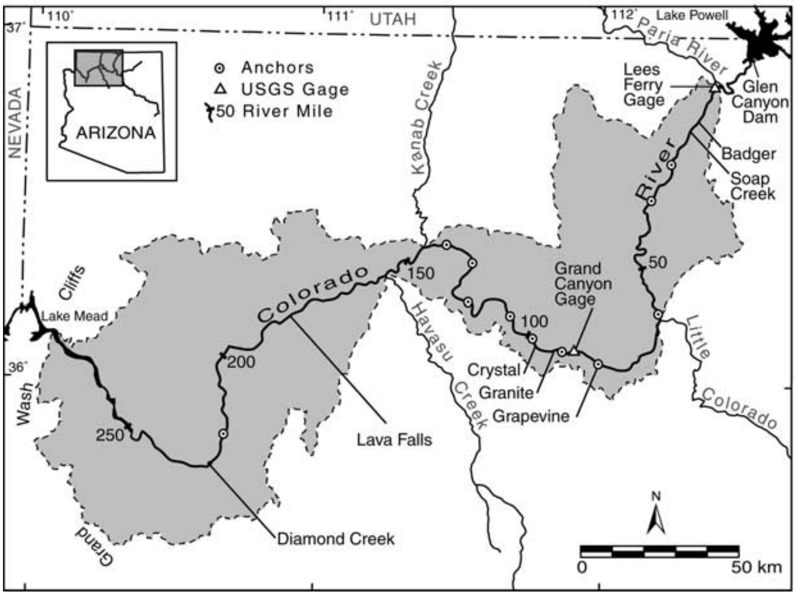

Figure 1. Map of Colorado River in Grand Canyon, Arizona, showing the locations of 11 lidar anchors and prominent rapids. See Table 1.

River mile locations originally published by the *USGS* [1924] and modified by *Stevens* [1983] were updated by the Grand Canyon Monitoring and Research Center (GCMRC) in September 2002 to fit a new river centerline. All references to river mile in this study are based on the GCMRC centerline.

2. Water Surface Profile Surveys

2.1. The 1923 USGS Expedition

[6] As part of a project to map the major rivers in the Colorado River Basin in search of potential dam sites, Claude H. Birdseye led a U.S. Geological Survey team though Grand Canyon. Starting at Lees Ferry, Arizona, on 1 August 1923, the survey party spent over two months mapping more than 400 km of the river corridor using theodolites and stadia rods [*USGS*, 1924]. The total drop was more than 600 m. In addition to publishing topographic maps of the river and its tributaries, the USGS produced a water surface profile map showing the location and elevation of pools and rapids along the river. Before 2000, this was the only such survey of the entire river corridor, although short segments have been surveyed in recent years [e.g., *Kieffer*, 1988; *Schmidt and Graf*, 1990; *Webb et al.*, 1999a]. The published water surface profile is constructed of piecewise linear segments linking individually measured survey points. In the reach from Lees Ferry to Diamond Creek, a distance of 364 km, 490 individual survey points were collected and published. The profile characterizes each long pool and the head of each significant rapid with a fall greater than 0.5 m.

[7] The discharge during the Birdseye expedition fluctuated between 425 and 850 m^3/s except for a brief high flow of 3300 m^3/s on September 18. The final water surface profile on published maps was normalized to 283 m^3/s using stage-discharge relations from the two newly established gaging stations in Grand Canyon (at Lees Ferry and Grand Canyon). The survey team carried the survey lines continuously with fore and back sites (C.H. Birdseye, unpublished expedition diaries, National

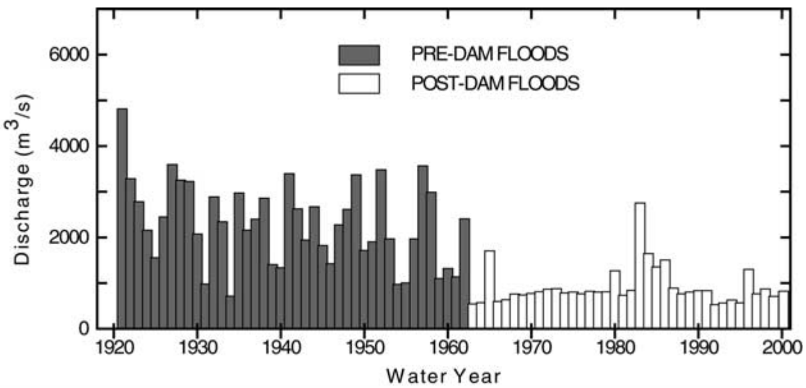

Figure 2. Annual peak flood series for the Colorado River at the USGS streamflow gauge at Lees Ferry, Arizona.

Archives, 1923). In addition to the benchmark at Lees Ferry, the survey was tied into established benchmarks at Hance Trail (RM 77.2), Pipe Springs Creek (RM 89.4), Havasu Creek (RM 157.2), Diamond Creek (226.0), and Last Chance Rapid (RM 252.0). While vertical closure error at the end of the 405 km survey was approximately 1.4 m and subsequently corrected, specific estimates of error in the survey were not published and detailed survey notes have not been found. It is probable, however, that because Birdseye was the chief topographic engineer for the U.S. Geological Survey [*Wilson*, 1941], the survey crew followed standard USGS operating procedures detailed later by *Birdseye* [1928]. Survey elevations were based on the North American Datum, later to become NGVD29.

2.2. The 2000 Lidar Survey

[8] In March of 2000, GCMRC commissioned a light detection and ranging (lidar) aerial overflight of Grand Canyon to collect high-resolution topographic data from the Colorado River corridor within Grand Canyon. An Altimeter Laser Mapping System (ALMS) lidar was flown at an altitude of 3048 m [*Davis et al.*, 2002a]. The ALMS lidar is a bidirectional, oscillating mirror system that operates at 1.064 μm wavelength. The average spot spacing was 3.75 m and the average spot diameter was 1.0 m. All elevation data were processed and delivered as orthometric heights (NVGD29, Geoid99) in Arizona state plane coordinates [*Davis et al.*, 2002b]. Absolute vertical accuracy was found to be about 0.5 m [*Davis et al.*, 2002b]. The discharge released from Glen Canyon Dam was held constant at 227 m^3/s during all mapping flights.

[9] Airborne laser-scanning systems work by firing a laser at the ground and measuring the return time of the beam reflected off the target surface. By comparing the return time of the laser beam and the relative global position of the aircraft, the location of the point of reflection in space is calculated [*Wehr and Lohr*, 1999]. While some systems were designed specifically for the purpose of mapping aqueous and subaqueous surfaces [*Irish and Lillycrop*, 1999], the ALMS lidar flown over Grand Canyon in March 2000 was tuned to measure terrestrial relief. Therefore all returns from the water surface of the river were removed and discarded by the lidar contractor in the final processing of the data. In order to produce a water surface profile of the river, we salvaged and reanalyzed the water surface returns. In rapids, lidar returns were plentiful and clustered near the centerline and largest waves. In contrast, there were fewer returns in calm water, and these returns were generally located near river's edge. The broken surface and entrained air bubbles in rapids may have improved lidar reflectance. In contrast, calm water may tend to absorb or to reflect lidar energy from a range of depths, reducing the number of effective returns and increasing noise.

[10] On average, we obtained 16 water surface returns for every 10 m of river distance. In some reaches, however, water surface returns were sparse with two or fewer measurements per 10 m. For unknown reasons, the paucity of water surface data was particularly acute in western Grand Canyon, which made it difficult to find the precise location of the water surface. Therefore, in addition to analyzing water surface returns, terrestrial elevation measurements within 9 m of the river shoreline were also plotted, producing an envelope that outlined the upper extent of the water surface. The density of shoreline data was typically around 15 counts per 10 m of river and never fell below 5 counts per 10 m. Where water surface returns were sparse along the river corridor, shoreline data were used to augment the detection of the water surface.

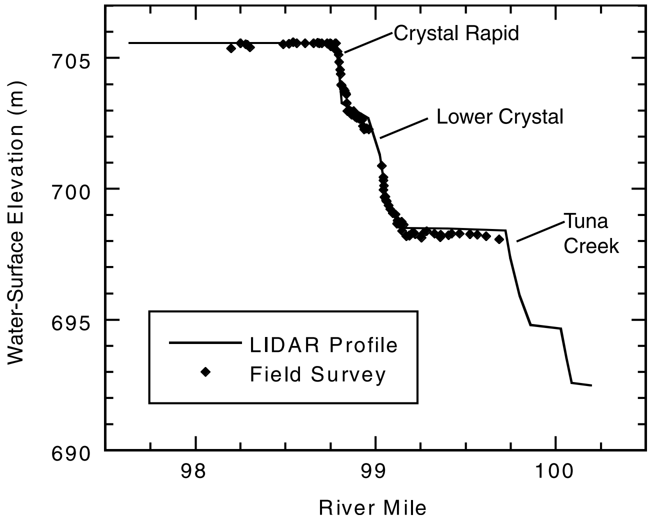

Figure 3. Comparison of 2002 survey data at Crystal Rapid with the 2000 water surface profile generated from lidar data.

[11] To produce a water surface elevation profile, each lidar point was first projected horizontally onto the river centerline to calculate its longitudinal position in river miles. Once projected onto the centerline, all river returns were plotted in profile with elevation values on the ordinate and river mile values on the abscissa. Despite noise, the lidar water surface returns showed a discernable interface or pattern when plotted. This pattern was interpreted as the water surface. The perceived water surface was not ubiquitous; instead, the surface was only visible at certain points in pools and at the heads of rapids. As such, the resulting profile of the river surface is piecewise linear, not continuous, from Lees Ferry to below Diamond Creek. In all, 1221 profile points were generated in the 364 km between Lees Ferry and Diamond Creek.

[12] Using ground survey data from long-term monitoring sites, *Davis et al.* [2002a] determined that the root-mean-square error of the interpreted water surface profile generated from lidar for this study ranged from 0.24 to 0.44 m relative to NGVD29 at four locations of tranquil water in upper Grand Canyon. We also evaluated the relative vertical precision of data points within the 2000 water surface profile by comparing them to data collected during two detailed field surveys: one through Crystal Rapid (RM 98.8) and another through Dubendorff Rapid (RM 132.2) in May 2002. Both surveys evaluated more than 2.0 km of river that had not been altered between 2000 and 2002. After projection on the river centerlines, the data sets were referenced to each other by assuming that the pool elevation at the upper end of each survey was unchanged between 2000 and 2002 (Figure 3). Though the field survey shows some details of the water surface profile not evident in the lidar water surface, the overall profiles are well

Table 1. List of 11 Anchor Points and Associated Tributaries Used to Register the 2000 Lidar and 1923 Survey Data

Rapid Name	River Mile	Side Tributary Enters River	Tributary Drainage Area, km^2
North Canyon	20.7	right	407.27
29-Mile	29.4	left	186.55
60-Mile	60.1	left/right	9.69
Grapevine	82.1	left	30.82
Horn Creek	90.8	left	4.28
Tuna Creek	99.7	right	59.62
Ruby	105.2	left/right	7.47
Blacktail	120.7	right	24.15
Dubendorff	132.3	right	12.27
Fishtail	139.7	right	19.63
217-Mile	217.7	left	23.98

aligned, indicating that the water surface profile produced from the lidar data is accurate at the scale of rapids and pools. Root-mean-square error between the lidar profile and the field survey data was 0.26 m at Crystal and 0.33 m at Dubendorff.

[13] Using these field study results combined with the accuracy measurements of *Davis et al.* [2002a] and the stated accuracy of the lidar data, we estimate the absolute accuracy of a given water surface value to be within ±0.5 m of the true value relative to NGVD29. In other words, the actual elevation at a given location on the lidar water surface profile is likely within a half meter of the stated value referenced to the established vertical datum.

3. Comparison of 1923 and 2000 Profiles

[14] The two elevation data sets are not directly comparable in raw form because they were generated on unique centerlines with different vertical reference data. The subjective choice of where to place the centerline differs slightly between the 1923 and 2000 surveys. To correct the longitudinal mismatch, the river miles of the 1923 survey were aligned to the lidar data by comparing the detailed river corridor maps produced by the two surveys. Adjustments were then made in the 1923 river miles to match the new centerline; the longitudinal adjustments ranged from −0.05 km to +1.22 km. The difference in vertical datum used for each survey resulted in discrepancies in absolute elevation. While this disparity in reference frame is potentially the largest source of error, it is also a disparity that can be eliminated by tying the surveys together at specific points along the river profile using essentially the same technique we used to compare the lidar data to our detailed survey data at Crystal and Dubendorff Rapids.

[15] Both the 1923 and 2000 longitudinal profiles are tied to different external frames of reference, including a unique vertical datum for each survey. While one technique for comparison would involve converting the elevations to a common vertical datum (e.g., from NGVD29 to NAVD88), such a conversion would not eliminate systematic error, or bias, present in each survey or error that arises from the comparison. Ideally, a better comparison would be achieved by linking together the surveys in a local vertical reference frame using local benchmarks common to both surveys. The benchmarks used by Birdseye in 1923, however, have not been resurveyed and rectified into a modern coordinate system and, as such, are not available for integration. Instead, different local benchmarks were used to link the two surveys together.

[16] Large rapids are prominent geomorphic features in the water surface profile of the Colorado River in Grand Canyon. In the absence of new debris flows or large reworking floods, the hydraulics of rapids and the boulders that form them can be stable for a century [*Webb*, 1996; *Webb et al.*, 1999a]. At such locations, matched photographs suggest that the change in elevation of the water surface at the head of a rapid subjected only to corrasion is negligibly small, probably much less than 10 cm/century. Making the assumption that the change in water surface elevation at the head of a stable rapid is zero between 1923 and 2000, we use these locations as “anchor points,” or local benchmarks, to tie the two surveys together into a single vertical reference frame.

[17] We identified anchor points using repeat photography and historical accounts of channel change [*Webb et al.*, 1999a, 2002]. Historic photographs used to identify anchor points came primarily from the Stanton collection of 1890 [*Webb*, 1996]; these photographs allowed us to identify rapids with no new debris flows from 1890 to the present. Of 160 prominent tributaries in Grand Canyon photographed in 1890, 37 had no obvious debris flows that reached the river [*Griffiths et al.*, 2004]. Distinct and prominent rapid heads were readily discernible in both the 1923 and 2000 profiles at 11 of the 37 stable rapids. These 11 locations, unevenly spaced along the river corridor, were used as anchor points (Table 1). At each anchor location, the water surface elevation of the 1923 survey was adjusted vertically to exactly match the elevation of the 2000 profile. Vertical adjustments of the anchors ranged from −2.02 m to +0.20 m. Intermediate points in the Birdseye survey between anchors were then adjusted vertically using linear interpolation in accordance with the ratio of the distance to the nearest upstream and downstream anchors. By linking the two surveys together with anchor rapids, both surveys can be directly compared without reference to an absolute global datum. Relative error, or precision of the survey data, however, remains an issue.

[18] Error in change detection at specific rapids between 1923 and 2000 originates from several sources. First, errors occurred in the measurement of the water surface elevation in both the 1923 and 2000 profiles intermediate to the anchor points. The relative precision of the lidar profile is probably not greatly different from the error of ±0.3 m measured when comparing the lidar profile and 2002 survey data collected at Crystal and Dubendorff Rapids. The relative precision of the 1923 profile is probably below ±0.5 m over 125 km, the greatest distance between adjacent anchors used in the current study.

[19] Another source of error is the difference in discharge reported for each survey (283 m^3/s verses 227 m^3/s). On the basis of results from a step-backwater model developed by *Randle and Pemberton* [1987], the difference in stage of each discharge throughout the river reach is probably less than ±0.25 m. The greatest potential source of error lies in the process of tying to the two surveys together using the anchor points. If a given anchor location, which is assumed to remain unchanged between 1923 and 2000, does change,

Table 2. Ten Rapids With the Largest Net Elevation Increase at the Head of the Rapid, 1923–2000

Rapid or Tributary Name	River Mile	Net Vertical Change, m	Number of Known Debris Flows[a]	Date of Debris Flows
House Rock	17.1	2.0	1	1966–1971
Badger	8.0	1.8	2	1897–1909, 1994
Crystal	98.8	1.6	2	1966, 1973–1986
Unkar	72.9	1.5	2	1890–1966, 1998
Doris	138.3	1.4	n.d.	
Waltenberg	112.8	1.4	4	1890–1923, 1938–1942, 1973–1984, 2001
205-Mile	205.7	1.2	2	1937–1956, 1998
Lava Falls	179.7	1.2	6	1939, 1954, 1955, 1963, 1966, 1995
Havasu	157.2	1.2	0	1990[b]
209-Mile	209.2	1.1	2	1999, 2000

[a]*Melis et al.* [1994] and *Webb et al.* [2000]; n.d., no data for this site.
[b]Although debris flows have not occurred here, a 1990 flood moved significant gravel into this rapid [*Melis et al.*, 1996].

a systematic error, or bias, is introduced into any nearby change measurements. To estimate the magnitude of potential error with the process of comparing the two profiles, each anchor was individually removed as an anchor and allow to float, adjusting to a new elevation determined by the influence of the nearest adjacent anchors. We have strong photographic evidence that these 11 anchors are unchanged and should report a difference in elevation of zero. The deviation from zero for the floating anchors gives an estimate of the overall error or accuracy in the process. The average measured change of the 11 floating anchors was +0.04 m with a standard deviation of ±0.68 m. These values suggest that while the anchoring process is relatively accurate, it is not particularly precise. Thus we report, with a 95% confidence (i.e., two standard deviations), that the error in measuring change of elevation for any individual rapid is ±1.4 m. While an individual measurement contains relatively large error, with multiple measurements, the standard error of the mean can be small.

[20] Once the profiles were aligned using anchor points, an evaluation of changes in the water surface profile was possible at many rapids. Comparison was easiest where a rapid was distinct and unambiguously related to a tributary junction in both the 1923 and 2000 surveys. Measurements of changes in the water surface profile were taken only when there was no ambiguity in the identity of the rapid in both profiles. For such rapids, the vertical difference between the head of the rapid in 1923 and 2000 was measured and recorded as the net change in elevation. Some new rapids were evident in the 2000 profile that did not exist in 1923. Because the topographic survey in 1923 at these locations showed only flat water, these newly formed rapids were not included in the analysis. While less common, reaches were also observed where a rapid measured in 1923 was flat water in 2000. These locations were also excluded from the analysis.

[21] In evaluating the potential change in pool-and-rapid morphology within Grand Canyon between 1923 and 2000, the question of resolution of the two disparate surveys arises. In comparing the relative resolution of the lidar profile with the 1923 Birdseye profile, the higher density of profile points generated from the lidar data does not necessarily represent higher resolution. Both to facilitate further studies with geographic information systems (GIS) and because it was inexpensive to do so, extra points were generated within long pools and rapids that were in line with other points of the lidar profile, providing no unique elevation information. As an exercise to evaluate density of points within the lidar survey, we removed extraneous data (i.e., those data in line with adjacent points) from the lidar profile producing a survey of 777 points with no decrease in the resolution of features represented. Also, evidence discussed in the section below indicates more rapids exist in the river in 2000 than in 1923. Had Birdseye resurveyed in 2000 using 1923 techniques, more than 490 points would be needed between Lees Ferry and Diamond Creek to capture the same resolution of detail. Finally, a sensitivity analysis was performed on the lidar profile, whereby points representing the smaller rapids were removed until only 490 remained. The sensitivity analysis showed that the geomorphic conclusions drawn below represent real changes in the pool-and-rapid morphology of the river, not a difference in the resolution of the techniques used to generate each water surface profile.

4. Results

4.1. Overall Changes in the Water Surface Profile

[22] The Birdseye and lidar survey data are available as auxiliary material.[1] Determining the number of distinct rapids in Grand Canyon is difficult due to ambiguity in defining the difference between the smallest rapids and fast moving water. Nonetheless, using the 2000 lidar profile, we identified 234 distinct features as rapids. In all, the change from 1923 to 2000 was determined at 91 rapids representing 39% of all rapids between Lees Ferry and Diamond Creek. This collection includes data representing the zero change at the 11 anchor points. The magnitude of change was determined for 67% of the 99 named rapids [*Stevens*, 1983] in the reach.

[23] The largest rise in elevation at the head of a rapid occurred at House Rock Rapid (+2.0 m), followed by Badger with a +1.8 m rise, Crystal Rapid with a +1.6 m rise, and Unkar Rapid with a +1.5 m rise (Table 2); all other increases were less than +1.4 m. Though generally not as large in magnitude as the increases, some elevation decreases were significant (Table 3). The greatest decrease was at 83-Mile Rapid (−1.5 m), while a rapid at river mile 103.2 changed by −1.4 m. The head at no other rapid decreased more than −1.4 m. Given the 95% confidence limit of ±1.4 m, most estimates of change are less than the

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/wr/2003WR002519.

Table 3. Five Tributary Junctures With the Largest Net Elevation Decrease at the Head of the Rapid, 1923–2000

Rapid or Tributary Name	River Mile	Net Vertical Change, m	Number of Known Debris Flows[a]	Date of Debris Flows
83-Mile	84.1	−1.5	n.d.	
Unnamed	103.2	−1.4	1	1890–1990
Zoroaster	85.3	−1.1	0	
Nautiloid	35.0	−1.0	1	1980–1984
23.5-Mile	23.5	−0.8	n.d.	

[a]*Melis et al.* [1994] and *Webb et al.* [2000]; n.d., no data for this site.

resolution of the measurement process. Overall, the mean change in elevation at the heads of all 91 measured rapids (including the anchors) was +0.26 m. Calculating the standard error of the mean for multiple measurements [*Taylor*, 1997], the average change in the elevation at the heads of rapids in Grand Canyon between 1923 and 2000 is +0.26 ± 0.15 m.

[24] The spatial distribution of elevation change at the heads of rapids was analyzed (Figure 4). Several divisions of the river corridor into geomorphic reaches have been proposed [*Leopold*, 1969; *Howard and Dolan*, 1981; *Schmidt and Graf*, 1990; *Melis*, 1997]. We applied a Kruskal-Wallis rank sum test [*Helsel and Hirsch*, 1992] to values of rapid-head elevation change gathered into six geomorphic reaches as defined by *Melis* [1997]. The resulting p value of 0.43 showed that there is little statistical difference between data grouped spatially (a p value less than 0.05 is needed to show dependence). Thus there is no correlation between changes in rapid-head elevation and geographic reach or position along the river.

[25] The temporal distribution of rapid-head elevation change was also measured to test the hypothesis by *Howard and Dolan* [1981] that prolific coarse-grained alluvium generated in tributaries would overwhelm the regulated Colorado River leading to long-term aggradation at tributary mouths. The change data we analyzed were not detailed enough to allow a definitive evaluation of the temporal signal. We did not the have detail of information to tie the observed aggradation of +0.26 m specifically to closure of Glen Canyon Dam.

[26] In *Leopold*'s [1969] analysis of the pool-and-rapid morphology in Grand Canyon, one figure presents the cumulative drop of the river in 1923 as a function of cumulative distance for the first 241 km below Lees Ferry. Leopold concluded that 50% of the total drop occurred in only 9% of the length of the river. We used 1923 survey data to recalculate and replicate Leopold's figure. We also produced an updated cumulative distribution curve based on the 2000 lidar data but expanded it to include 365 km of river from Lees Ferry to below Diamond Creek (Figure 5). This extended scope gives a better overall representation of both eastern and western Grand Canyon. In 2000, 66% of the total drop in river occurred in only 9% of the length. When only the first 241 km of river is considered for direct comparison with *Leopold*'s [1969] results, 71% of the total rapid occurs in 9% of the distance, showing that eastern Grand Canyon has a more prominent pool-and-rapid morphology than western Grand Canyon. It is possible that the change illustrated in Figure 5 may have been caused by a difference in the resolution of data point density of the two surveys. As described above, a sensitivity analysis was performed on the lidar profile whereby the number of points representing the profile was reduced to 490 by removing redundant points and points around the smallest rapids. With this artificially reduced resolution, the altered 2000 profile had a 64% cumulative drop in only 9% of the length, a result still significantly different that the results calculated using 1923 data. Therefore Figure 5 does represent a true and significant geomorphic change in the Colorado River between 1923 and 2000. Evidence of local rapid-head elevation increase (e.g., Crystal Rapid, 18-Mile Wash) also points to a trend of steeper and more numerous rapids.

4.2. Specific Changes Documented in Grand Canyon 1923–2000

[27] Comparisons at selected reaches illustrate the processes involved in maintaining the pool-and-rapid profile of

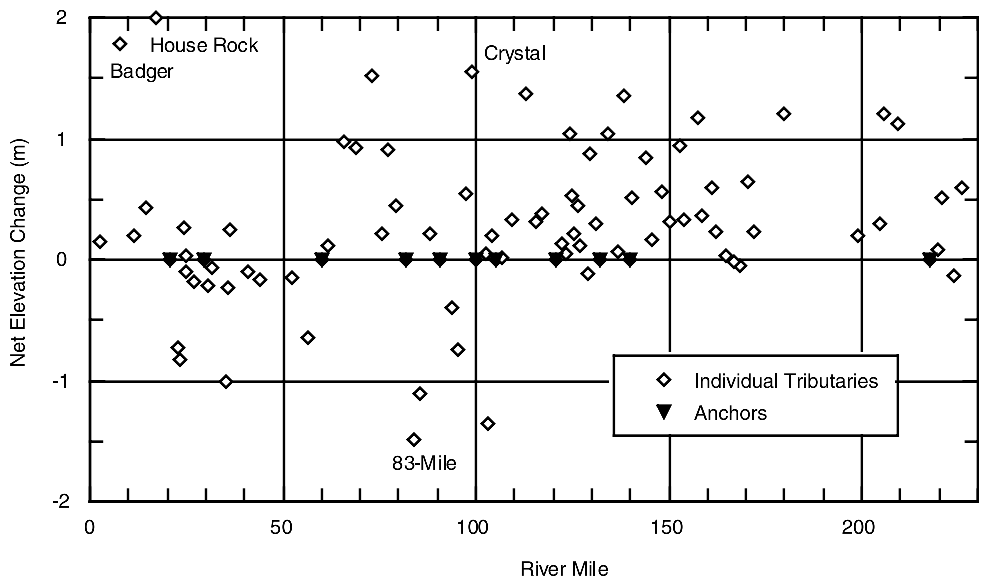

Figure 4. Measured net change at 80 rapids plotted as a function of river location. The anchor locations are also shown.

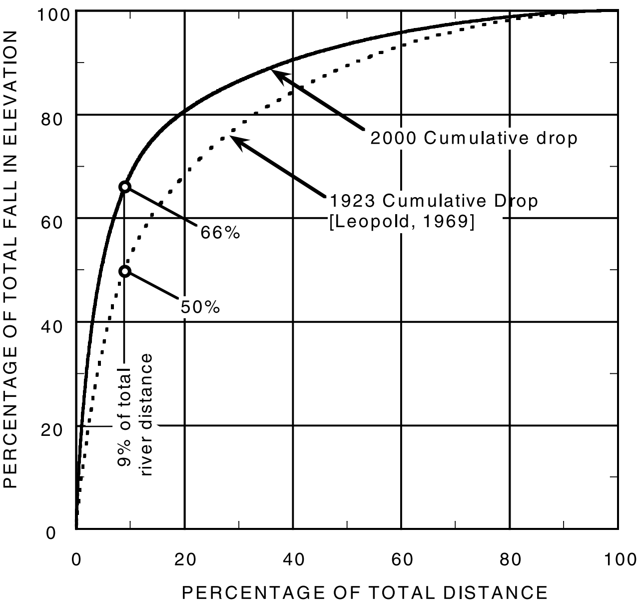

Figure 5. Cumulative vertical drop in the first 365 km of the Colorado River in Grand Canyon as a function of the total distance. In 2000, 66% of the drop occurs in just 9% of the river distance. The curve generated by *Leopold* [1969] is also included, when 50% of the drop occurred in 9% of the distance in the first 241 km below Lees Ferry.

the Colorado River. For example, Figure 6 juxtaposes the 1923 and 2000 water surface profiles between Lees Ferry (RM 0.0) and North Canyon (RM 20.7). The pool-and-rapid morphology is evident in the four large rapids: Badger Rapid, Soap Creek Rapid, Sheer Wall Rapid and House Rock Rapid. The elevation at the head of Badger Rapid (RM 8.0) increased +1.8 m between 1923 and 2000, one of the largest changes observed (Table 2). Though a large debris flow enlarged the debris fan at Badger Creek between 1897 and 1909, the only known post-1923 debris flow came in 1994 from Jackass Canyon on river left. This debris flow, however, was relatively small [*Melis et al.*, 1994] and probably does not account for the full elevation increase. One or more unidentified debris flows from either Badger Creek or Jackass Canyon most likely caused the observed aggradation. Downstream, Soap Creek Rapid (RM 11.4) had an increase in rapid-head elevation of only 0.2 m, despite two known debris flows since 1923, one between 1935 and 1941 and a second, smaller event between 1973 and 1984 [*Melis et al.*, 1994]. In addition, several predam floods reworked the first debris flow, and a 2755 m^3/s flood in 1983 reworked the second, resulting in a relatively small net change. At Sheer Wall Rapid (RM 14.5), at least one debris flow between 1890 and 1990 raised the rapid-head elevation by +0.4 m.

[28] A rise of +2.0 m at the head of House Rock Rapid (RM 17.1) was measured between 1923 and 2000, and this is the largest change we documented in the study. Between 1966 and 1971, one or more debris flows in Ryder Canyon on river right [*Webb et al.*, 2000] enlarged the fan, constricted the rapid, and extended the upper pool to the base of Sheer Wall Rapid (Figure 7). Between House Rock and North Canyon Rapids, the 1923 survey mapped flat water, an observation confirmed by boatman H. Elwyn Blake who noted, "the river was smooth. . .for five miles" (H.E. Blake, unpublished diaries, National Archives, 1923). By 2000, however, two distinct rapids appeared in this reach. The first was Redneck Rapid (RM 17.7), created by a rockfall in 1979 (R. Dye, Grand Canyon Expeditions Co., personal communication, 2003), and the second is at 18-Mile Wash where a 1987 debris flow created a new rapid with a fall of 1.1 m [*Melis et al.*, 1994]. Because these two rapids formed after 1923 and no comparative topography was available in 1923, they were not included in the overall change analysis.

[29] Within upper Granite Gorge, reliable anchors at Horn Creek and Tuna Creek Rapids allow confident analysis of the four major rapids (Figure 8). Though Monument Creek, the source of alluvium forming Granite Rapid, had three debris flows between 1966 and 1996 [*Webb et al.*, 2000], the net change in rapid head elevation is −0.4 m. Because

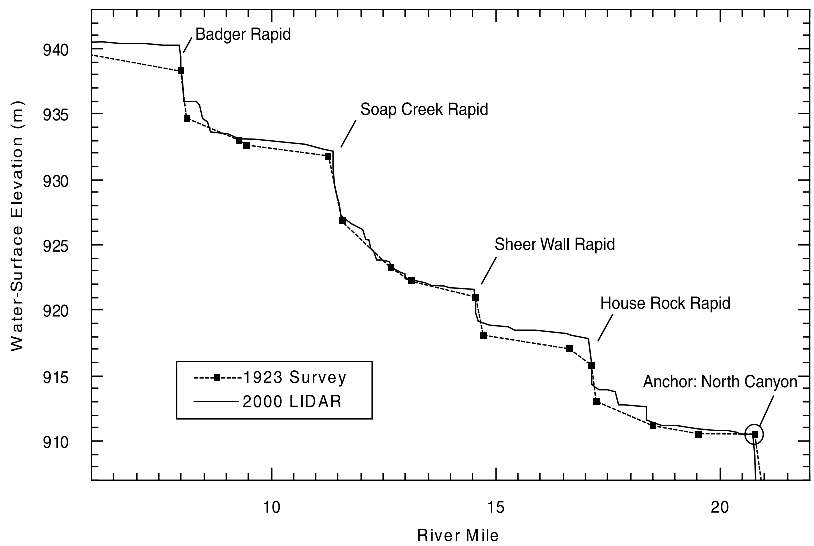

Figure 6. Comparison of 1923 and 2000 profiles of upper Marble Canyon. Note the prominent net increase in elevation at Badger Rapid and House Rock Rapid.

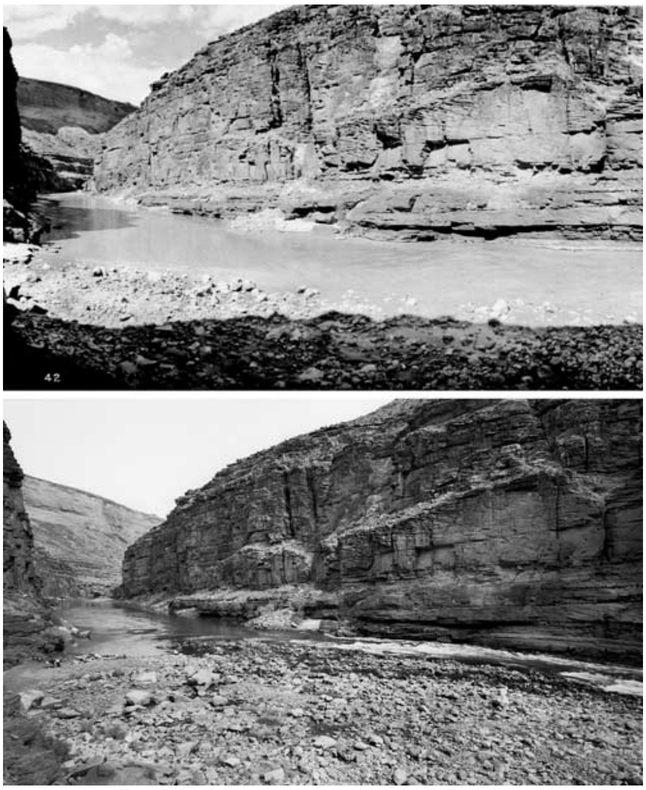

Figure 7. Repeat photographs of House Rock Rapid showing the large debris flow that constricted the right side of the river. (top) E.C. LaRue's photograph of the rapid taken during the 1923 survey (E.C. LaRue, number 348, courtesy of the U.S. Geological Survey Photographic Library). (bottom) Matching photograph taken in 1990 (R.H. Webb, stake 1701A).

of the tight controls of close anchors and the distinct morphology, we are confident of this measurement. It is possible that each of these debris flows merely aggraded the subaerial debris fan and had little impact on the river, or that Granite Rapid was affected with a debris flow just before the 1923 survey that was subsequently reworked; the three new debris flows in the latter half of the 20th century could have then simply constricted the rapid again to its 1923 dimensions. Between Hermit and Tuna Creek Rapids, the most substantial change is at Crystal Rapid (RM 98.8), where a 1966 debris flow [*Cooley et al.*, 1977] followed by the 1983 flood [*Kieffer*, 1985] created a net rise of +1.6 m. The rise in elevation at the head of Crystal Rapid created a rise at the base of Boucher Rapid 2.7 km upstream, decreasing its fall. Boucher Rapid itself also had a debris flow in 1951 or 1952 [*Webb et al.*, 2002] that raised the upstream pool by +0.6 m and created the Fifth Wave in Hermit Rapid, a prominent hydraulic feature 2.7 km upstream from Boucher Rapid.

[30] One of the more complex stories of changing rapids in Grand Canyon is at Doris Rapid (RM 138.3). In 1890, Stanton photographed the canyon in the upstream and downstream directions from the alluvial fan, but he did not photograph the fan or the rapid. In his diary, he noted a 2.4–3.0 m rapid [*Webb*, 1996]. During the 1923 survey, a total fall of only 0.3 m was recorded at this site. By 2000, however, the total fall at Doris Rapid again increased to 1.6 m (Figure 9). Using the three distinct observations and a chronology of reworking floods, we constructed a series of events to explain the changes observed at this rapid. First, because the largest flood on record in Grand Canyon (5900 m^3/s [*O'Connor et al.*, 1994; *Topping et al.*, 2003]) would have removed all but the largest particles in the river in 1884, we assume that a debris flow created the Doris Rapid viewed by Stanton between 1884 and 1890. Between 1890 and 1921, this debris flow was removed by one of the many large floods common on the predam Colorado River. When Birdseye encountered it in 1923, Doris Rapid was a 1-foot riffle. Then, in 1940, early river runner Norm Nevills ran a newly enlarged rapid that took him by surprise; in fact, he was so unprepared that his wife Doris was ejected from the boat, lending her name to the restored rapid [*Crumbo*, 1981]. Thus it appears that a second debris flow enlarged Doris Rapid between 1923 and 1940. By piecing together

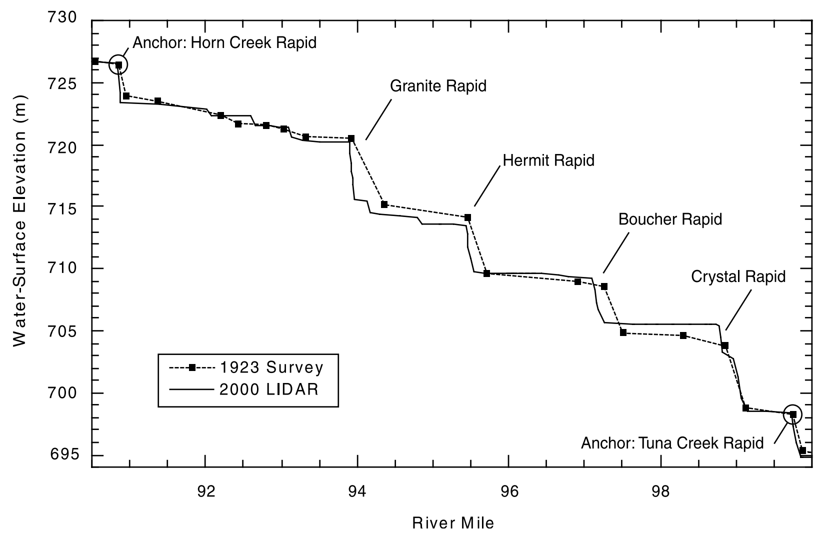

Figure 8. Comparison of 1923 and 2000 profiles in Upper Granite Gorge. Despite three debris flows the head at Granite Rapid has changed little in 77 years. In contrast, aggradation from a debris flow at Crystal Rapids is clearly visible in the comparison.

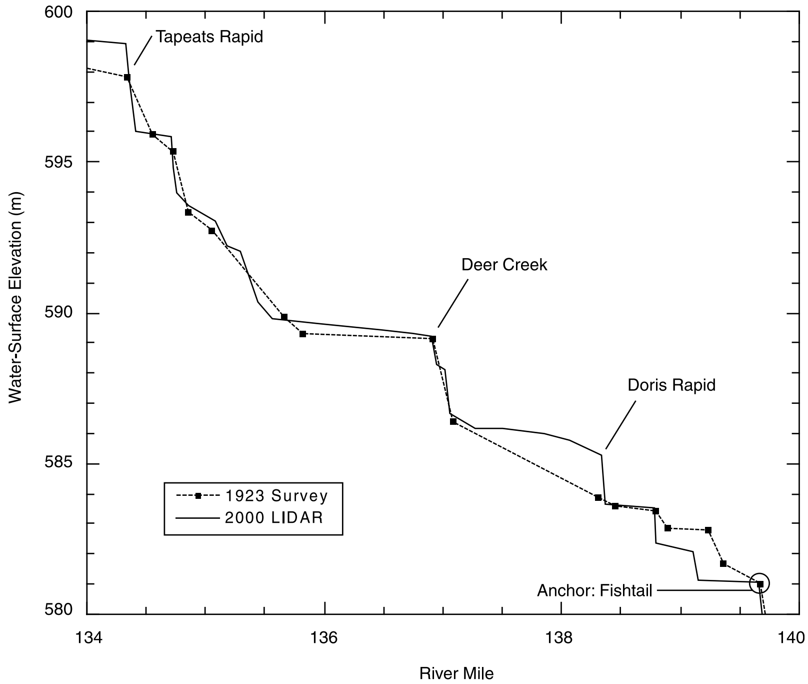

Figure 9. Comparison of the 1923 and 2000 profiles near Fishtail Rapid showing aggradation at Tapeats Rapid as well as the creation of a new rapid at Doris.

historic observation and river hydrology in this manner, we identified these two previously unknown debris flows.

5. Discussion and Conclusions

[31] On the basis of water surface profiles derived from 1923 survey data and 2000 lidar data as well as repeat photography, geomorphic change detection on the Colorado River in Grand Canyon was determined at 91 locations between Lees Ferry (RM 0.0) and Diamond Creek (RM 225.9), representing 39% of all rapids and 67% of named rapids. At these 91 locations, 11 rapids were known to have not changed between 1923 and 2000, 6 rapids exhibited a rise in the elevation at the head of the rapid of +1.4 m or more, and the elevation at the head of two rapids decreased more than −1.4 m. Though it has long been proposed that closure of Glen Canyon Dam would allow tributary input of coarse sediment to raise the level of the riverbed [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1989; *Melis et al.*, 1994; *Griffiths et al.*, 2004], the precise rate of increase of the water surface in the postdam era throughout Grand Canyon was impossible to quantify without a new synoptic survey of the water surface profile. This study shows that the water surface elevation at the head of 91 rapids has increased by a mean value of +0.26 ±0.15 m from 1923 to 2000. The increase results primarily from channel constrictions in the river due to debris flow input from tributaries. Thus the current rate of aggradation in the main stem Colorado at the confluence of a given tributary is roughly 3 cm/decade. While the general trend along the river is toward aggradation, several rapids were eroded with consequent lowering of the pool at the head of the rapid.

[32] Also measured in the current study was an enhanced pool-and-rapid morphology within the river corridor. While in 1923, 50% of the cumulative drop through the river corridor occurred in just 9% of the distance, by 2000, this number increased to 66%. One possible explanation for enhanced pool-and-rapid morphology could be increased debris flow activity in Grand Canyon during the later half of the 20th century. However, previous research shows that debris flow frequency in Grand Canyon has been constant over the past 100 years [*Griffiths et al.*, 2004]. Because debris flow frequency did not change after 1923, aggradation in the river corridor can be principally tied to a reduced flood regime in the main stem. While continuous gaging records extend only back to 1921 at Lees Ferry, gauge records from the lower Colorado River and flood accounts from the late 19th century indicate that the general climate in the southwestern United Stated was cooler and wetter with larger floods. Fluctuation to a drier climate and subsequent reduced natural flood regime in the early 20th century may partially explain the net aggradation. The more probably cause for aggradation, however, is the introduction of a regulated flood regime due to closure of Glen Canyon Dam in 1963. Because the timeframe of measurement of change almost exactly spans the predam and postdam period, however, the current study is unable to determine specifically how Glen Canyon Dam might have affected the rate of aggradation.

[33] Finally, while *Kieffer* [1985] stated that exceptionally large floods (11,320 m^3/s) are required to completely rework some large debris flows, we found several examples of small and moderately sized debris flows that were effectively reworked by modest floods. For example, it seems that a 2.4–3.0 m Doris Rapid was nearly completely removed by a 4800 m^3/s flood in 1921. While large floods are needed to rework large debris deposits, effective reworking can occur at a variety of flood magnitudes.

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