DEBRIS FLOW DEPOSITION AND REWORKING BY THE COLORADO RIVER IN GRAND CANYON, ARIZONA

by

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A Prepublication Manuscript Submitted to the Faculty of the

DEPARTMENT OF GESCIENCES

In Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA
2005

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As members of the Research Committee, we recommend that this prepublication manuscript be accepted as fulfilling the research requirement for the degree of Master of Science.

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ACKNOWLEDGEMENTS

Without the assistance of a number of individuals, this prepublication manuscript would not have been possible. I would like to thank my parents, John and Nancy, for their unwavering support over the years. In addition, I would like to thank my advisor, Victor Baker, and committee member, Jon Pelletier, for their support and time. I would also like to extend great thanks to committee member, Robert Webb, for his guidance, support, and time both in the field and in the office. Chris Magirl provided a critical review and suggestions that greatly improved this manuscript in addition to general research support. Peter Griffiths helped tremendously with numerous aspects of this project. Diane Boyer provided access to the repeat photography used in this study. Stephanie Wyse provided imagery and data from the Grand Canyon Monitoring and Research Center. I am grateful for all the time and assistance provided by these people.

Debris Flow Deposition and Reworking by the Colorado River in Grand Canyon, Arizona

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AGU Index Terms: geomorphology, debris flows and landslides, dams, instruments and techniques: monitoring

Keywords: debris flows, regulated rivers, geomorphology, Grand Canyon, Colorado River

Submitted to Water Resources Research

8/5/2005

Abstract. Debris flows from 740 tributaries transport sediment into the Colorado River in Grand Canyon, Arizona. The resulting debris fans constrict the river forming rapids that respond to river flows, which entrain particles and transport them downstream. Since river regulation due to operations of Glen Canyon Dam beginning in 1963, the geomorphic character of the debris fans has been adjusting to the change in flow regime. Previous studies have suggested that the debris fans have and will aggrade in response to flow regulation, particularly flood control. I create surface models for two frequently aggraded debris fans (75-Mile Wash and Monument Creek) using ground surveys and photogrammetry for all years in which low-scale stereo-photography exists. Acceptance of a surface model occurred only if it passes stringent qualitative and quantitative tests. The results confirm that these two debris fans have recently aggraded owning to multiple debris flows that occurred from 1984 through 2003. Volume, surface area, and river constriction have increased at both debris fans. Profiles derived from the surface models show maximum aggradation near the middle of the debris fan as the surface morphology has shifted from a concave-up to a concave-down shape. Small controlled-flood releases partially reworked both fans, although in general, reworking removed far less sediment than was added by debris-flow deposition. I show that photogrammetry, if carefully analyzed for surface-model quality, can be an effective tool to monitor canyon river systems affected by debris-flow deposition.

1. Introduction

Debris flows are an important sediment-transport process for 740 tributaries of the Colorado River in Grand Canyon, Arizona [*Webb et al.,* 2000; *Griffiths et al.*, 2004]. Distributed along 444 km of river between the Paria River and the Grand Wash Cliffs, these tributaries drain 12,000 km^2 of steep terrain (Figure 1). These debris flows typically are more than 80% sediment by weight with individual particles ranging from fine clays to boulders larger than 2 m in b-axis diameter. Flows often reach the river, depositing the poorly sorted sediment both into the river and onto a debris fan. These fans constrict the Colorado River at tributary junctures, raising the riverbed until mainstem flows rework the coarse-grain deposits to remove or reposition boulders and winnow finer-grained particles [*Webb et al*., 1999b]. Boulders in the river are also subject to slow, long-term removal through dissolution and corrasion by smaller river flows.

Despite reworking, the riverbed has risen at tributary confluences during the Holocene [*Webb et al*., 1999a] and historically [*Magirl et al.*, 2005] owing to debris-flow deposition. The large boulders deposited in the river by debris flows form the core of rapids that shape the longitudinal water-surface profile and locally control the geomorphic framework of the Colorado River in Grand Canyon [*Webb*, 1996]. Rapids account for most of the vertical drop 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]. This metric is significantly higher than the 50% drop in 9% of the river's length estimated by *Leopold* [1969] using 1923 data.

A better understanding of the annual variation of the morphology of the debris fan is critical to understanding the effects of dam operations on the geomorphic character of the Grand Canyon river corridor. This study uses photogrammetry to measure volumetric, surface-area, river-constriction, and surface profile-changes for two debris fans photographic documentation back to 1965. Previous studies have shown that when used carefully, photogrammetry can be an effective tool in extracting morphological information [*Brasington et al.,* 2003; *Lane et al.,* 2000]. The two debris fans, 75-Mile Wash and Monument Creek (Figure 1), were chosen for their relatively frequent debris-flow activity in addition to the previous work done there [*Melis et al.,* 1994; *Webb et al.,* 1988; *Webb et al.,* 1989; *Webb et al.,* 2001]. The morphological variables presented in this paper show significant change for each fan. Although previous studies have described changes of debris-fan morphology resulting from a single debris flow [*Webb et al.,* 1988] and from mainstem floods [*Webb et al.,* 1999b; *Larsen et al.,* 2004], no study has quantified high-frequency changes over decades that reflect the net effects of debris-flow deposition and river reworking.

2. Background

In 1963, the closure of Glen Canyon Dam altered the hydrologic framework of the Colorado River through the Grand Canyon. Before the closure, peak stream discharges averaged 2645 m^3/s [*Schmidt and Graf*, 1990] and were as large as 5900 m^3/s [*O'Connor et al.*, 1994; *Toppings et al.,* 2003]. Flows of this magnitude can entrain all but the largest fraction of sediment from a debris-flow deposit [*Webb et al.,* 1996]. Since closure of the dam, the average annual peak flood event dropped dramatically (Figure 2) to just 932

m^3/s. This reduction in discharge has decreased the river's ability to rework new debris-flow deposits. As a result, aggradation has been documented on select debris fans along the river [*Howard and Dolan*, 1981; *Melis et al.,* 1994; *Webb et al.,* 1999b; *Magirl et al.,* 2005]. Few floods have reworked these aggraded deposits. In 1983, a flow release of 2,724 m^3/s, the largest post-dam flood to date, resulted from above-average runoff into a nearly full Lake Powell. This event was followed by high releases from 1984 through 1986 (1342-1515 m^3/s). In March 1996, the dam's spillways were opened to produce a controlled flood with a peak discharge of 1,356 m^3/s. *Webb et al.* [1999b] documents the effects of the flood on 18 aggraded debris fans showing a variable magnitude of response and conclude that the amount of reworking is a function of stream power and the previous hydrologic history, which is loosely dependent on the elapsed time between debris flow and flood. Regulated flow continued on the river until November 2004, when another controlled flood had a peak discharge of 1,223 m^3/s.

Existing methods of debris-flow monitoring include ground surveys of select debris fans, which have been conducted since 1986, and rudimentary image analysis of aerial photography [*Webb et al.,* 1999b]. Although the point accuracy of ground surveys is very high, other methods of producing digital-terrain models, such as photogrammetry, may allow sufficient accuracy to provide surface derivatives that characterize changes in debris-fan morphology and size [*Lane et al.,* 2000]. Photogrammetry allows the representation of surfaces remotely and can produce up to 20,000 individual three-dimensional points on the highly irregular fan surfaces in Grand Canyon. This density of information is appealing for monitoring debris fans in Grand Canyon due to the high cost and logistical difficulty of obtaining accurate ground survey along a wilderness river. In addition, photogrammetry allows the production of surface models in Grand Canyon for all years in which overlapping aerial photography of sufficient scale exists, providing morphological information back to 1965.

In this study, geographical positions along the Colorado River are denoted as "River Mile (RM)" to maintain consistency among published material and conventional usage in Grand Canyon. *Stevens* [1983] is the most common source of river mile reference and is used here. All other data is reported in metric units.

3. Geomorphic Setting

When discussing the geomorphic character of the Colorado River corridor in Grand Canyon, it is important to clearly describe the terminology used for the landforms. Tributaries are often steeply bounded ephemeral streams of which debris flows and flash floods are the dominant sediment-transport processes. A debris fan refers to the mainly depositional surface that begins at the mouth of a tributary and extends to the river, often causing channel constriction. It usually does not include the upstream and downstream sandbars formed by eddy processes.

3.1 75-Mile Wash

Draining 11.47 km^2, 75-Mile Wash has experienced four debris flows in the past 18 years (August 1987, September 1990, August 2001, and August 2003). At least one other debris flow occurred between 1890 and 1960 [*Melis et al.*, 1994]. The basin has a total relief of 1531 m. Recent debris flows were initiated on the south, footwall side of this fault-controlled drainage. The channel empties onto a large debris fan at river mile 75.5 that controls Nevills Rapid (Figure 3). The debris fan is dominated by coarse particles (Figure 4). A long bar extending 500 m downstream of the fan is comprised of reworked Holocene debris-flow deposits.

An early photograph from the Robert Brewster Stanton expedition of 1890 reveals numerous changes that have taken place over the course of the past century (Figure 4). Increasing vegetation may be the most obvious change, as the encroachment of riparian vegetation has implications for photogrammetry as well as debris-fan stability. Further, and more noteworthy to this study, is the inflation of the debris-fan surface. A large boulder can be seen in the 1890 photograph on the upstream side (river flows from center-right of the photograph to the left) of the fan, just to the right of the middle of the photograph. Part of this same boulder is visible in the 1990 photograph, but a considerable portion of it has been buried. In 2005, the boulder is almost completely buried, found only by field inspection and careful photographic analysis. The photographs also show an expansion of the aerial coverage of the surface by 1990.

3.2 Monument Creek

Monument Creek drains 9.73 km^2 of steep terrain with a maximum relief of 1413 m. Four debris flows have been documented at Monument Creek in the last 40 years (1966-67, July 1984, July 1996, and August 2001). The confluence of Monument Creek with the Colorado River at river mile 93.5 forms a debris fan that maintains Granite Rapid (Figure 5), one of the largest rapids in Grand Canyon in terms of navigational severity. Previous work has described the fan and 1984 debris flow in detail [*Kieffer*, 1987; *Webb et al.,* 1988]. Sieve analysis of 1984 deposits on the distal end of the debris fan revealed a median diameter of 720 mm. A large cobble island composed of reworked debris-flow deposits is exposed at low flows approximately 100 m downstream of the fan, and higher debris-flow deposits on the downstream margin of the debris fan suggest sustained Holocene debris-flow production.

John K. Hillers, a photographer during the Powell expedition in 1872, captured a revealing composition at Monument Creek (Figure 6). Although discharge was high during exposure, the changes apparent in the repeat photographs are clear. As with the debris fan at 75-Mile Wash, the increase in riparian vegetation is substantial. By 1968, debris-flow deposition had already considerably constricted the river channel. Inflation of the surface by debris flows and the increase in riparian vegetation has nearly blocked any view of the river from this perspective by 2005.

4. Methods

4.1 Image Acquisition

Aerial photographs were taken frequently along the Colorado River in Grand Canyon over the last 40 years because of concerns about the environmental impacts of Glen Canyon Dam. Photograph date, scale, and river discharge for each available set of images are in Table 1. Photographs were taken with a metric camera or, after 1999, with a digital-frame camera.

Digitization of the photograph diapositives was conducted using an Epson Expression 1640XL. Scanning resolution was kept constant at 1600 dpi (15.875 microns).

Previous studies have shown this resolution provides the maximum retention of information while keeping noise levels to a manageable level [*Davis et al.*, 2002]. All black-and-white images were scanned in grayscale, and color images were converted to grayscale in Adobe Photoshop Elements (note: the use of trademarked names in this study does not imply endorsement). Processing was done to maximize image texture on debris fans while taking care to not increase noise levels beyond manageable levels.

4.2 Photogrammetric Model

Photogrammetric models were created using the Leica Photogrammetry Suite (LPS) associated with ERDAS Imagine 8.7. Processed stereo-pairs were imported into the block file. The LPS software uses a bundle block adjustment that simultaneously produces solutions for all images in the file. It utilizes an iterative least-squares adjustment, which is a statistical technique that 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.

Interior orientation parameters were entered from camera calibration reports for the camera used in each overflight. These parameters included a calibrated focal length, position of fiducial marks, and radial distortion values. To orientate the scanned image to the original location of the film plate with respect to the camera, the location of the fiducial marks were visually located and marked.

Establishing numerous and well distributed ground-control points (GCPs) is key in performance of the photogrammetric model. GCPs are distinguishable features on the surface that help establish the relation between the ground, camera/sensor, and image.

The unique topography of the Grand Canyon makes it difficult to measure GCPs in more conventional methods due to the lack of line of sights to orbiting geographical satellites and to benchmarks. In addition, ground panels were not installed for these photographs. I used LIDAR data overlaid on orthorectified images to locate GCPs. The individual point accuracy of this is not as high as a more conventional survey or differential GPS, but this method allows the location of numerous control points (15-20 in most cases), which accommodates for the loss of point accuracy. Collection of GCPs this way also allows for extensive use of three-dimensional photogrammetry in Grand Canyon. Check points were also gathered using this method.

Tie points are collected in order to establish the relative orientation between the two dimensional photographs. Each tie point was visually analyzed to check for accuracy and to remove tie points at unreliable positions, such as in shadows and whitewater. LPS has a built-in automatic tie-point generation function which was used to collect numerous tie points (40-100 per block file).

Triangulation was performed on the model using the bundle-adjustment method expained above and in more detail by *ERDAS* [2001]. Interior orientation parameters were fixed. GCPs were allowed to deviate slightly from the inputted values (0.1 m), which is within the range of error reported by *Davies et al*. [2002] for LIDAR points. Triangulation results were accepted if the root mean-squared error (RMSE) of the independent check points was less than 0.40 m (Table 1).

Using an automatic extraction tool, digital terrain models (DTMs) were created in the form of three-dimensional shapefiles. Optimized point collection parameters were determined by following the methods outlined in *Gooch and Chandler* [1999]. Because of the roughness of these fan surfaces, parameters were set to greatly reduce the chance of poor matches.

4.3 Data Post-Processing

Data was post-processed to increase accuracy of the surface models. All points lying within the river were deleted since the dynamic nature of whitewater is insufficient for photogrammetric analysis. Points that represented the tops of readily identified trees and shrubs were also removed to ensure representation of sedimentary deposits.

For each pixel match, a correlation coefficient, r, is calculated between the 5 pixel by 5 pixel windows used in the matching procedure [*ERDAS,* 2001]. The quality of each point was assessed by LPS and designated as "excellent, good, fair, poor, and suspicious," fair and poor matches were subsequently excluded from the shapefile. A point is deemed excellent if the r value calculated between the corresponding windows is ≥ 0.90. A point is deemed good if $0.80 \leq r < 0.90$. Each point elevation is then compared to the average elevation of points within a window measuring roughly 0.5 m along the side, and the difference of the average elevation and point elevation is compared to the standard deviation of the neighboring extracted elevation values (outside of the 0.5 m window). If the difference is greater than 3σ, the point is deemed suspicious and was removed [*ERDAS,* 2001]. Finally, preliminary triangular integrated networks (TINs) were produced and overlaid on orthorectified images to check for erraneous points, obvious inaccuracies not detected by LPS's status procedure. Examples of these types of points include spikes on smooth sandbars and depressions on debris fans deeper than the river level.

4.4 Morphological Derivatives

In addition to the morphological derivates explained below, profiles of debris-fan surfaces were produced for years of expected significant change (*i.e.* before and after a debris flow) and for the earliest and most recent surface models (Figures 3 and 5). Quantifying pre-1984 surface conditions is difficult owing to the limited number of years with aerial photography, the coarse of resolution of these images, and the relatively high and unsteady discharge of the Colorado River. Despite these problems, some information about debris-fan morphology was derived from these early photographs.

4.4.1 Debris Fan Volume

The shapefiles extracted from each set of aerial photographs were used to create TINs. For certain morphological variables, TINs provide the most accurate surface representation because there is no smoothing of the data from interpolation effects. For consistency among volumetric calculations, a base plane elevation was chosen of 714 m for Monument Creek and 785 m for 75-Mile Wash; these elevations are the lowest points on the respective surface models. A base plane is a horizontal plane of constant elevation. Selecting a base plane allowed for absolute year-to-year comparisons.

In March 2005, intensive ground surveys were conducted on both debris fans to estimate a volume. The surveys at 75-Mile Wash and Monument Creek had 739 points and 607 points, respectively. As with the photogrammetry generated surfaces, the survey data were used to create TINs to represent surface topography.

4.4.2 Debris Fan Area

The edges of the debris fan were delineated using survey data. These boundaries were adjusted for years in which debris-flow deposits extended beyond the previously defined boundary. The water/debris-fan edge was considerably more variable as slight variations in discharge or fan morphology have a large effect by exposing or covering boulders resolvable in the imagery. Debris-fan edges were determined for every year of survey or aerial photograph to maximize the confidence of debris-fan extent.

4.4.3 River Constriction

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]. I produced percent constriction (C_w) to estimate the effects of debris flows and reworking on channel width using

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

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.

In addition, I developed a new method of measuring percent constriction of the river by a debris fan. The new method was developed in response to analyzing the effects of the July 1996 debris flow at Monument Creek (Figure 4). The main deposition of this flow occurred upstream of the narrowest point of the rapid and was therefore undetected by conventional percent constriction estimates. To incorporate the entire fan's effect on channel width, I estimated an average constriction, by incorporating an area/length ratio of the rapid and the upstream and downstream stretches of river, as

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

where C_a is percent constriction, 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 stretches of river used in the analysis. This method gives an average percent constriction along the rapid as it integrates the width along the entire debris-fan in addition to an average width of the upstream and downstream reach of river. It should therefore signal any net deposition or erosion along the water/debris-fan boundary, instead of just depicting changes at the point of narrowest constriction.

4.5 Discharge Correction

For some surface models, a significant amount of the debris fan is not visible because of submergence during discharges higher than the typical steady 226 m^3/s of most aerial photographs. I normalized the surface area to the average of the years in which a steady discharge of 226 m^3/s was recorded. A conservative assumption was made in that the submerged surface was just below water level, and the volume was then calculated using the selected base plane. 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.

In some cases, photographs were taken at discharges lower than 226 m^3/s. The 1984 photographs were taken at an unsteady discharge of 144-226 m^3/s, exposing additional debris-fan surface. The base planes I choose for morphological derivatives were the low point on the exposed consistent discharge debris fans. By using this base plane during analysis of low discharge fan, I only evaluated the fan surface above the 226

m^3/s stage line.

5. Surface-Model Quality Assessment

The acceptance of a digital terrain model 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 assessment of DTM quality. Areas where distortion is high suggests failure of the surface model, whereas if there was no indication of high distortion, the DTM is deemed acceptable. Resultant TINs were overlaid on orthophotographs and assessed on relative representation of surface features, such as sand bars, river banks, incised channels, old debris-flow terraces, and highly textured debris-fan surfaces.

Three methods of quantifing the overall performance of a photogrammetric survey were assessed: (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 stereo-pairs of the same overflight.

The least-squares adjustment used by LPS provides a measurement of the stereo matching precision. A root mean-square error (RMSE) is calculated between the predicted pixel matching location and the actual matched location. This value represents the internal precision of the pixel-matching algorithm. All algorithms reported a RMSE of 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 gauged the model's ability to predict real coordinate values. I 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 SD, which shows a consistent accuracy assessment.

Reliability was assessed using DTMs produced from 1999 photographs 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 confirms the reproducibility of this photogrammetric procedure.

Lane et al. [2003] showed that photogrammetric techniques can produce more reliable volume estimates than direct survey because photogrammetric techniques produce high density spatial data even though the precision from point to point may be lower. In the above quantitative tests, residuals were found to be random in orientation. With no detectable systematic error in the DTMs and assuming a Gaussian distribution of error [*Lane et al*., 2003], the derived volume assessments appear to be highly accurate. Because of the high quality surface models and high point density, these results are likely of greater accuracy than any other previously published Grand Canyon debris-fan volumes. Because of the low distortion in areas of interest, the orthophotograph derivatives of surface area and percent constriction are considered highly accurate and are reported here as ± 15 m^2 and ± 0.2 %, which is insignificant when considering the effects of discharge on these measurements.

6. Results

Results at both debris fans show significant aggradation over the period of aerial photography and direct survey. From 1984 to 2005, the debris fan at the mouth of 75-Mile Wash increased over 10,000 m^3, and the debris fan at the mouth of Monument Creek grew by almost 8000 m^3 (Table 2, Figure 7). As expected, the largest increases in debris-fan volume occurred after the occurrence of a debris flow. Surprisingly, both fans exhibit a gradual increase in volume from June 1992 to March 1996, which was a period of quiescence at the study areas, since no debris flows occurred and the river experienced normal regulated flow conditions. In subsequent years, debris-fan volume remained relatively stable. The largest decreases in debris-fan volume were after relatively high river discharge.

6.1 Changes in the Debris Fan at 75-Mile Wash

Two-dimensional data for 1965 and 1973 reveals a relatively small debris fan; however, unsteady river discharge during these overflights prevents any conclusive quantification to be made. The 1984 aerial photographs provided the earliest surface model representation at this fan (Figure 7, Table 2). A debris flow in August 1987 increased the fan volume by 4200 m^3, and a second debris flow in 1990 caused an increase of nearly 10,000 m^3; this value is similar to the 12,000 m^3 estimated by *Melis et al.* [1994]. A peak discharge of 966 m^3/s in January 1993 reworked part of this debris fan and decreased the volume by ~3000 m^3. A gradual increase totaling just over 5000 m^3 was documented from May 1993 to March 1996, probably resulting from sand deposition at the margins of the debris fan and growth of riparian vegetation. From March 26 to April 2 in 1996, a controlled flood of 1,357 m^3/s reworked many debris fans in Grand Canyon [*Webb et al.,* 1999b], and the debris fan at 75-Mile Wash decreased in volume by about 4600 m^3. Afterwards, relatively low dam releases through 1999 resulted in slight increases in volume at a similar rate as the increase from 1993 to the controlled flood, again probably resulting from the contribution of sand deposition and growth of riparian vegetation. Three significant events—debris flows in August 2001 and 2003 and the second controlled flood in November 2004—led to a surveyed volume of 58,800 m^3 in March 2005, which is very close to the values measure before these events.

Interannual change in surface area was insignificant for 75-Mile Wash. A slight increase was detected through from 1992 to 1996; however, all other variations were proportional to discharge. The significant decreases in surface area recorded for 1998 and 1999 are an effect of relatively high discharge at the time of photographic overflights. A similar trend was found for both constriction techniques.

Profiles extracted from the surface models reveal significant increases in surface elevation (Figure 8). For both transects (A-A' and B-B', Figure 8), the 1984 surface is considerably lower than more recent surfaces. The 1988 surface shows the changes brought about by the 1987 debris flow, and the 1992 profiles show the effects of the 1991 event. Not only do these profiles exhibit substantial aggradation (as documented by *Webb* [1996] using repeat photographs, Figure 4), but they also show a shift in the shape of the profiles. The A-A' comparisons reveal a more negative curvature in the cross-fan profile. The B-B' transect shows that the largest increase in volume is near the geometric center of the debris-fan, causing a shift from an overall positive curvature of the profile to an overall negative curvature.

6.2 Changes in the Debris Fan at Monument Creek

Estimates of the 1966-1967 and 1984 debris flows could not be made due to missing imagery or failure of resultant DTMs of Monument Creek before and between these dates. The cumulative result of these events along with high flows in 1983 and 1984 are detected as the 1984 surface model, which produced a volume of 43,200 m^3. The 1984 deposit was further reworked by relatively high flows from 1984-1987 as is depicted in the 1989 surface model, which has a volume of about 42,400 m^3. As was the case with 75-Mile Wash, I observe a gradual increase in debris-fan volume during the low flows from June 1990 through March 1996. Reworking from the 1996 controlled flood caused a volume decrease at the Monument Creek debris fan of nearly 2000 m^3. In July 1996, a debris flow reached the river at Monument Creek, aggrading the fan surface by 4,300 m^3. Afterwards, debris-fan volume remained fairly constant with a small increase until 1999. Debris flows in August 2001 and 2003 in addition to significant reworking by the November 2004 controlled flood resulted in a surveyed volume of 51,000 m^3 in March 2005, which is an increase of less than 2000 m^3 since the 1996 debris flow.

Surface-area changes were more significant at Monument Creek than at 75-Mile Wash; the 1996 debris flow increased surface area here by 800 m^2, most of the increase occurred in the upstream stream pool (Figure 5). The significant decreases in surface area recorded for 1998, 1999, and 2005 are an effect of relatively higher discharge during photograph exposure or ground survey. The constriction ratios showed conflicting results for the 1996 debris flow. The more conventional method showed virtually no change in river constriction, but the method developed in this paper showed an increase of greater than 4% constriction.

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 (Figure 8). Further comparisons reveal a more negative curvature for modern surfaces along the D-D' transect.

7. Discussion and Conclusions

Previous researchers have suggested that the change in flood regime brought about by closure of Glen Canyon Dam will affect the morphology of coarse-particle deposits downstream in Grand Canyon [*Howard and Dolan*, 1981; Kieffer, 1985]. It follows from earlier ideas that a quasi-equilibrium relation will exist even within a dynamic river system such as the Colorado River through Grand Canyon and that a long-lasting change in that system will see a response by the morphology to form a new quasi-equilibrium state [*Langbein and Leopold*, 1964; *Leopold,* 1969]. The time it takes for a landform to respond to a system change depends on many variables including the magnitude of change, the processes at work, and the characteristics of the landform, most notably particle-size distribution. It has been well documented that sandbars lining the river banks of the Colorado in Grand Canyon have already undergone a system-wide response to the change in flow regime brought about by Glen Canyon Dam [*Howard and Dolan*, 1981;

Schmidt and Graf, 1990; *Schmidt et al.,* 1995]. Although time since the closure of the dam has not been long enough to observe a system-wide change in debris-fan morphology since not all debris fans have experienced debris flows, it has been suggested that the morphology of certain debris fans has begun to respond to the change in the river's flow regime [*Melis et al.*, 1994; *Webb et al.,* 1999a; *Magirl et al.,* 2005].

Our results quantify recent changes in debris-fan size and shape for 75-Mile Wash and Monument Creek. From 1984 to 2005, I measured increasing debris-fan volumes due to distinct depositional events and gradual fill of topographic lows (Figure 7). The debris fans at 75-Mile Wash and Monument Creek have both experienced four debris flows since flow regulation began. The effects pertaining to the deposition of the September 1990 event at 75-Mile Wash and the July 1996 event at Monument Creek are easily detectable using photogrammetry owning to sufficient quality aerial photography available previous and post event. These are not true representations of total volume of sediment delivery because matrix dewatering delivers fine-grained sediments to the river immediately and it has been shown that some reworking occurs at relatively low dam releases [*Webb et al.,* 1988; *Larsen et al.,* 2004]. The aerial photographs were taken at least one month after the events, and therefore they capture net deposition. Ignoring the controlled floods of 1996 and 2004, I see no reduction in debris-fan volume, surface area, or percent constriction; the reworking by the controlled floods was minimal compared to the amount of deposition on the fans. This suggests the relation between morphology and stream power at these debris fans is in a transitory state.

The gradual increase in debris-fan volume observed for both fans through the 1990s is likely an effect of visually smoothing the fans. Numerous processes act to produce this effect, including the preferential growth of small, non-resolvable plants and settling of sediments in local topographical lows. The debris-fan surfaces in Figure 5 illustrate the end members of this gradual change. This creates a positive feedback relation in that the establishment of plants can enhance sediment entrapment, and the presence of sediment can enhance vegetation establishment. This effect is enhanced by the inability for photogrammetry to detect elevation points on smooth surfaces. A better understanding of these processed on fans in Grand Canyon could be important in reevaluating long-term changes in debris fans in addition to reworking events. Flash flooding occurs more regularly in these tributaries than debris flows and could be a process responsible for fine-grained aggradation and topographic smoothing. As the flood disperses on the debris fan, it would likely transport its load and the fines from the matrix that usually forms the core of the boulder piles to local topographic depressions in addition to depositing sediment transported from the tributary. Although no systematic error was detected in the photogrammetric models, part of the volume creep could be due to random noise. The fact that similar trends are observed at both fans during the same period of quiescence suggests this source of error is minimal.

Although it is probable that surface area has increased historically, high water during the earliest photographs does not allow conclusive interpretations of area changes. The most significant change was the nearly 800 m^2 increase due to the July 1996 debris flow at Monument Creek, which was mostly confined to the upstream pool. While surface area remains relatively unchanged, the volume has intermittently increased since

1984. This is not surprising as bedrock to the upstream side and old debris flow terraces to the downstream side of the debris fan confine the debris flows; therefore, any increase in surface area occurs mostly into the river, constricting the flow, which increases the river's reworking potential. The surface of the debris flow is unconfined, allowing for significant aggradation in the vertical direction.

Our results of river constriction are consistent with those of *Webb et al.* [1999b] in that neither method is very sensitive to changes brought about by small floods. However, based on my results, I conclude that the area/length method of determining river constriction can be more sensitive than previous methods to changes caused by debris flows if aggradation of the fan occurs anywhere besides the point at the narrowest reach of the river. Although determining maximum constriction is important in considering maximum stream power, it does not necessarily reflect the entire change in the rapid's hydrology. Again, the inconclusiveness of this metric in regards to aggradation, suggests the increases in observed volume are mainly due to vertical inflation of the debris-fan surface.

It is apparent in repeat photography that the surfaces at these sites have expanded, further constricting the river in addition to inflating the surface since 1890 (Figures 4 and 6). Because the time frame represented by aerial photographs with comparable discharges is limited to the past 21 years, I conclude that the events causing the most significant river constriction happened before the aerial photograph flight of October 22, 1984. *Melis et al.* [1994] report evidence for a debris flow for 75-Mile Wash occurring between 1890-1960, and *Webb et al.* [1988] report debris flows during 1966-1967 and July 1984 at

Monument Creek. These events combined with any undocumented events at these sites are the likely causes of the presently observed constriction. Recent debris flows have had a greater effect in increasing the volume of sediment stored on the debris fans, not constricting the river, at these two major debris fans.

The increases in debris-fan elevation are likely to have occurred more recently. Evidence for this lies in the comparison of surface profiles (Figure 8). In every profile, the most recent surface models are the highest overall surface. In addition to the fans increasing in size, they have also changed in form. Early surface models depict a downslope profile have a roughly concave up (positive curvature) shape to it. Most recent profiles show a modification to a concave down (negative curvature) profile. The likely cause of this is a shift of dominant reworking processes. Today, most reworking of fresh debris-flow deposits occurs along the water/debris-fan interface as bank collapse, thus leaving intact the majority of the original deposit. The dominant reworking process before river regulation was natural floods with high stages that would overtop the debris fan, entraining surface particles, in addition to bank reworking. Only the debris fan near the mouth of the tributaries was preserved in form. Not only would this change the concavity but would also lower the surface. Cycles of debris flows and large floods would leave the fan in a relatively stable morphology. Since flow regulation, fans experiencing debris flows have likely not only aggraded as previously suggested [*Howard and Dolan*, 1981; *Webb et al.,* 1999b] but also changed in form (*i.e.,* more negative concavity).

The reduction of discharge by Glen Canyon Dam has likely reduced the river's potential for reworking of debris fans [*Howard and Dolan,* 1981; *Keiffer,* 1985; *Webb et al.,* 1989; *Magirl et al.,* 2005], particularly higher stages that were exceeded by typical pre-dam floods. Because of the coarseness of the debris-flow deposits, significant stream power is necessary to entrain and transport large particles. The river's control on the geomorphic framework of the debris fans is dictated by its potential for reworking. The debris fan's control on river hydraulics is contingent on the amount of material deposited on the fan and into the river, thereby constricting the channel width. An increase in river constriction will increase the 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 has resulted in larger debris fans.

Photogrammetry, when used with care, is a very powerful tool to derive morphological variables in Grand Canyon. It allows the production of surface models for years which aerial photographs exist. Since aerial surveys of Grand Canyon have occurred on a yearly basis since 1988 and intermittently since 1965, it is possible to explore the changes in debris-fan morphology throughout the time of dam operations.

From the quantification of morphological variables, the comparison of surface profiles, and the analysis of repeat photography, I conclude that significant aggradation at 75-Mile Wash and Monument Creek has occurred since closure of Glen Canyon Dam. Previous floods have slightly reworked debris flow deposits; however, the material removed during these events is far less than amount deposited by the debris flows. The high frequency of debris flows at these locations is an important cause of this surface inflation; however, I must consider other influences such as climate and the reduction of flow from the closure of Glen Canyon Dam. This conclusion is consistent with previous speculation by *Howard and Dolan* [1981] that debris fans will likely aggrade because of the reduction in flow volume brought about by Glen Canyon Dam. In addition, I conclude that dam operations have altered the concavity of these surfaces by changing the dominant reworking process at higher stages.

Although it is uncertain if the debris fans at 75-Mile Wash and Monument Creek will continue to aggrade, it is probable that fans at tributary junctions that have not experienced significant debris flow events since dam closure will aggrade when a debris flow does occur and if the current flow regime of the Colorado River continues. To further stabilize the system downstream of Glen Canyon Dam, more frequent flooding should occur. Management of flow regulation should consider debris flow events when deciding on controlled flooding especially debris flows that greatly constrict the river, producing potentially hazardous conditions to whitewater recreationalists.

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.

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

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 withing the Colorado River ecosystem, *U.S. Geol. Surv. Open-File Rep., 02-470*, 65 pp.

ERDAS (2001), *Imagine OrthoBASE User's Guide*, ERDAS Inc., 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.

Griffiths, P.G. (1996), Initiation and frequency of debris flows in Grand Canyon, Arizona, M.S. Thesis, Univ. of Ariz., Tucson.

Griffiths, P.G., R.H. Webb, and T.S. Melis (1997), Initiation of debris flows in bedrock canyons of the Colorado River, USA, in *Debris-flow hazards mitigation: Mechanics, prediction, and assessment*, edited by C. Chen, pp. 12-20, American Society of Civil Engineers, New York.

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.

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.

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.

Langbein, W.B., and L.B. Leopold (1964), Quasi-equilibrium states in channel morphology, *Am. J. Science, 262*, 782-794.

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-Resources Investigations 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. Geology, 102*, 1-9.

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. Survey Prof. Paper 1493*.

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

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

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. Survey Prof. Paper 1677*.

Webb, R.H. (1996), *Grand Canyon, a century of environmental change*, 290 pp., University of Arizona Press, Tucson, Ariz.

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, J.G. Elliott (1999b), Reworking of aggraded debris fans, in The controlled flood in Grand Canyon: Scientific experiment and management demonstration, edited by R.H. Webb, J.C. Schmidt, G.R. Marzolf, and R.A. Valdez, pp. 37- 511, 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-Resources Investigations Rep.*, *00-4055*, 67 pp.

Webb, R.H., T.S. Melis, T.S., and P.G. Griffiths (2003), Debris flows and the Colorado River, in *Grand Canyon Geology*, 2nd edition, edited by S.S. Beus, and M. Morales, pp. 371-390, Oxford University Press, New York.

Table 1. Metadata for aerial photography used in image analysis of changes in debris fans at 75-Mile Wash and Monument Creek.

Aerial Photograph Date	Estimated River Discharge (m3/s)	Scale	Pixel Resolution (cm)	RMSE (pixels)	RMSE of Z (m) for check points
75-Mile Wash					
5/14/1965	680-792	1:12000	19.05	--	--
6/17/1973	76-396	1:14400	22.86	--	--
10/22/1984	144-226	1:3000	4.76	0.6100	0.311
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	226	1:4800	7.62	0.6727	0.3236
5/31/1993	226	1:4800	7.62	0.3971	0.2979
5/30/1994	226	1:4800	7.62	0.6743	0.3135
5/29/1995	226	1:4800	7.62	0.5101	0.1931
3/25/1996	226	1:4800	7.62	0.7003	0.3919
4/6/1996	226	1:4800	7.62	0.4789	0.3074
9/2/1996	226	1:4800	7.62	0.7078	0.3907
9/1/1997	226	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	226	1:4800	10.00	0.7707	0.3902
Monument Creek					
5/14/1965	680-792	1:12000	19.05	--	--
6/17/1973	76-396	1:14400	22.86	--	--
10/22/1984	144-226	1:3000	4.76	0.7764	0.2429
5/28/1988	320	1:4800	7.62	--	--
10/8/1989	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
6/30/1992	226	1:4800	7.62	0.5739	0.2859
5/31/1993	226	1:4800	7.62	0.4742	0.3448
5/30/1994	226	1:4800	7.62	0.7394	0.2287
5/29/1995	226	1:4800	7.62	0.4213	0.3855
3/25/1996	226	1:4800	7.62	0.8002	0.2922
4/6/1996	226	1:4800	7.62	0.9175	0.3388
9/2/1996	226	1:4800	7.62	0.9412	0.3666
9/1/1997	226	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	226	1:4800	10.00	0.9076	0.3350

Table 2. Debris-fan volumes, surface areas, and constriction ratios for 75-Mile Wash and Monument Creek.

	Volume	Surface Area	Maximum Constriction (Cw)	Average Constriction (Ca)
75-Mile Wash				
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	--	--

Figure Captions

Figure 1. Colorado River in Grand Canyon, Arizona. Shaded area represents the drainage area of the Colorado River, not including the Little Colorado River, Kanab Creek, and Havasu Creek, between the Paria River and Grand Wash Cliffs. Canyon rims are denoted by the dotted line. Locations of the debris fans at 75-Mile Wash and Monument Creek are indicated by the bullseye.

Figure 2. Annual peak flood series for the Colorado River near Grand Canyon, AZ (USGS station 09402500). Arrow signifies the beginning of river regulation by Glen Canyon Dam.

Figure 3. Aerial photograph of 75-Mile Wash taken September 2, 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 4. Photographs of Nevills Rapid, (RM 75.5) showing the general aggradation of the 75-Mile Wash debris fan. The view is from river left looking upstream. (A) Photograph taken in 1890 by R.B. Stanton 407; courtesy of the National Archives (B) Taken January 27, 1990 by Ralph Hopkins; courtesy of the Desert Laboratory Repeat Photography Collection (C) Matched photograph taken March 6, 2005 by Steve Young; courtesy of the Desert Laboratory Repeat Photography Collection stake 1445.

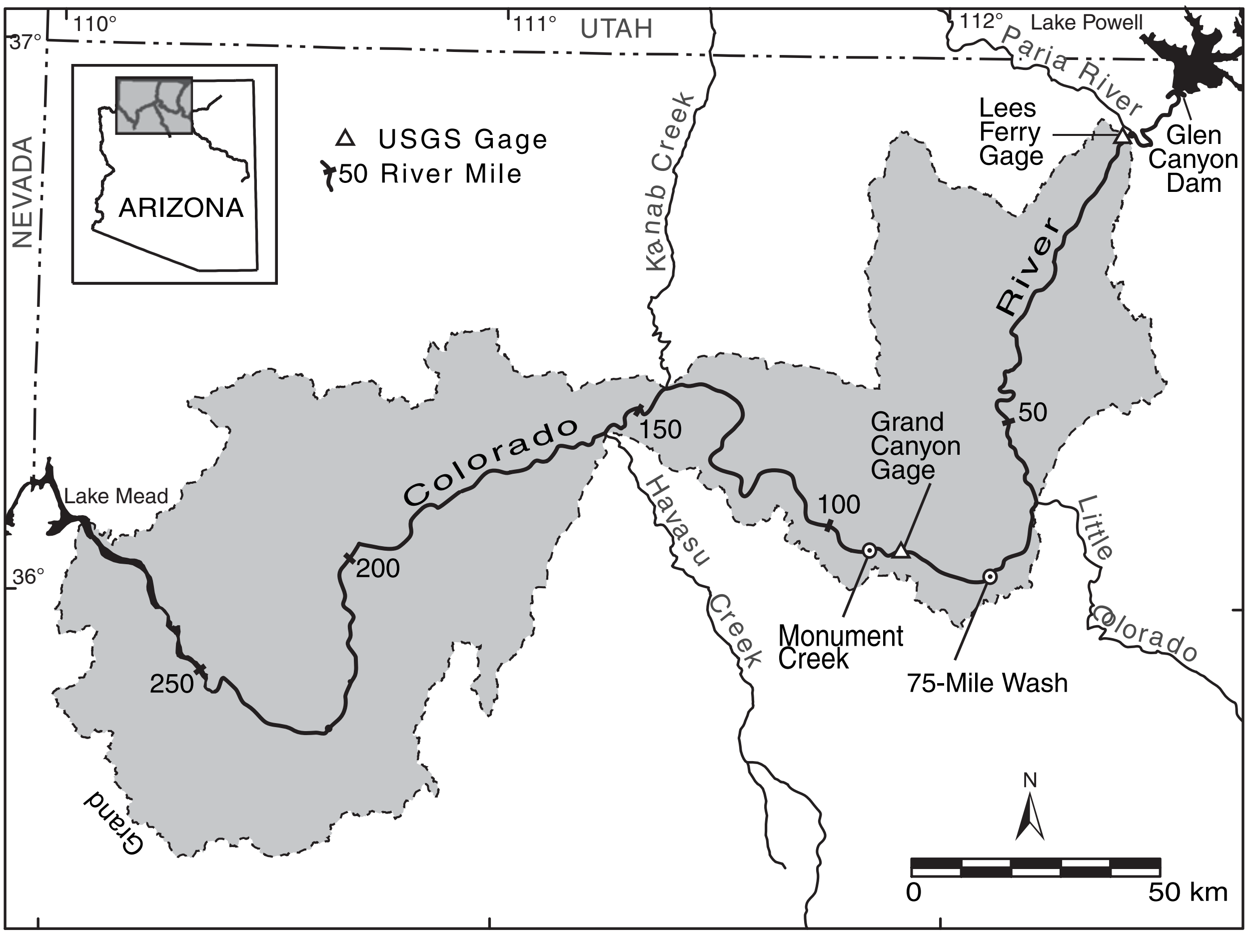
Figure 5. Comparison of aerial photographs for Monument Creek showing the effects of the July 1996 debris flow on the debris fan. (A). Aerial photograph taken April 6, 1996. Line representing the maximum constriction (C_w) and constriction at the head of the rapid (W_h) are shown. Thicker lines represent profiles extracted for Figure 6 at C-C' and D-D'. The arrow indicates flow direction. (B) Aerial photograph taken September 2, 1996. Maximum constriction (C_w) has not changed, but constriction at the rapid's head (W_h) has increased. Note the increased surface texture of fresh debris-flow deposits.

Figure 6. Photographs of Granite Rapid looking upstream and showing debris fan aggradation. (A) Taken September 1, 1872 by John K. Hillers; courtesy of the National Archives. (B) Taken September 16, 1968 by Hal Stephens; courtesy of the Desert Laboratory Repeat Photography Collection (C) Taken January 30, 1990 by Tom Brownold; courtesy of the Desert Laboratory Repeat Photography Collection (D) Taken March 8, 2005 by Bruce Quayle; courtesy of the Desert Laboratory Repeat Photography Collection stake 1462.

Figure 7. (A-D) Results of the surface model and orthophotograph analysis for 75-Mile Wash (grey line) and Monument Creek (black line). (A) Estimated volume for years beginning in 1984. (B) Debris-fan surface area derived from orthophotographs. (C) Percent constriction (equation 1). (D) New percent constriction (equation 2). (E) Plot of the average daily discharge values for the Colorado River near Grand Canyon, AZ (USGS gauging station 09402500).

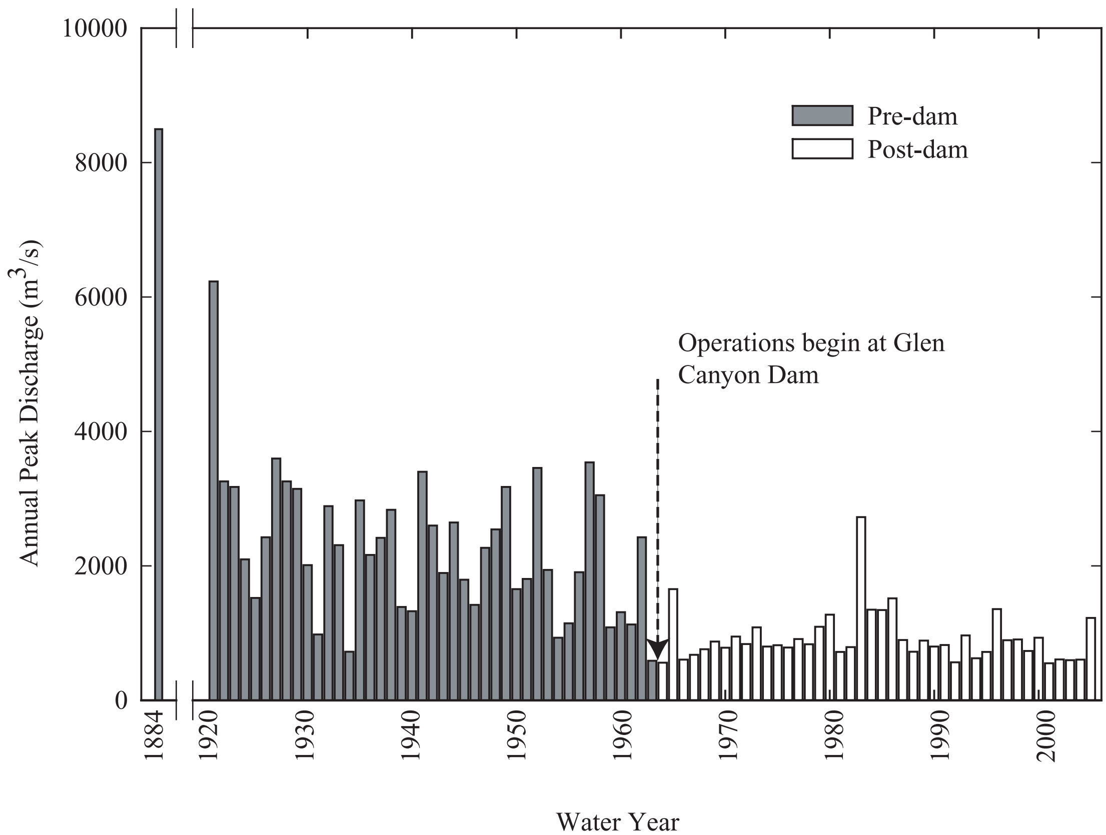
Figure 8. Profiles derived from select surface models showing surface inflation and a change in curvature. Locations of transects can be found on Figures 3 and 5. (A) Profiles extracted from 75-Mile Wash surface at transect A-A'. (B) Profiles extracted from 75-Mile Wash surface at B-B'. (C) Profiles from the Monument Creek surface at C-C'. (D) Profiles from the Monument Creek surface at D-D'.

Figure 1.



110°
111°
UTAH
112°
Lake Powell
37°
Paria River
NEVADA
ARIZONA
USGS Gage
50 River Mile
Kanab Creek
Lees
Ferry
Gage
Glen
Canyon
Dam
River
50
Grand
Canyon
Gage
150
Colorado
Lake Mead
100
Little
Colorado
Havasu
Creek
36°
200
Monument
Creek
75-Mile Wash
250
Grand
N
0
50 km

Figure 2.



10000
8000
6000
4000
2000
0
Annual Peak Discharge (m3/s)
Pre-dam
Post-dam
Operations begin at Glen
Canyon Dam
1884
1920
1930
1940
1950
1960
1970
1980
1990
2000
Water Year

Figure 3.

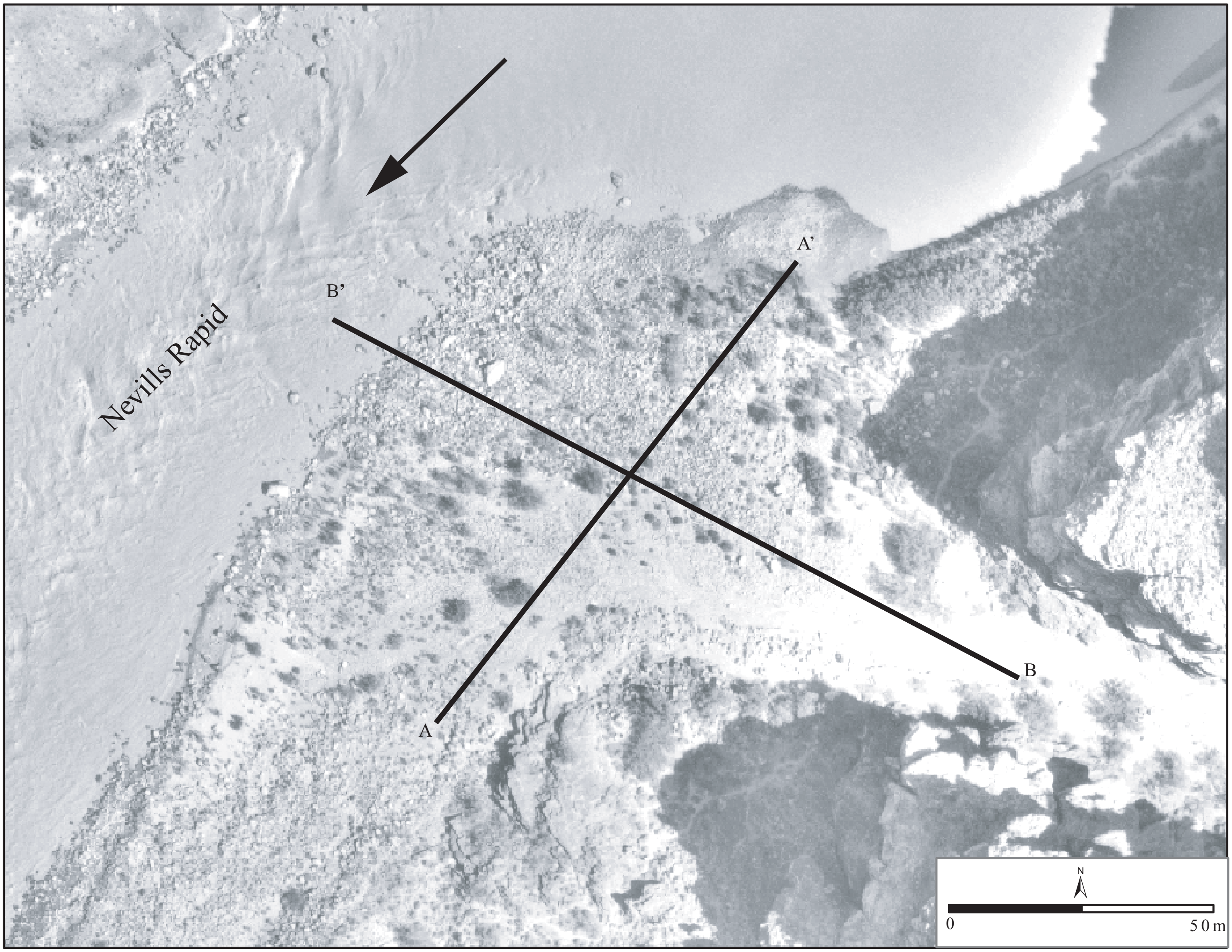


Figure 4A.

Figure 4B.

Figure 4C.

Figure 5.

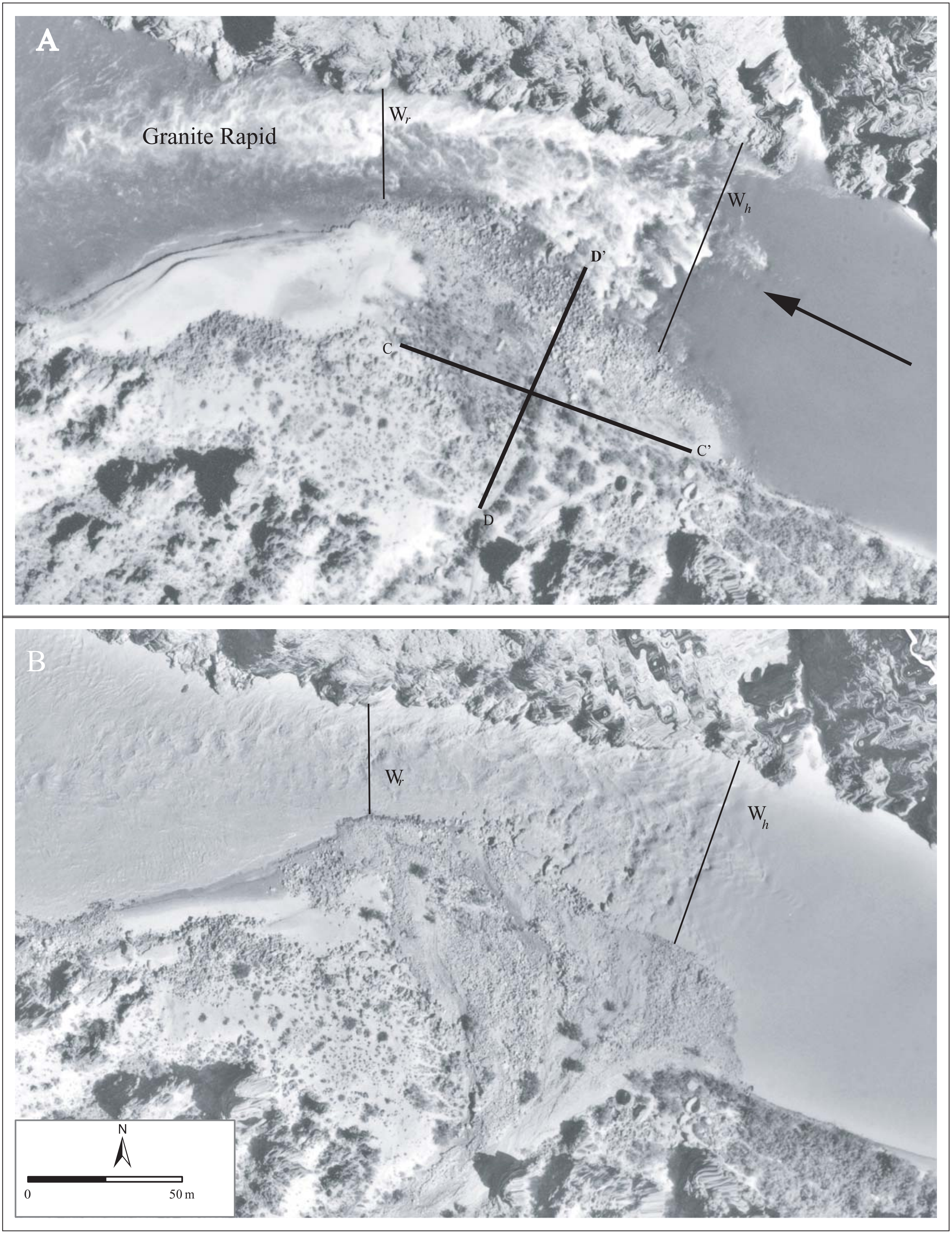


Figure 6A.

Figure 6B.

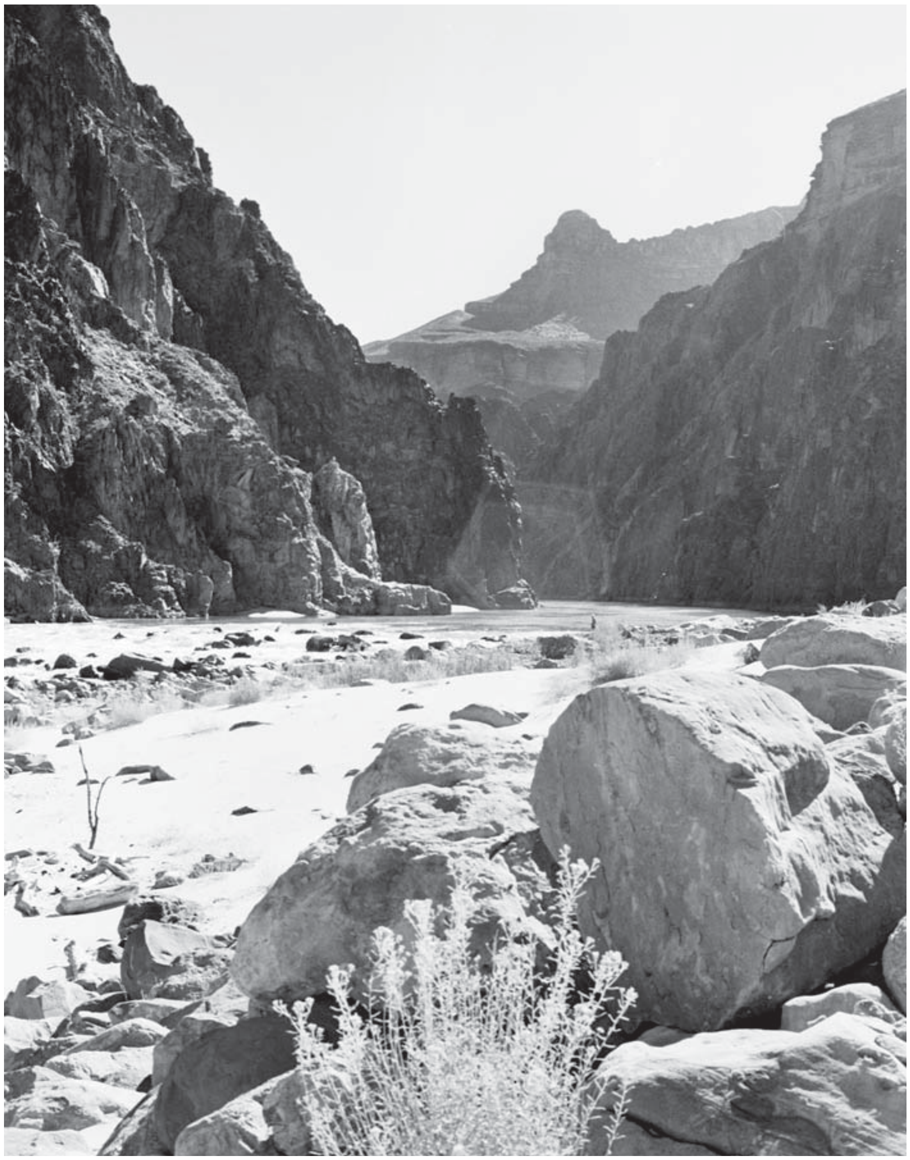


Figure 6C.

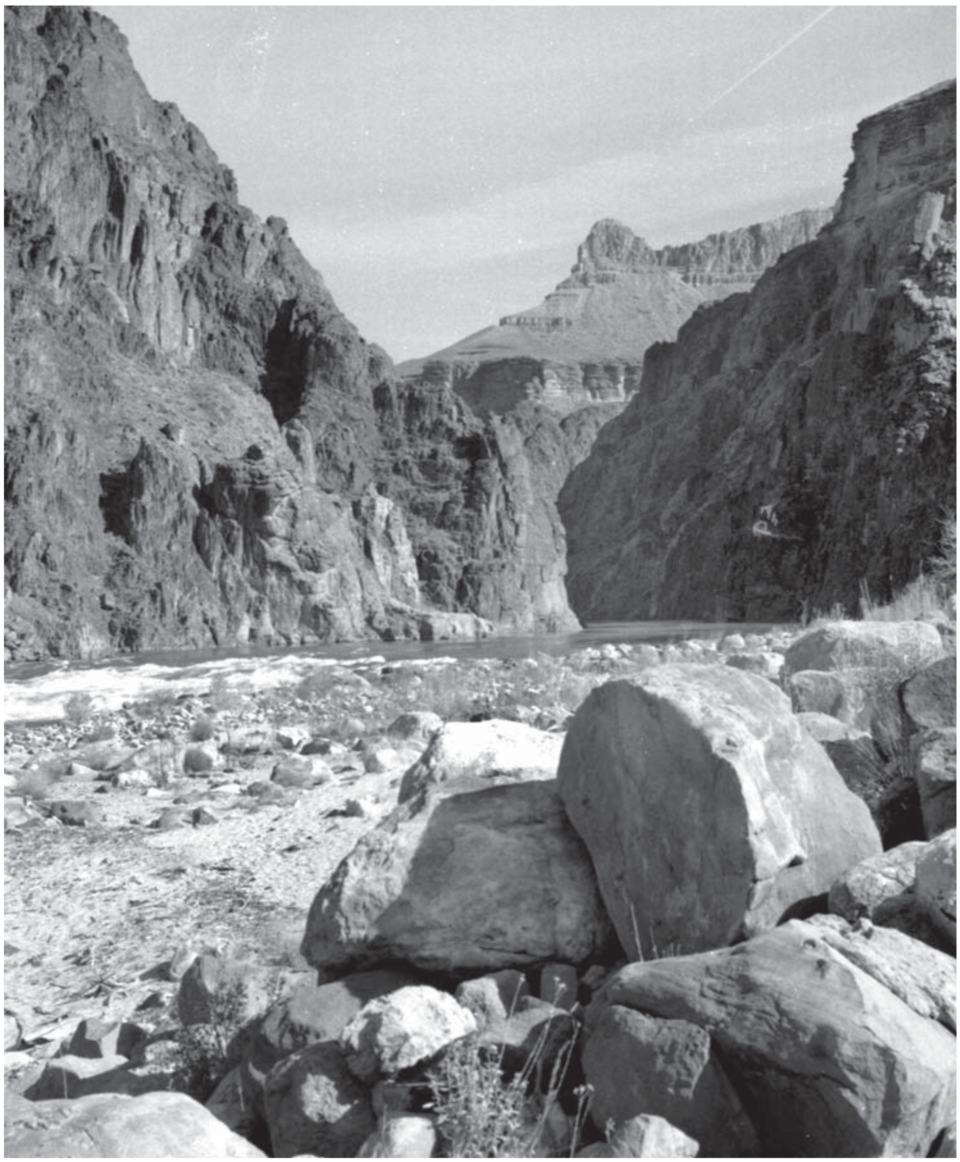


Figure 6D.

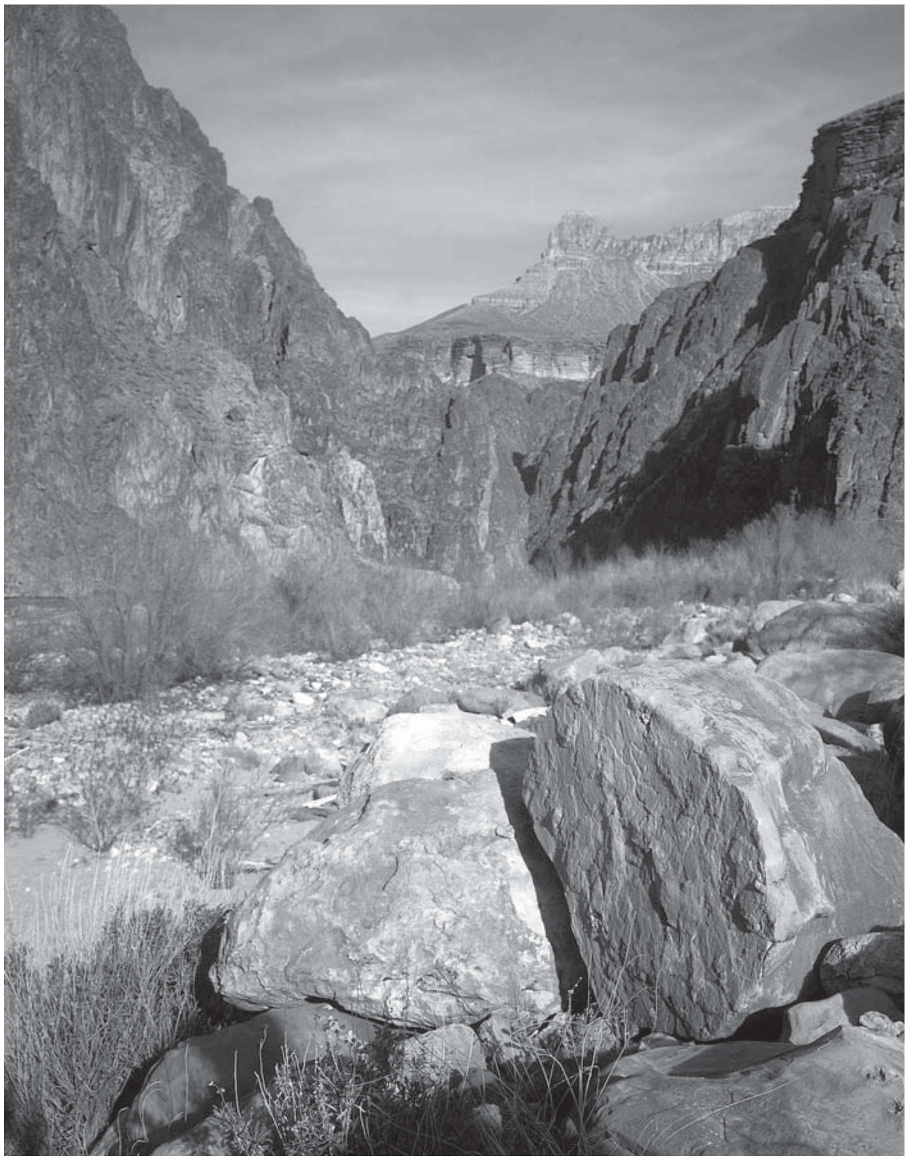


Figure 7.

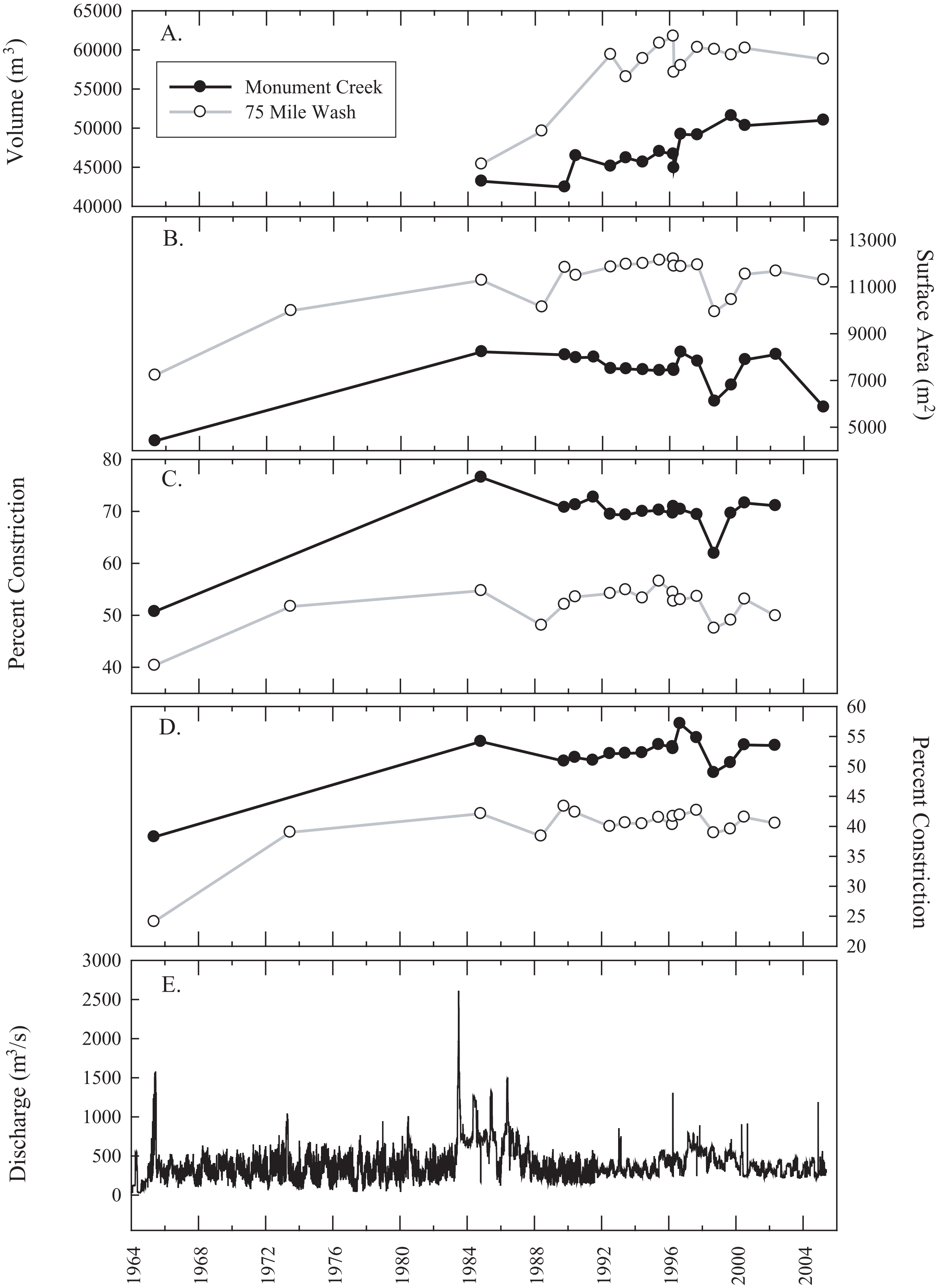
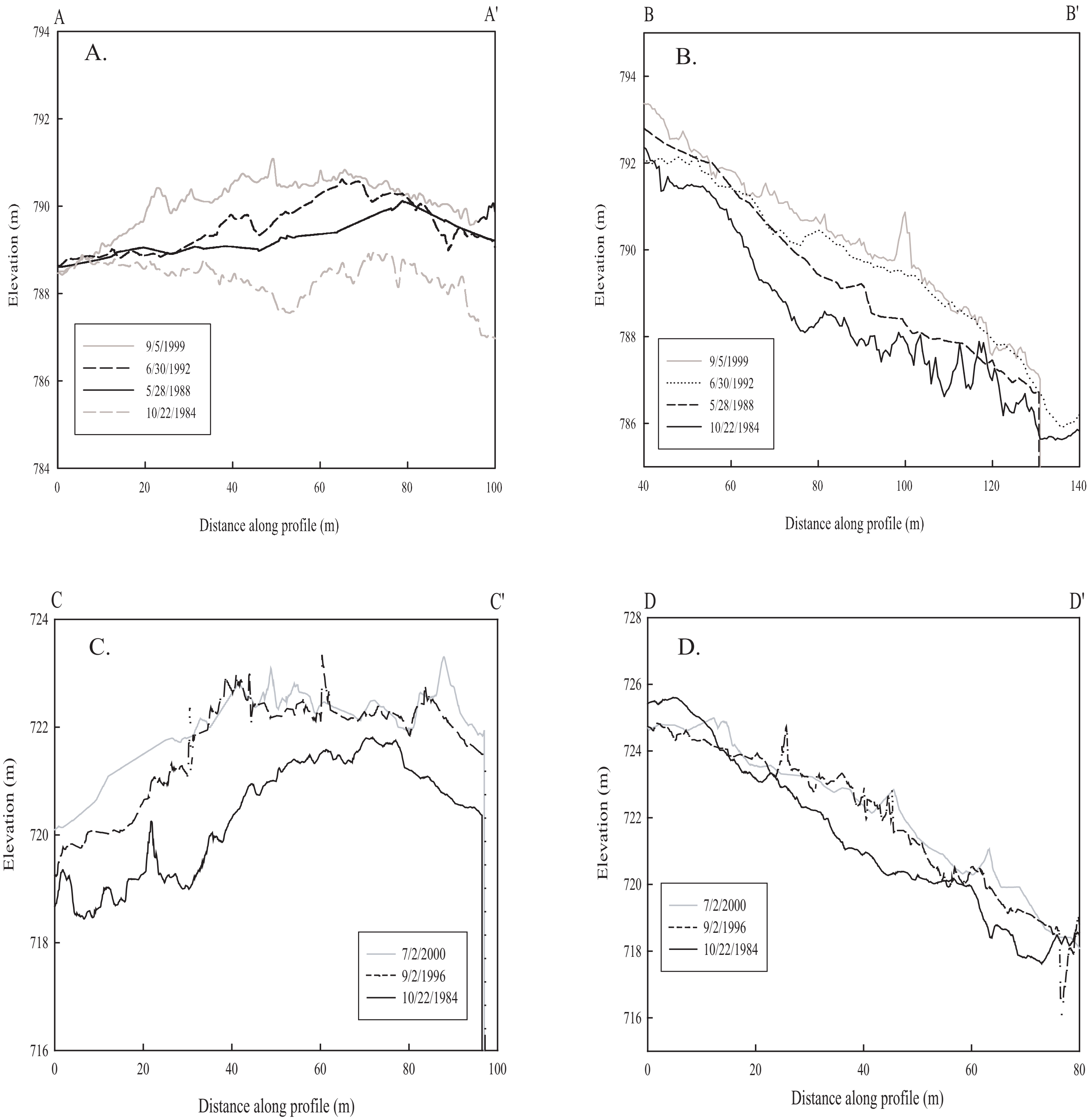

A.
B.
C.
D.
E.
Monument Creek
75 Mile Wash
Volume (m3)
Surface Area (m2)
Percent Constriction
Percent Constriction
Discharge (m3/s)
65000
60000
55000
50000
45000
40000
13000
11000
9000
7000
5000
80
70
60
50
40
60
55
50
45
40
35
30
25
20
3000
2500
2000
1500
1000
500
0
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004

Figure 8.


A
A'
A.
794
792
790
788
786
784
Elevation (m)
0
20
40
60
80
100
Distance along profile (m)
9/5/1999
6/30/1992
5/28/1988
10/22/1984
B
B'
B.
794
792
790
788
786
Elevation (m)
40
60
80
100
120
140
Distance along profile (m)
9/5/1999
6/30/1992
5/28/1988
10/22/1984
C
C'
C.
724
722
720
718
716
Elevation (m)
0
20
40
60
80
100
Distance along profile (m)
7/2/2000
9/2/1996
10/22/1984
D
D'
D.
728
726
724
722
720
718
716
Elevation (m)
0
20
40
60
80
Distance along profile (m)
7/2/2000
9/2/1996
10/22/1984