Prepared in cooperation with Northern Arizona University and Utah State University

Monitoring Fine-Grained Sediment in the Colorado River Ecosystem, Arizona—Control Network and Conventional Survey Techniques

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By Joseph E. Hazel, Jr., Matt Kaplinski, Roderic A. Parnell, Keith Kohl, and John C. Schmidt

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Cover: View to the southeast of Comanche Point in eastern Grand Canyon National Park, Arizona (Photograph courtesy of Matt Kaplinski, Northern Arizona University).

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
megagram (Mg)	1.102	ton, short (2,000 lb)

Horizontal and vertical coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Monitoring Fine-Grained Sediment in the Colorado River Ecosystem, Arizona—Control Network and Conventional Survey Techniques

By Joseph E. Hazel, Jr.[1], Matt Kaplinski[1], Roderic A. Parnell[1], Keith Kohl[2], and John C. Schmidt[3]

Abstract

In 2002, fine-grained sediment (sand, silt, and clay) monitoring in the Colorado River downstream from Glen Canyon Dam was initiated to survey channel topography at scales previously unobtainable in this canyon setting. This report presents the methods used to establish the high-resolution global positioning system (GPS) control network required for this effort as well as the conventional surveying techniques used in the study. Using simultaneous, dual-frequency GPS vector-based methods, the network points were determined to have positioning accuracies of less than 0.03 meters (m) and ellipsoidal height accuracies of between 0.01 and 0.10 m at a 95-percent degree of confidence. We also assessed network point quality with repeated, electronic (optical) total-station observations at 39 points for a total of 362 measurements; the mean range was 0.022 m in horizontal and 0.13 in vertical at a 95-percent confidence interval. These results indicate that the control network is of sufficient spatial and vertical accuracy for collection of airborne and subaerial remote-sensing technologies and integration of these data in a geographic information system on a repeatable basis without anomalies. The monitoring methods were employed in up to 11 discrete reaches over various time intervals. The reaches varied from 1.3 to 6.4 kilometers in length. Field results from surveys in 2000, 2002, and 2004 are described, during which conventional surveying was used to collect more than 3000 points per day. Ground points were used as checkpoints and to supplement areas just below or above the water surface, where remote-sensing data is not collected or is subject to greater error. An accuracy of ±0.05 m was identified as the minimum precision of individual ground points. These results are important for assessing digital elevation model (DEM) quality and identifying detection limits of significant change among surfaces generated from remote-sensing technologies.

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Introduction

Recent developments in surveying, mapping, geodesy, remote sensing, and digital terrain modeling have made it feasible to study continuous lengths of the river bed and banks of the Colorado River, in the Colorado River ecosystem (CRE), downstream from Glen Canyon Dam. Previous geomorphic studies in this remote canyon setting have focused primarily on planimetric changes (for example, Cluer, 1995; Schmidt and others, 1999), coarsely spaced cross sections (for example, Graf and others, 1995; Flynn and Hornewer, 2003; Grams and others, 2007), and three-dimensional evaluation of change at a limited number of study sites (for example, Schmidt and Graf, 1990; Beus and others, 1992; Kaplinski and others, 1995; Hazel and others, 1999). These studies were limited in their ability to fully examine the three-dimensional relationship between river form and process and resulted in conflicting conclusions regarding impacts of dam operations and associated sediment storage change. The different methods were hampered by low-frequency sampling, the limited observable areas above the subaqueous zone in aerial photographs, the limited size of detailed topographic surveys, and the inherent variability among limited numbers of detailed study sites (Schmidt and others, 2004).

In an attempt to better study channel change and fine-sediment (sand, silt, and clay) transport in the CRE, the Grand Canyon Monitoring and Research Center (GCMRC), in cooperation with Northern Arizona University and Utah State University, initiated a channel mapping project in 2002. This project required a remote-sensing approach of sufficient accuracy to detect potentially small changes in sediment volume at the reach scale (10^2–10^3 meters [m]). The approach needed to be applied biannually and also rapidly repeated before and after experimental floods from Glen Canyon Dam. Remote-sensing data, including airborne laser scanning or light detection and ranging (LIDAR), acoustic multibeam bathymetry, aerial photography, and underwater imagery, were collected at various intervals in 11 study reaches (fig. 1). To enable and ensure the collection of accurate topography, the remotely sensed technologies required a high-accuracy global positioning system (GPS) control network and also conventional surveys for groundtruthing checkpoints and filling in data gaps. Bathymetry of shallow nearshore environments that could not be surveyed with multibeam bathymetry and areas of dense vegetation were measured by ground-survey crews. These spatial datasets were then combined into high-resolution digital elevation models (DEMs) in a geographic information system (GIS) and used to compare maps of topography, grain size, and other information in order to study the spatial and temporal distribution of sand-sized sediment in this system (for example, Topping and others, 2006; Kaplinski and others, 2007). The techniques and errors associated with remote sensing (Davis, 2004), acoustic multibeam bathymetry (U.S. Geological Survey, unpub. data), and subaerial and subaqueous instrumentation (Rubin and others, 2006; Rubin and others, 2007) are not described herein. This report presents an overview of the conventional surveying procedures employed during this study, including establishment of the GPS control network and conventional surveying using electronic (optical) total stations. The methodological background is reviewed and the potential source and nature of errors are outlined.

Study Area

The study area is the CRE in Glen, Marble, and Grand Canyons, Ariz. (fig. 1). Locations in the study area are traditionally defined by river-mile (RM) distance downstream or upstream from Lees Ferry, Ariz. (RM 0). Although we use metric units for describing our methods and results, we adhere to the use of river miles as well as informal names to specify study-site locations. The river miles used in this report are defined by the location along the river centerline developed by the GCMRC (U.S. Geological Survey, 2006). This river-mile centerline was developed in a GIS utilizing spatial data referenced to the GPS network and is considered more accurate than previous river-mile estimates (for example, Stevens, 1983; Belknap, 2001).

The 11 reaches selected for repeat surveys are shown in figure 1 and listed in table 1. This subset of the channel comprises approximately 10 percent of the CRE between Glen Canyon Dam and Diamond Creek. Protocol development was accomplished in four of the reaches during June, August, and September 2000, as part of a separate project during the low

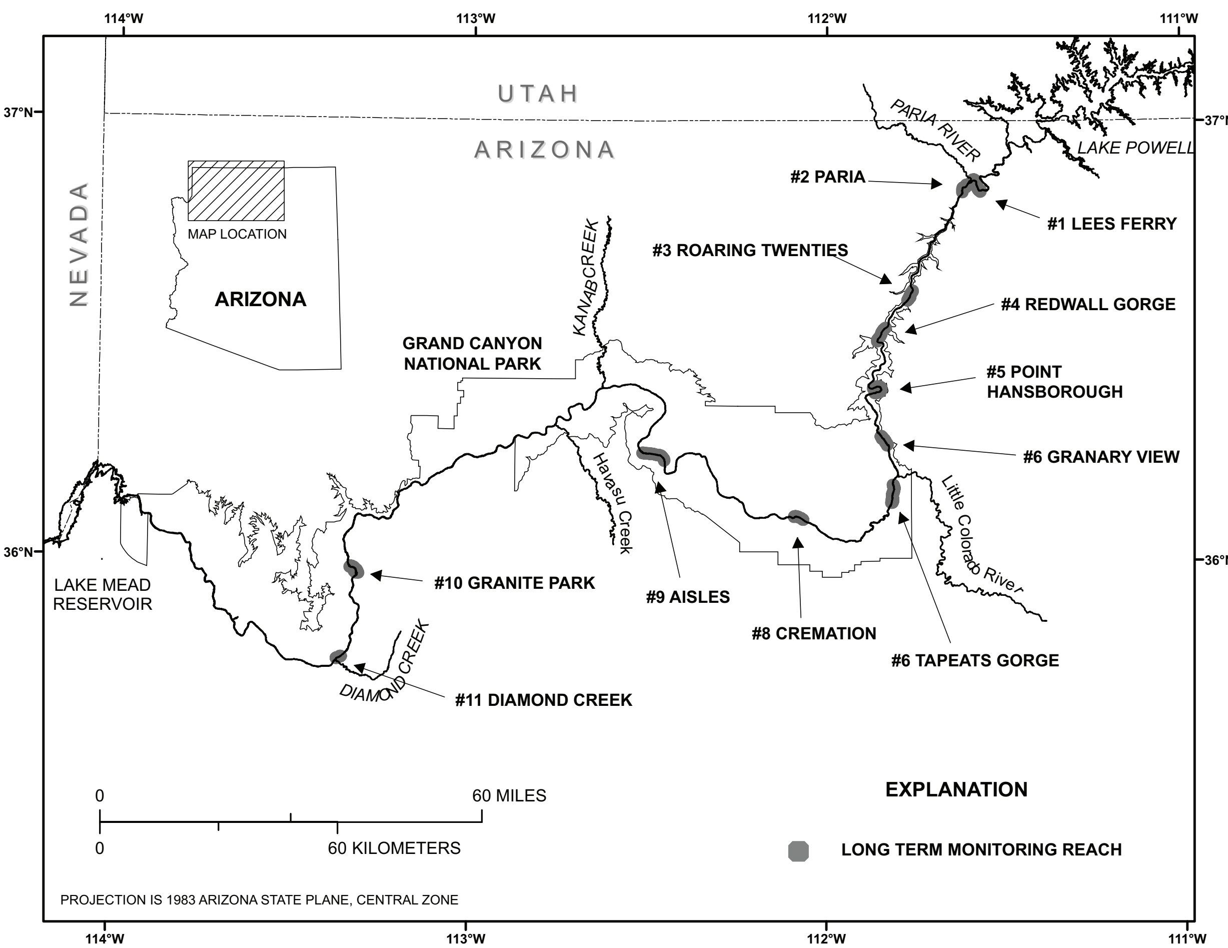

Figure 1. Map showing major tributaries and locations of the long-term monitoring reaches in the Colorado River in Grand Canyon National Park, Ariz.

Table 1. Characteristics of the long-term monitoring reaches within the study area.

Long-term monitoring reach number	Local name of long-term monitoring reach	Starting river mile[1]	Ending river mile	Average channel width[2] (meters)	Channel slope[3]
1	Lees Ferry	–2.4	0.0	123	0.0001
2	Paria	1.1	2.7	113	0.0002
3	Roaring Twenties	21.9	23.7	56	0.0016
4	Redwall Gorge	29.4	32.1	64	0.0009
5	Pt. Hansborough	42.5	45.5	82	0.0009
6	Granaries	54.5	56.3	90	0.0003
7	Tapeats Gorge	63.4	66.4	95	0.0012
8	Cremation	86.6	88.1	64	0.0020
9	Aisles	119.3	123.3	65	0.0010
10	Granite Park	207.7	209.2	72	0.0013
11	Diamond Creek	224.8	225.6	66	0.0002

[1]Based on the river-mile centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry (river mile 0) in Grand Canyon National Park, except for the Lees Ferry reach, which is in Glen Canyon National Recreation Area.

[2]At 227 m^3/s, an average based on cross-section data from Magirl and Breedlove (2005).

[3]Based on measured water-surface elevations at a steady discharge of 227 m^3/s.

summer steady flow experiment (Schmidt and others, 2007). The reaches vary from 1.3 to 6.4 kilometers (km) in length, and the average length is 3.5 km. One reach is located in Glen Canyon between Glen Canyon Dam and Lees Ferry (RM –15 to 0). Five reaches are located in Marble Canyon between Lees Ferry and the confluence with the Little Colorado River (RM 0 to 61.7). Two reaches are located in eastern Grand Canyon between the Little Colorado River and Phantom Ranch (RM 61.7 to 88). Three reaches are located in western Grand Canyon between Phantom Ranch and Diamond Creek (RM 88 to 226). In 2004, emphasis was placed on reaches in Marble Canyon and eastern Grand Canyon. These reaches compose approximately 18 percent of this portion of the CRE. The reaches located in Glen and western Grand Canyons were only surveyed once in 2002.

Geodetic Control Network

Overview

In the 1990s, 0.5-m topographic contours of kilometer-scale lengths of the channel in the CRE were developed from aerial photographs using stereo photogrammetry (Werth and others, 1993). Control was monumented and surveys performed to set photo panels, which were then used to position the aircraft at the time of film exposure. These methods only required that the field measurements of the distances between photo panels be accurate, and did not necessitate a high- accuracy geodetic control network to position reach-scale channel morphology to a datum. Analysis of vertical change in the CRE, such as topographic surface aggradation and degradation and positioning of important features, was limited by the poor resolution of the aerial photography. As a result, quantitative geomorphic studies of three-dimensional channel form in the CRE were restricted to individual sites.

By 1999, technological developments in the application of GPS had made it possible to solve kinematic positioning of spatial data collected from an aircraft. Photo panels were not required to position the aircraft in the CRE, but were still necessary to check the accuracy of the spatial data (Davis, 2004). This was a fundamental change in mapping scope and presented new opportunities for geomorphic investigation at scales previously unobtainable. As part of this effort, 16 geodetic control-network points were established along the canyon rim and connected to the National Spatial Reference System (NSRS). Doyle (1994) describes the NSRS as a combination of discrete geodetic components: horizontal positions (latitude and longitude, State Plane Coordinates) referenced to a two-dimensional datum, the North American Datum of 1983 (NAD83), and elevations (Helmert orthometric heights) referenced to a one-dimensional datum, the North American Vertical Datum of 1988 (NAVD88). Primary monumented river-corridor control points used for spatial referencing in the

1980s and 1990s were then referenced to the NSRS rim point network with GPS, and other river-level control points were referenced to the primary river network with conventional survey measurements. The control points are stable survey marks monumented by a chiseled or scribed x, a Parker-Kalon–hardened masonry nail, a carriage bolt, or aluminum and brass caps.

Methods for Acquiring Multivector Global Positioning System-Based Control

Coordinates for the NSRS rim stations and for primary river-corridor control points were obtained by using simultaneous dual-frequency GPS techniques. GPS observations yield ellipsoidal heights, which reference the Geodetic Reference System of 1980 (GRS80) ellipse fixed to the geocentric NAD83. GPS receivers provide position information by repeated measurements on the travel times of digitally tagged radio signals generated by a constellation of satellites. Comparison of data from four or more satellites provides vector information (Δx, Δy, Δz distances) for the trilateration of latitude, longitude, and altitude. The coordinates of primary river-corridor control points were determined by multiple 8–10-hour occupations using dual-frequency full-wavelength receivers stationed on each control point and on three nearby NSRS rim stations (fig. 2), using the procedures described by Zilkowski and others (1997). Points determined by single- or shorter-period occupations are less accurate and were considered a secondary level of the control network. Conventional vector measurements (using total stations) were added in areas where GPS was not functional due to canyon wall obstructions; these tertiary control points were referenced to the GPS network adjustment using least-squares adjustment software for survey networks. The control network coordinates were converted to the Arizona State Plane central zone 0202 grid in meters. Ellipsoidal heights were not converted to the NAVD88 orthometric heights because the current national geoid model (GEOID03) does not incorporate sufficient gravity measurements in the region to account for the effects of topography (mass/void) on height measurements. As a result, spatial data collected for resource monitoring by the GCMRC are currently referenced to the NAD83 ellipsoid (Saleh and others, 2003).

Accuracy Assessment of the Control Network

Project requirements for the rim-level control network points were to ensure 0.02-m local accuracy in the horizontal component, as well as 0.02-m local accuracy for ellipsoid heights. General statistics and accuracies of the different levels of the control network are shown in table 2. These values were computed in a manner consistent with the Federal Geographic Data Committee. At the time of this study, the control network points have positioning accuracies of less than 0.03 m and ellipsoidal height accuracies of between 0.01 and 0.10 m at a 95-percent degree of confidence. The positional accuracy of the 0.01-m–0.03-m height of the rim points ensures the desired standard of 0.05-m horizontal and 0.08-m vertical at secondary and tertiary levels of the control point network (table 2). These results suggest that the spatial and vertical accuracy of the control network is sufficient for integration of

Figure 2. Global positioning system receiver on control point SO123209R in reach 9 (location shown in fig. 1) (U.S. Geological Survey photograph).

Table 2. Summary statistics for each level of the Grand Canyon Monitoring and Research Center control network.

Control network levels	Number	Vector measurements	Horizontal accuracy (meters) at 95-percent confidence	Vertical accuracy (meters) at 95-percent confidence
National Spatial Reference System rim points	16	153	0.019	0.029
Primary river points (PC)	25	224	0.021	0.053
Secondary river points (SC)	170	1633	0.031	0.061
Tertiary river points (TC)	130	>500	0.062	0.108

multiple datasets on a repeatable basis without anomalies. In the section titled Accuracy Assessment of Topographic Surveys, we independently evaluate network point quality with repeated conventional measurements at a subset of network points.

Conventional Surveying

Overview

Ground-based capture of terrain data and spatial referencing of sampling technologies was undertaken with traditional survey methods. The canyon setting and associated environmental conditions precluded the use of kinematic-GPS techniques for rapid acquisition of field survey data. The reaches are characterized by steep slopes and, in places, dense vegetation, which leads to loss of satellite lock and position fix during GPS surveying. As a result, conventional total-station surveying provided the best compromise of speed, accuracy, and coverage. Nonetheless, the irregular channel planform and topographic characteristics of each reach required development of efficient procedures for ensuring quality control of collected data, and also to minimize offset between datasets collected from different control points.

The following were collected using conventional surveying techniques: (1) topographic data for gaps in remote-sensing coverage, (2) checkpoints for groundtruthing airborne laser scanning or LIDAR and acoustic multibeam technologies, (2) photo panels for image rectification and photogrammetry, and (3) spatial locations of subaerial and subaqueous sampling instrumentation (for example, scour chains, digital microscopes for determining sediment grain size [Rubin and others, 2006; Rubin and others, 2007] and underwater video cameras for determining bed-sediment texture). The data acquisition process involved two stages. First, the points in the GCMRC control network utilized as benchmark and backsites were verified on all total-station setups. This was required to establish the precision of the total-station setup, and for periodic rechecking of benchmark-backsite angle and distance to ensure validity of measurements. The second stage involved field data collection and processing.

Instrument Precision and Control Point Verification

Surveying protocol was developed and documented according to standard practices for ground surveying. Line-of-sight requirements dictated which control points were utilized as a benchmark for a total station (fig. 3). Control points that could be viewed by more than one benchmark were preferred as backsites. A backsite consisted of one or more Sokkia reflective prisms mounted on an optical plummet-equipped tribrach (Seco or Sokkia) attached to a Crain Tri-Max slip-leg adjustable tripod. The optical plummet has a push-pull slide focus to ensure that when leveled, the prism is centered directly over the control point. To maintain tripod stability in windy conditions, rocks were placed on the tripod feet. Upon

Figure 3. Total station on control point SC0299854R in reach 4 (location shown in fig. 1); view looking upstream (Photograph courtesy of Joseph E. Hazel, Jr., Northern Arizona University).

Table 3. Average conventional survey positional errors and summary statistics at control points utilized as backsites.

[Control-network point identification (ID) names are given by location along the river-mile centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry in Grand Canyon National Park. PC, SC, and TC refer to primary, secondary, and tertiary levels, respectively, of the control network. C, O, and S indicate points determined by multiple GPS or conventional observations, single GPS observation, and single conventional observation, respectively. L and R refer to the left and right banks, respectively, as viewed in a downstream direction.]

Point ID	N	Horizontal distance (meters)	Horizontal distance standard deviation (meters)	Vertical distance (meters)	Vertical distance standard deviation (meters)
TS001285R	15	0.024	0.019	–0.004	0.022
SC001473L	7	0.010	0.008	0.020	0.013
SC002045R	9	0.022	0.011	0.018	0.035
SC002473L	25	0.014	0.009	–0.005	0.020
PC021601R	5	0.011	0.010	0.007	0.010
SC022082L	11	0.008	0.011	–0.003	0.008
SC022744L	25	0.009	0.008	0.013	0.020
TC023460L	11	0.016	0.016	0.004	0.013
SO029428L	7	0.011	0.005	0.028	0.018
TC030051R	14	0.011	0.007	–0.003	0.018
PC030653R	22	0.011	0.007	0.006	0.015
SC030696L	4	0.013	0.004	0.031	0.012
SC031518R	6	0.007	0.007	0.000	0.017
SC031851R	5	0.004	0.006	0.003	0.021
TC032089R	5	0.012	0.011	–0.009	0.014
SO042766L	11	0.019	0.028	0.017	0.019
TC043281L	11	0.014	0.004	0.016	0.030
TC043289R	6	0.006	0.003	0.006	0.009
SC043508L	12	0.006	0.004	0.006	0.004
TC043589L	3	0.018	0.012	–0.001	0.013
TC043971L	12	0.014	0.008	0.016	0.011
SO044411L	16	0.007	0.006	0.012	0.010
PC044480L	6	0.007	0.005	0.017	0.014
SC044914L	8	0.009	0.008	0.010	0.009
TC054325L	7	0.015	0.013	–0.029	0.032
SC054895R	8	0.008	0.005	0.008	0.019
SC055320L	4	0.006	0.004	0.002	0.008
SC055630R	11	0.007	0.005	0.006	0.015
TC055751R	6	0.008	0.006	0.008	0.024
SO063760R	3	0.006	0.001	0.012	0.011
SC064301L	14	0.009	0.009	0.008	0.016
SC065131R	15	0.013	0.012	0.002	0.007
SO065738L	5	0.005	0.006	0.003	0.016
SO065978L	10	0.009	0.006	0.004	0.009
TC065956R	4	0.007	0.003	0.002	0.008

Table 3. Average conventional survey positional errors and summary statistics at control points utilized as backsites.—Continued

Point ID	N	Horizontal distance (meters)	Horizontal distance standard deviation (meters)	Vertical distance (meters)	Vertical distance standard deviation (meters)
SC086644R	4	0.016	0.017	0.012	0.044
SC087128L	6	0.012	0.007	0.006	0.018
SC087628R	4	0.017	0.018	0.008	0.010
SC087734L	5	0.002	0.001	–0.005	0.013
MEAN	9.3	0.011	0.008	0.006	0.016

careful measurement, the height of the target was radioed back to the surveyor and recorded.

The coordinate values for each benchmark and backsite were verified by the surveyor using multiple angles in both direct and reverse scope and by multiple distance measurements using Topcon GTS–313 and GPT–2003 total stations (table 3). Vertical angles were adjusted for Earth curvature and refraction, and horizontal distances were adjusted by appropriate Arizona State Plane scale factors, atmospheric pressure, and temperature. Prism constant was set to –30 millimeter (mm) on each total station and 0 mm in the data collector to allow measurement distance correction for prism offset and to negate the possibility of double correction. Tripod Data Systems (TDS) handheld Rangers with TDS Survey Pro surveying software were used for data collection and storage in the field. Unlike older digital data collectors, collected data are immediately written to internal storage. Even with complete loss of power or software lockup, the data are retained.

Field Data Collection

Ground surveys utilized 7.6-m collapsible rods mounted with tilting Sokkia reflective prisms. To minimize target height error, all rods were Crain LR STD-series fiberglass leveling rods of the same height. The rods telescope smoothly through four extensions, have minimal sway when extended, and are waterproof. Round rods are better than oval rods in windy conditions. The rods have internal locking and stop mechanisms to ensure that under- or overextension of the collapsible sections does not occur. Ground surveys included breaks of slope such as sandbar and bank tops and bottoms, but generally slope points were collected with the intention of supplementing and groundtruthing photogrammetric- and LIDAR-derived topography (table 4). More intensive surveys were conducted in areas such as wet sand where LIDAR is subject to spurious returns (Davis, 2004) and shallow subaqueous shoreline areas not covered by concurrent bathymetry surveys (U.S. Geological Survey, unpub. data). To enhance rapid point collection a sideshot (a single bearing and distance measurement) was used for ground surveying.

Dry, bare, and relatively flat surfaces were chosen for photogrammetry panel location and placement. Typically, the panels were spaced about 250 m apart, alternating on either side of the river, and two were placed on both sides of the river at the upstream and downstream terminus of surveyed monitoring reaches. In addition, care was taken to place panels so they were not observable from the river by recreational users (for example, hikers, anglers, and boaters). A collapsible metal prism pole with a level bubble and thumb-release bipod legs was placed over the center of each panel (fig. 4). All panels were surveyed to the same accuracy as the control points using

Table 4. Types of survey data collected during reach-based monitoring river trips. NC, data not collected.

Survey trip	Reaches[1]	Ground points (pts/km)	Subaqueous camera location	Subaerial camera location	Subaqueous video transects	Photogrammetric panels	Scour chains
August 2000	2,4,5,7	487	80	NC	NC	NC	65
September 2000	2,4,5,7	511	316	NC	NC	169	NC
May 2002	1,2,3,4,5,6,7, 8, 9,10,11	224	1623	NC	NC	NC	NC
June 2004	2,3,4,5,6,7,8	211	1220	NC	30	NC	NC
November 2004	2,3,4,5,6,7	364	1129	581	NC	NC	115
December 2004	2,3,4,5,6,7	672	947	569	17	NC	NC

[1]Numbers describe reach designations shown in table 1.

Figure 4. Metal prism pole, equipped with bipod legs for accurate leveling, used to locate each photogrammetry panel. Photograph by T. Gushue, U.S. Geological Survey.

multiple angle and distance measurement. The panel edges were anchored with rocks for stability. Where suitable, control points were also used as panel locations. The panels were recovered on a subsequent river trip after the aerial overflight.

Onshore spatial positioning included the locations of scour chains and sediment-grain-size measurement stations. Scour chains were installed in November 2004. The 1-m-length chains were emplaced vertically and the locations marked with pinflags. A sideshot using a leveling rod was used to record each pinflag location. Pinflag number and rod height were recorded in a notebook and also radioed to and recorded by the surveyor. Sedimentologic analyses of the excavations at recovered chain locations aid in the ability to identify flood deposits and to measure scour and fill (Schmidt and others, 1999). Likewise, locations where sediment grain size was determined with a handheld digital microscope camera were marked with pinflags and surveyed with a single sideshot (fig. 5). The digital images acquired by the microscope system were used to analyze grain size and negate the need to manually collect samples (Rubin and others, 2006; Rubin and others, 2007).

The underwater version of the grain-size microscope system and a video sled were both tracked and spatially referenced with a total station (fig. 6). Both instruments were winched and lowered to the riverbed from a 7-m motorized raft. The position was targeted with a round cluster of eight reflective prisms mounted on a mast adjacent to the winch. Spatial-location acquisition required close coordination between the camera console operator, the radio operator/notetaker, the boat operator, and the surveyor. Each digital video image of the riverbed was tagged with a number that was then relayed to the surveyor via radio. When a sideshot number was recorded, it was repeated back to the notetaker by the surveyor to minimize error. The raft was held stationary until getting a signal from the notetaker that the sideshot had been acquired.

Upon completion of each survey trip, the field data were transferred to computers and edited. Preliminary maps were made to detect anomalous survey points using Sokkia MapVista mapping software. Survey data were modeled using triangular irregular networks (TINs), by Delaunay triangulation (McCullagh, 1988; McCullagh, 1998). Interpolation by Delaunay triangulation is exact, directly incorporating the survey points as vertices, thus simplifying erroneous rod height detection and subsequent correction.

Results and Discussion

Spatial Point Distribution

An example of the distribution of survey-point data in a reach is shown in figure 7 and summarized for all surveys in table 4. The average reach ground-point distribution for each survey ranged from 211 to 672 points (pts) per kilometer. The variability reflects changes in sampling strategy as spatial location requirements increased and as refinement of the accuracy and utility of remotely sensed data evolved. Even so, the conventional survey methods permitted the acquisition of up to 3000 total points within a typical 10-hour field day, including periods of downtime due to changes in control-point occupation and inclement weather.

In August and September 2000, ground-point data collection focused on the water surface margins for more accurate TIN interpolation of gaps in point coverage between multibeam and LIDAR data. However, there were substantial systematic errors present in the 2000 LIDAR dataset that required the development of procedures to reduce the errors to tolerable levels (Davis, 2004). In May 2002, the GCMRC implemented aerial photogrammetry rather than LIDAR for mapping exposed topography in the reaches, but dense vegetation remained problematic in both the photogrammetric and LIDAR approaches (Davis, 2004). In areas where the ground was obscured by vegetation, we increased point density to fill in perceived gaps in terrain coverage and also to produce checkpoints for photogrammetric point accuracy. Considerable time was also spent placing and surveying a total of 169 photogrammetric panels. The number and quality of checkpoints utilized for photogrammetry and LIDAR are reported elsewhere and are not repeated here (Davis and others, 2007).

As channel bed data from the multibeam hydrographic surveys became available, it became apparent that the multibeam transducer did not function well at shallow depths (U.S. Geological Survey, unpub. data). As a result, the June 2004 dataset reflects an increase in ground-point sampling frequency of shallow, offshore areas and a decrease in point density of vegetated areas. Approximately 75 percent of the ground points were collected in offshore areas. The low point density of 211 ground pts/km reflects the greater time and effort involved in acquiring topographic data in water depths up to 2 m. In addition, 30 underwater video transects were collected in potentially sensitive areas (for example, eddies and pool exit slopes with rapid bed-sediment spatial changes). A total of 503 sideshots, with an average spacing of about 3 m, were collected along the transects to spatially position the video images.

The highest ground point density (672 pts/km) was collected in December 2004 (table 4), immediately following the release of the November 2004 high experimental flow (HEF) (Topping and others, 2006). The sampling frequency was increased in areas of substantial topographic change because it was believed that the LIDAR data collection overflight had failed. As a result, new deposition from the 2004 HEF was surveyed with the intent of providing enough three-dimensional coordinates for terrain modeling (fig. 8). Although the spatial distribution and density of points was highly variable, points concentrated in areas of substantial change varied from 0.5 to 1 pt/m^2. In contrast to the June 2004 data, approximately 23 percent of the ground points were collected in offshore areas (fig. 7). In addition, 17 video transects were collected with a point spacing similar to that collected in June 2004.

Spatial referencing of the underwater microscope occurred on all monitoring trips. Application of the system was limited in August and September 2000 by cable breakage. Point distributions were roughly similar in May 2002 and June 2004, with densities ranging from 40 to 50 pts/km (table 4). In addition, in November and December 2004, a total of 581 and 561 subaerial microscope grain-size locations were surveyed,

Figure 5. Pinflags used to mark the location of each grain-size measurement. Inset: digital microscope camera. Photographs by D. Rubin, U.S. Geological Survey.

Figure 6. Seven-meter motorized raft equipped with the grain-size microscope system. The approximate position of each measurement was spatially referenced with a total station by targeting the cluster of eight reflective prisms mounted on a mast adjacent to the winch. Photograph by D. Rubin, U.S. Geological Survey.

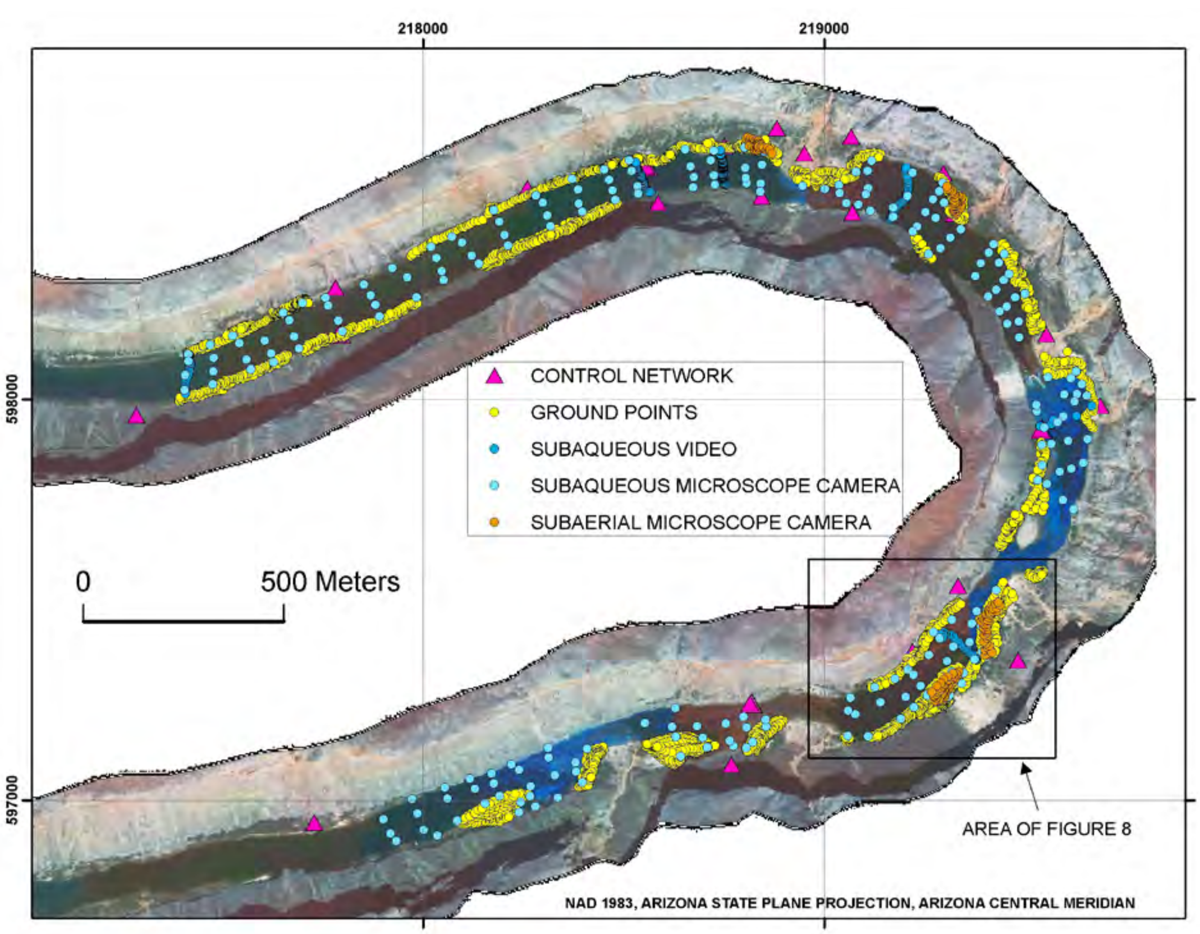

Figure 7. Global positioning system control-network points and survey-point distribution for the December 2004 survey of reach 5. The total number of points surveyed during 2 field days was 4013. Of this total, 3544 were ground points (22 percent of which were collected in offshore areas), 195 were locations of underwater video positioned along 5 transects, 149 were subaerial microscope camera locations, and 125 were subaqueous microscope-camera measurement locations. Location is shown in figure 1. Locations of control network points are also shown.

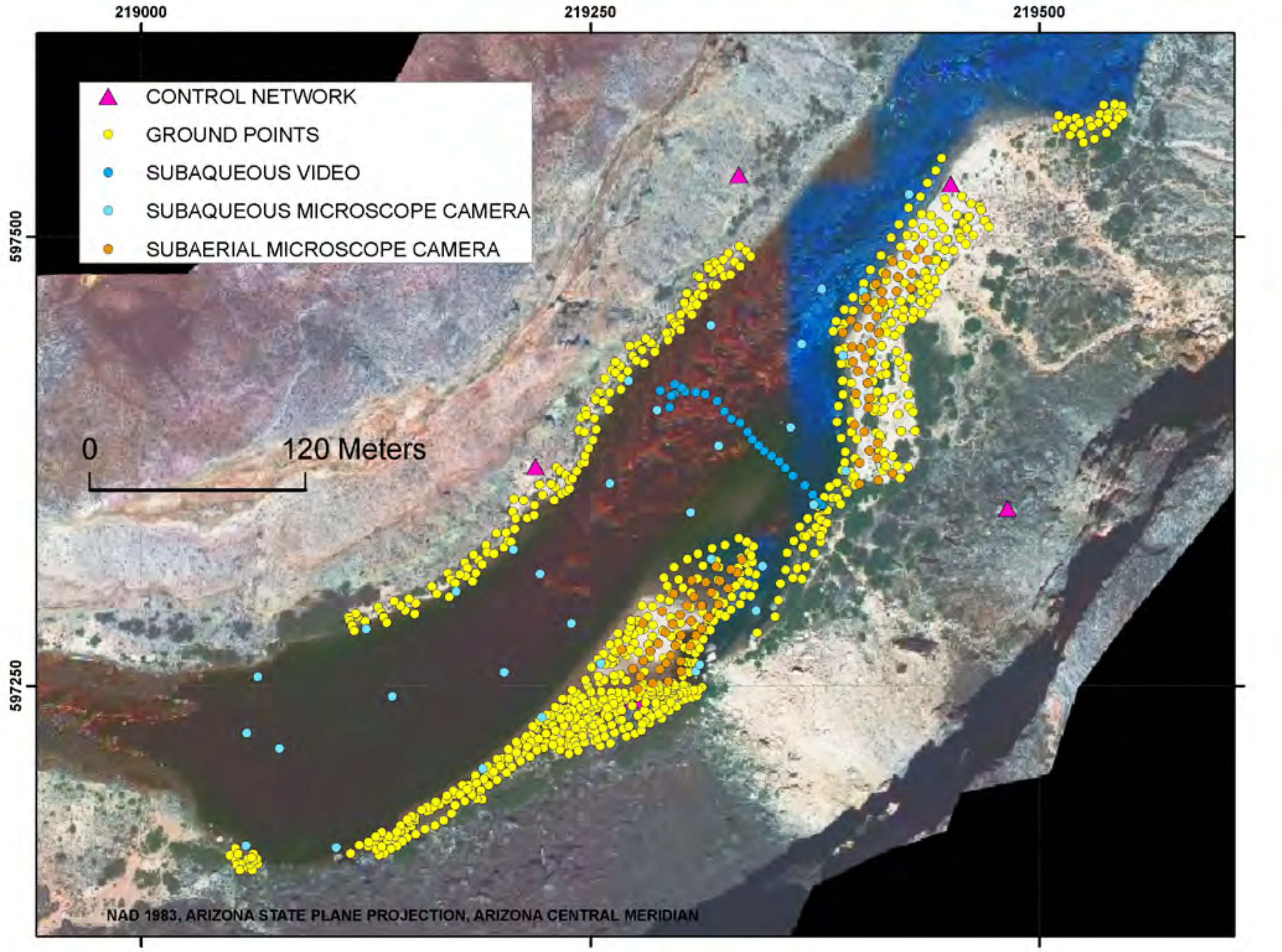

Figure 8. Detail of the topographic survey and point distribution of the December 2004 survey at river mile 44.6 in reach 5 (location is shown in fig. 5).

respectively. In contrast to the underwater microscope positions, which are a record of boat position and do not include measurements of bed elevation, the subaerial spatial positions also serve as ground points and were used for terrain modeling.

Accuracy Assessment of Topographic Surveys

We assessed control network quality and survey point accuracy as a first step in quantifying uncertainty in the generation of DEMs from multiple data sources and determining an appropriate threshold for detection of significant change between surfaces. Reoccupation of benchmarks and backsites in seven of the original eleven reaches, totaling 26 surveys, can be used to identify the presence of setup errors, or identify spurious control points due to errors arising from incorrect antenna heights or offsets during GPS measurements. Summary statistics of the distance range and standard deviation of the measurements to control points used as backsites are shown in table 3.

Individual observations at 39 backsites ranged from 3 to 25 in a total of 362 measurements (table 3). The distribution of observations is approximately normal. No systematic errors were detected. Because total-station drift is also reflected in this analysis, individual observations may deviate markedly from the mean. Leveling drift occurs as the tripod and instrument are subjected to changing environmental conditions; as a rule, the backsites were checked and the error recorded about every 50 sideshots, at which point the total station was releveled and rezeroed on the backsite. Vertical precision was slightly superior to horizontal precision. The mean horizontal distance error was 0.011±0.008 m; the mean vertical distance error was 0.006±0.016. The mean range of 0.022 m in horizontal and 0.13 in vertical at a 95-percent confidence interval, with some points having a distance vector greater than 1000 m, indicates that positional accuracies of the river-level points in the control network are sufficient for collecting spatially referenced field data

The appropriate level of accuracy to assign to individual ground-survey points is difficult to determine. The most easily

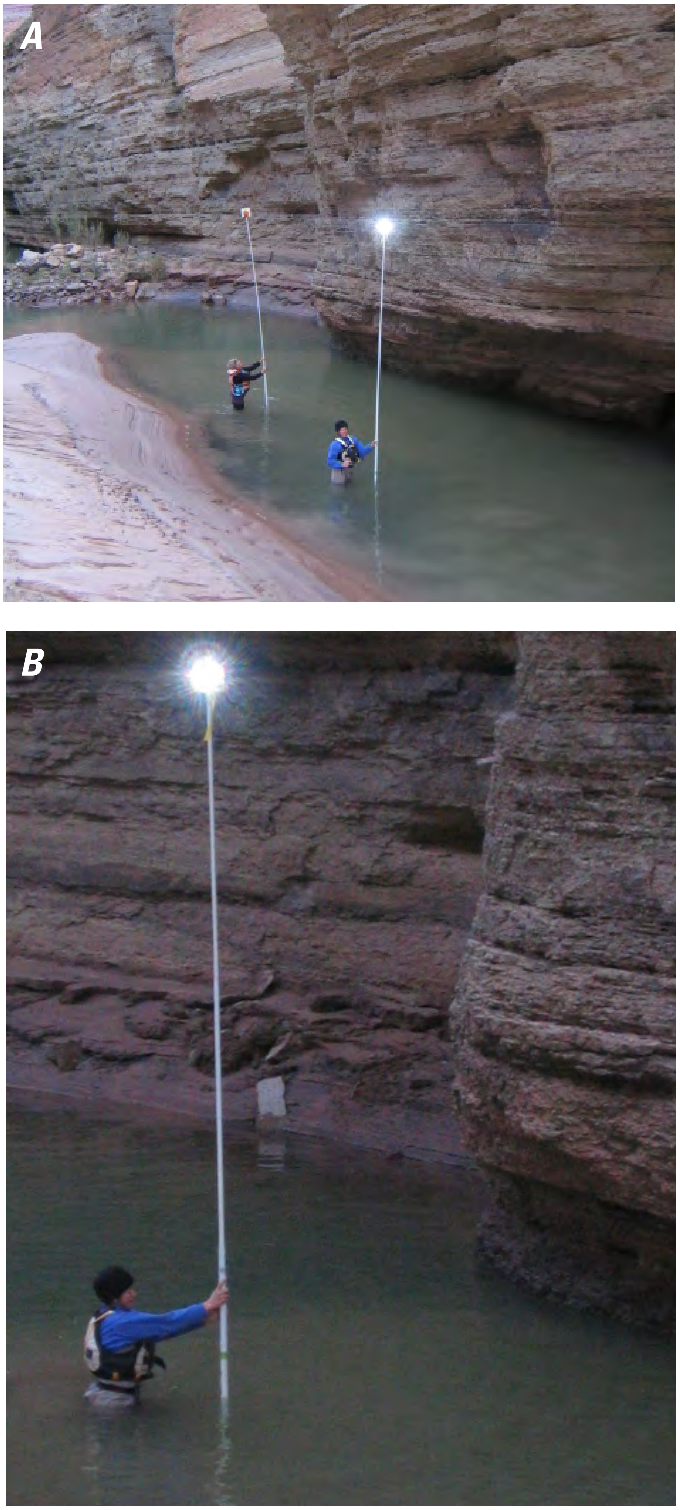

Figure 9. Topographic surveying in offshore areas in December 2004. *A*, Two rodmen positioning for sideshots at three rods (two extensions) in a water depth of more than 1 m. *B*, When in position and plumb, the prism is turned toward the total-station location and readiness radioed to the surveyor, ensuring an accurate measurement. Location is the return-current channel shoreward of the sandbar platform in the last pool of reach 5 (Photographs courtesy of Matt Kaplinski, Northern Arizona University).

quantified source of error in conventional survey-point collection is spatial integrity of the control-point network. The analysis of control points revealed a standard deviation in the planform of 0.008 m, implying a measurement limit ±0.016 m, 95 percent of the time (table 3). Likewise, the standard deviation in the vertical of 0.016 m implies a measurement limit ±0.022 m, 95 percent of the time. Because these results are within the stated control network accuracy in table 2, these values were assigned as the horizontal and vertical error for the control points utilized in this study. We consider setup error by assuming a 0.003-m horizontal centering error of the tribrach over the control point and 0.003-m tape measurement error of the total-station height above the control point, respectively. Horizontal rod error must account for plumbness and the different heights to which the rod can be extended. This error is difficult to quantify and depends on the rodman's ability to plumb the rod, environmental conditions, and rod condition (for example, fig 9). Thus, we assign a conservative estimate of 0.05-m horizontal error for the standard rod height (1.837-m height), 0.10 m for 1 extension (3.285-m height), 0.15 m for 2 extensions (4.735-m height), 0.20 m for 3 extensions (6.185-m height), and 0.25 m for 4 extensions (7.579-m height), respectively. These estimates were determined by measuring the precision of multiple measurements on the same control points using the standard rod height and each of the 4 extensions. Precise positioning of the leveling rod also constitutes a source of random sampling error, which will result in vertical inconsistencies depending on the substrate upon which the rod is placed (for example, mud, wet sand, gravel, etc.). This source of error is impossible to quantify and we assign an arbitrary estimate of 0.05 m for vertical rod error and assume this increases by 0.01 m for each extension of the leveling rod. The propagated error associated with these various sources of error can be determined by the following expression:

$$E = \sqrt{e_1^{\;2} + e_2^{\;2} + e_3^{\;2}}\ ,$$

where E is the combined error, e_1 is the error associated with the spatial and vertical integrity of the control network, e_2 is the vertical and horizontal setup error at the benchmark and backsite, and e_3 is the error associated with placement and plumbing of the leveling rod. The results of the equation for each rod extension are shown in table 5. Horizontal and vertical rod accuracy ranged from 0.05 to 0.25 m and 0.05 to 0.09 m in the vertical, respectively. About 90 percent of the sideshots collected during the surveys were collected at the standard rod height, and the accuracy is closer to the minimum level of 0.05 m; we conclude that the point data collected with conventional surveying in our study is within an acceptable margin of error compared to the errors associated with airborne and bathymetric data collection. These results also indicate that sampling errors associated with individual survey points should be considered when ground points are utilized as checkpoints. The checkpoints should not be considered free

Table 5. Leveling-rod horizontal and vertical accuracies.

Error (meters)	1 rod height	One extension	Two extensions	Three extensions	Four extensions
Horizontal	0.053	0.101	0.151	0.201	0.251
Vertical	0.055	0.064	0.073	0.083	0.093

of error, especially if collected from areas of dense vegetation where the rod was presumably telescoped to two or more extensions. Other technologies spatially referenced with total stations during the study (for example, the video sled and subaqueous digital microscope) have far greater error associated with the spatial measurements, primarily because of streamflow, boat positioning, and cable slant. These factors are highly variable, and we assume a conservative horizontal error of ±3 m.

The sampling strategy employed in this study was designed to augment digital terrain modeling (DTM) constructed from remote-sensing data and to provide accurate spatial location for other sampling technologies. With the exception of one survey trip (December 2004), the ground points alone were not intended to provide full and accurate three-dimensional coordinates for DTM development. In addition, the sampling strategy and point density changed with each successive survey as more was learned about the utility of each remote-sensing technology. As a result, problems associated with point-sampling frequency in DTM quality were not examined in this report.

Summary

A high-resolution GPS-based control network and conventional survey techniques were used to collect topographic data in large areas of the channel at scales previously unobtainable in the Colorado River ecosystem. The accuracy of the control network and survey points is sufficient to generate repeatable, combined topographic surfaces when combined with remotely sensed data. A detailed assessment of survey errors is presented and an accuracy of ±0.05 m was identified as the minimum precision of individual survey points. These results are important for assessing DEM quality and identifying detection limits of significant change between surfaces generated from remote-sensing technologies. The data collection techniques in this study would be useful for establishing sampling strategies in other rivers where topographic characteristics preclude GPS methods in direct, geomorphological investigations. Real-time kinematic (RTK) data acquisition requires longer occupation times at individual points in this canyon setting because satellite lock is often blocked by steep slopes or vegetation canopy. Conventional surveying provided the best compromise of speed, accuracy, and coverage but increased the need for large-scale field surveys. The methods employed in this study permitted the acquisition of up to 3000 points during a typical field day. Data was collected in a variety of environmental conditions, ranging from subfreezing to temperatures greater than 110°F. The major disadvantages of the surveying procedures employed during this study, compared to high-resolution GPS surveying, are requirements for increased manpower, an extensive and accurate control network, and direct line-of-sight operations. A dedicated robotic total station (geodimeter) could possibly increase data collection speed of boat-collected data, but the required setup time would likely negate the increase in survey speed. Medium-range GPS equipment can track boat position at 2–3-m horizontal accuracies but will include periods of downtime due to loss of satellite lock.

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