Measuring and modeling high-resolution topographic change at archaeological sites in Grand Canyon National Park, Arizona, U.S.A.

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Key Points

- Archaeological sites in Grand Canyon National Park, Arizona, USA date to more than 11,000 B.P. and are currently threatened by ongoing erosion.
- We used terrestrial-lidar five times between 2006 and 2010 to document archaeological site changes.
- We developed deterministic and empirical error analysis methods to guide creation of change detection thresholds.
- Changes occured from both aeolian and alluvial processes and indicate that some sites are potentially unstable.
- Results are being used to guide the development of long-term monitoring protocols and process-based models for scenario-based planning and management, in conjunction with evaluating the potential effects from Glen Canyon Dam, located i25Km upstream from Grand Canyon.

ARCHAEOLOGICAL SITES IN GRAND CANYON NATIONAL PARK

Human occupation in Grand Canyon, Arizona, USA dates from at least 11,000 years before present to the modern era. For most of this period, archeological sites provide the only evidence of human occupation in this iconic landscape. Past and present inhabitants of this area include those from the late Paleoindian and Archaic eras, through the emergence of ancestral Puebloan farmers, and leading up to contemporary Native American cultures. Archaeological sites exhibit considerable variability and include habitation structures, granaries, roasting pits, and extensive collections of pottery sherds and hand tools.

EROSION, DAM OPERATIONS AND SAND RESOURCES

Because archeological sites contain valuable information about the past and serve as tangible evidence of Native American's prehistoric and historic use of this area, topographic change and potential degradation of archeological sites within the Colorado River corridor of Grand Canyon National Park, downstream of Glen Canyon Dam, is a subject of considerable interest and concern.

As part of the Glen Canyon Dam Adaptive Management Program, the U.S. Department of Interior is directed to research and mitigate potential negative impacts of the dam on downstream resources including archeological sites, among others. One aspect of the program is to determine whether controlled releases from the dam are affecting rates of archeological site erosion. Because many archeological sites are located within or adjacent to the historic river flood zone, potential effects could be related to a reduction in sediment resources and/or effects of smaller, cyclical controlled river flows (as a result of power generation). These effects have already been documented with respect to erosion of sand bars (e.g., Hazel and others 2010); these bars contribute sand to nearby archeological sites through aeolian transport. It has been hypothesized that a reduction in the number and size of river sand bars has resulted in a reduction in aeolian sand cover at archeological sites and that a reduction in the extent and depth of aeolian sand cover has resulted in an increase in surface run-off and a consequent increase in the rate of site erosion via precipitation-induced surface water gullying.

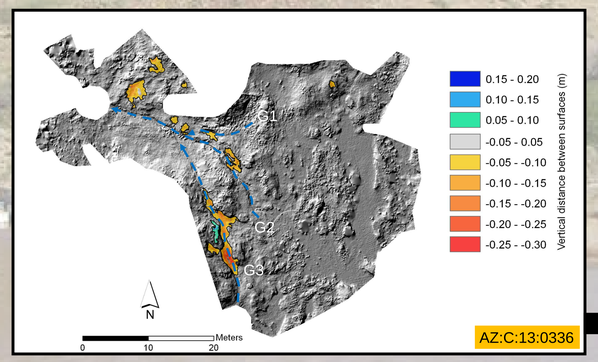
TERRESTRIAL LIDAR MONITORING

We performed a total of five surveys at 13 archaeological sites over a five year time period (2006-2010). All equipment was transported by whitewater raft and backpack to the remote locations of each of the sites in Grand Canyon. Each survey improved upon the previous data collection protocols through innovations in laser technology, surveying methods, and processing techniques. Change detection thresholds (i.e., twice the individual survey error) were determined on a conservative basis to represent the maximum possible errors.

Survey Date	Laser instrument	Georeference method	Registration method	Change detection threshold (between consecutive surveys)
May 2006	Riegl Z210	Total station	Point nearest neighbor	-
May 2007	Riegl Z210	RTK DGPS	Point nearest neighbor	8 cm
Sept. 2007	Riegl Z210	RTK DGPS	Point nearest neighbor	8 cm
April 2010	Riegl Z420i	RTK DGPS + total station	Control point	5 cm
Sept. 2010	Riegl Z420i	RTK DGPS + total station	Control point	3 cm

CHANGE DETECTION MAPS

We used a custom-designed suite of filtering, tinning, gridding, and differencing algorithms to calculate change detection at each site for each survey interval. The algorithms were built to obtain a consistent point density (minimum 96 points/m^2) prior to surface building in order to avoid the creation of artifacts that might be related to different data collection methods. TIN surfaces (with minimum point spacing of 5 cm) were used to identify change areas and to compute volumes. Grid surfaces (5 cm by 5 cm) were used to compute depths of either erosion or accretion at each site.

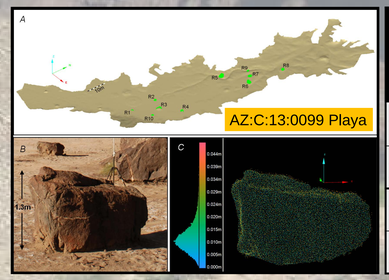


ERROR ANALYSIS

We evaluated change detection accuracy by performing deterministic calculations of point cloud error and empirical comparison analyses of fixed objects. Deterministic calculations compute the maximum possible errors (E_{total}) from each error source: survey, laser, and registration. In all cases, the errors are relative to each archaeological site – identical benchmarks were used during each of the surveys and therefore global georeferencing errors can be ignored. Survey errors (E_{survey}) were determined by precision measurements from the survey instrument used (total station or GPS). Laser errors (E_{laser}) were determined from manufacturers specifications and from independently published calibration studies. Registration errors (E_{reg}) were determined via calculations of the root mean square error (RMSE) either between point clouds or control points, depending on the methodology used in each survey.

$$E_{total} = \sqrt{E_{survey}^{2} + E_{laser}^{2} + E_{reg}^{2}}$$

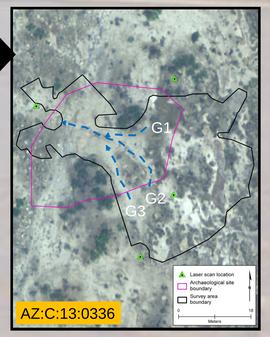
We computed empirically-based errors to determine the actual errors (as opposed to the maximum possible) inherent in the data sets. These were computed by computing two sets of statistical averages (mean vector distance and iterative closest point-ICP distance) for the RMSE between temporally-consecutive point clouds of "fixed" objects located within each site. The fixed objects were rocks and other large (0.25 to 2 m diameter) objects deemed improbable of independent movement between surveys. Our results indicate that the empirically-determined errors are lower than the deterministic-determined errors, as expected. Because they are more representative of the inherent errors in the point clouds, we adopted the empirical errors in determining the final change detection thresholds.



Archaeological site ID and time period	# of objects	Mean ± 1σ vector distance between points (cm)	Mean ± 1σ pre-ICP best-fit-based distance (cm)	95% confidence interval (μ+2σ) change detection threshold based on vector distance for all sites (cm)
AZ:C:13:0099 Playa Sept. 2007-April 2010	10	2.3 ± 1.5	1.4 ± 0.5	
AZ:C:13:0099 Playa April 2010-Sept. 2010	10	1.2 ± 0.5	1.1 ± 0.4	
All sites Sept. 2007-April 2010	39	2.2 ± 1.2	1.6 ± 0.6	4.6
All sites April 2010-Sept. 2010	35	1.5 ± 0.6	1.2 ± 0.4	2.7

EVIDENCE FOR GEOMORPHIC AGENTS AND FUTURE WORK

Final analyses indicate that 11 of 13 archaeological sites underwent either erosion, accretion, or both during the study period. In all cases, we were able to identify the likely geomorphic agent (typically either precipitation-induced overland flow and gullying or aeolian transport) responsible for the measured topographic change. Detected vertical erosion from overland flow ranged from 4 to 160 cm within the 13 study sites. Detected vertical deposition from aeolian transport ranged from 3 to 55 cm; this deposition could be potentially protecting sites from future overland flow. These results provide the highest resolution data available for determining the influence of climatic verses anthropogenic causes for archaeological site change in Grand Canyon National Park. We are now beginning an extended modeling effort to calibrate aeolian transport and overland flow models. These models will be used to analyze the expected effects of future management scenarios,



Arch Site AZ:C:13:0336 - location	Sediment eroded (Sept. 2007-Sept. 2010) (m^3)	Sediment deposited (Sept. 2007-Sept. 2010) (m^3)
Gully G1	0	0
Gully G2	0.63	0
Gully G3	2.21	0
Outside of gullies	1.37	0.21

Summary of net topographic change between Sept. 2007, April 2010 and Sept. 2010

Site number (monitoring period)	Area w/ measured erosion (m^2)	Area w/ measured deposition (m^2)	Total percent of site area modeled w/change (percent)	Average, (max.) height of erosion (cm)	Average, (max.) height of deposition (cm)	Approx. volume of erosion (-) (m^3)	Approx. volume of deposition (+) (m^3)
AZ:C:05:0031 (April 2010-Sept. 2010)	134.9	0	5.4	4 (30)	0 (0)	-5.7	0
AZ:C:13:0006 (Sept. 2007-April 2010)	27.0	8.8	2.8	15 (33)	9 (22)	-3.3	+0.8
AZ:C:13:0006 (April 2010- Sept. 2010)	2.2	0	0.2	6 (16)	0 (0)	-0.1	0
AZ:C:13:0336 (Sept. 2007-April 2010)	39.1	2.2	2.9	7 (27)	7 (15)	-3.6	+0.2
AZ:C:13:0336 (April 2010- Sept. 2010)	16.5	1.5	1.3	3 (9)	3 (5)	-0.6	+0.1
AZ:C:13:0099 (Sept. 2007-April 2010)	103.0	22.5	19.6	12 (63)	12 (59)	-17.3	+2.8
AZ:C:13:0099 (April 2010- Sept. 2010)	0.4	2.3	0.4	4 (6)	5 (9)	-0.02	+0.1
AZ:C:13:0099 playa (Sept. 2007-April 2010)	3.6	0.4	0.1	7 (13)	6 (7)	-0.2	+0.02
AZ:C:13:0099 playa (April 2010- Sept. 2010)	0.02	0	0.001	5 (6)	0 (0)	-0.001	0
AZ:C:13:0321 (April 2010-Sept. 2010)	13.9	0	10.0	4 (14)	0 (0)	-0.6	0
AZ:B:10:0225 (Sept. 2007-Sept. 2010)	254.2	81.3	28.7	22 (160)	13 (55)	-120.3	+11.2
AZ:G:03:0072 US (Sept. 2007-Sept. 2010)	92.1	50.8	11.8	11 (52)	16 (60)	-13.8	+6.4
AZ:G:03:0072 DS (Sept. 2007-Sept. 2010)	0	0	0	0 (0)	0 (0)	0	0

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