Using Land-based Photogrammetry to Monitor Sandbar Stability in Grand Canyon on a Daily Time Scale

Leland R. Dexter, Brian L. Cluer,[1] and Mark F. Manone

Department of Geography
Northern Arizona University
P.O. Box 15016
Flagstaff, Arizona 86011

Abstract. We report on the development of a method used to monitor spatial characteristics of subaerial alluvial sediment storage using automatic, time-lapse, 35-mm cameras. The cameras are fixed to bedrock in a protective canister, aimed at low oblique angles toward alluvial deposits of interest, and set to trigger once every 24 h. Presently, 43 sandbars are monitored with single cameras, and one sandbar is monitored with two cameras arranged to give stereographic coverage. The color 35-mm images are scanned electronically for input into PC ERDAS for digital manipulation and analysis, and the original transparencies are archived. Digital images are then sequenced and written to compact disk or video tape to produce time-lapse visualizations. Methods were developed to transform the digital image from oblique to planimetric. Aerial extent of sediment cover could then be estimated by several methods. Error analysis of transformed images showed that third-order transformations provided the optimal balance between control and accuracy. Third-order transforms were within ±1 m to 95% confidence. We captured significant changes in 28 separate sandbar deposits in at least 79 separate events displaying typical return intervals of 105 to 110 days. Most beach failures recorded by these methods occurred following low-flow discharges on weekends. We document rapid erosion (typically complete within 1 day) followed by slower deposition (typically lasting 2 weeks).

Key words: Colorado River, fluvial erosion, image analysis.

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[1]Present address: National Park Service, National Natural Resource Center, 1201 Oak Ridge Drive, Suite 250, Fort Collins, Colorado 80525.

Until recently, water resource management policies in the West were not evaluated for effect on the downstream riparian environment (Ingram et al. 1991). The construction and operation of Glen Canyon Dam seems to have profoundly influenced the downstream riparian environment throughout Grand Canyon (Dolan et al. 1974; Andrews 1991; Dawdy 1991; Johnson 1991). The task of assessing the types and magnitudes of these changes has fallen to the Glen Canyon Environmental Studies (GCES; Committee to Review the Glen Canyon Environmental Studies 1987).

A major research emphasis of the GCES has been sediment in the Colorado River system in Grand Canyon. The amount of sediment, the dynamics of sediment transport, and the resulting deposit morphology of sediment are components of the overall river ecosystem. Sediments serve as substrates for plants, as water-stilling structures and water-warming structures for various plants and animals, and as camping sites for river runners (Johnson 1991; Valdez and Williams 1993).

Most sandbars form in predictable locations based on the interaction between river hydraulics and landform features of bedrock or boulders. Typically, runoff from intense localized storms drains down steep-gradient tributary canyons and produces bouldery debris fans at the mainstem confluence. The debris fan constricts the mainstem channel and creates supercritical or shooting flow of the rapid. The supercritical flow separates from the bank near the toe of the debris fan and leaves a low velocity, recirculating eddy zone downstream of the fan and a bounding shear zone between the shooting flow and the eddy zone called the eddy fence. As the shooting flow of the rapid decelerates, the flow reattaches to the bank at some point downstream (Fig. 1; Schmidt and Graf 1990; Bauer and Schmidt 1993).

Sand and finer grain clastics are within the critical particle size range for erosion, transportation, and deposition in these types of hydraulic environments. The usual resulting deposits are visible (Fig. 1) under low-stage conditions. Typically, sandbars are found along the upstream face of the debris fan (upper pool bars), along the downstream face of the fan in the quiet water of the eddy (separation bars), and at the stagnation zone of the flow attachment (reattachment bars). Other depositional environments include point bars on the insides of meanders and thin channel margin deposits not otherwise associated with debris fans or meanders. In addition, a poorly quantified volume of sediment is stored subaqueously on the channel bottom (Schmidt and Graf 1990; Bauer and Schmidt 1993).

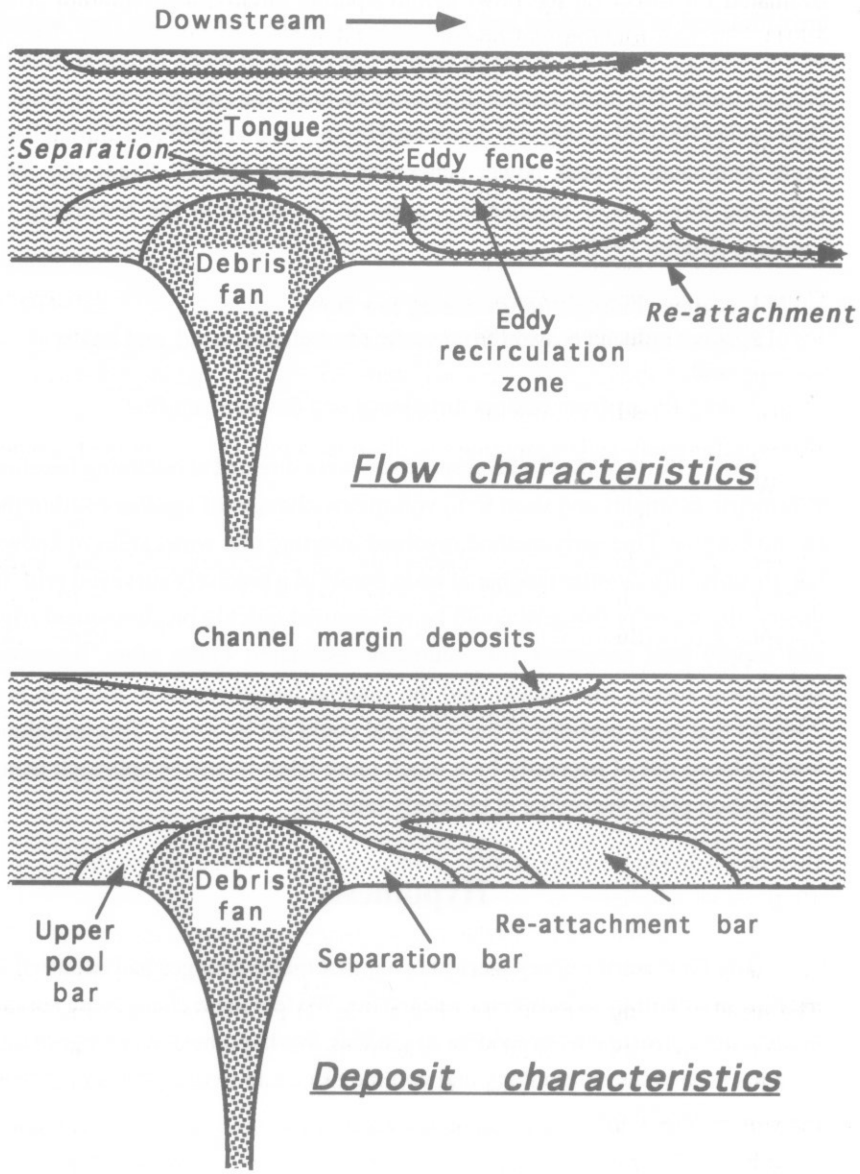

Fig. 1. The major hydraulic components of a Grand Canyon rapid (*top*) and the resulting alluvial deposits (*bottom*).

The mechanisms by which these deposits can change form and volume are of interest to researchers and planners, especially because the flow regime of the postdam Colorado River in Grand Canyon is so much different than in predam times. The most notable difference includes the change from an annual flow cycle (100,000–2,000 cfs) dominated by snowmelt runoff to a diurnal flow cycle dominated by peak power generation demand (30,000–8,000 cfs). The following three major mechanisms seem to be active in the reworking of sandbars (Budhu 1992):

1. seepage induced failure during low flow;
2. wave induced erosion from surface turbulence, wind, and boats; and
3. drag forces from bottom turbulence and downstream flow.

Early efforts of the GCES researchers were directed at obtaining baseline volumetric estimates and short term volumetric changes of sandbars within the Grand Canyon. One early method involved inserting thin wire cables of known length vertically into the sandbar at node points of a precisely surveyed grid. In theory, the wires in this grid could be remeasured quickly on subsequent trips and supply data necessary for volumetric estimates. Quite often, however, subsequent survey trips would find the sandbar had changed so much in just 2 weeks that large portions of the wire grid could not be found. This technique was replaced out of necessity by a much more labor intensive approach using total station plane surveying at biweekly intervals.

Hypothesis

The volumetric survey work showed that major changes had occurred in sandbar morphology in between survey visits. We feel these changes are neither gradual nor consistent from sandbar to sandbar. We hypothesize that significant changes in sandbar morphology and volume can occur over a period of several hours to several days.

Objectives

Our objectives are

1. to obtain daily photographs for a year of 43 sandbars along the Colorado River between Lees Ferry and Diamond Creek;
2. to digitize some of the photographs for analytical and other purposes;
3. to develop procedures to assess the errors involved and rectify these images from oblique to planimetric views;
4. to develop animated visualization to help assess short time step changes in sandbar morphology over the sampling period; and
5. to use the results of the previous objectives to analyze the nature, timing, and extent of short term change in sandbar morphology.

Methods

Field Methods

We needed an inexpensive replacement for precision aerial photogrammetry because aerial photography is expensive even for a single time step. Also, we needed daily photography, but daily aerial photography is intrusive on wilderness and dependent on favorable flying conditions.

We used a land-based camera system built from relatively inexpensive off-the-shelf products. We chose Pentax IQ 105 programmable cameras as the core of the system. The microprocessor-controlled cameras allow the built-in timer to be set for repeat exposures once every 24 h at a preset time of day. Each camera was secured to a base, which was fastened snugly inside a standard military ammunition can. A large, round hole was cut into the side of the can congruent with the position of the camera lens and fitted with glass. A small metal gable was fashioned to protect the glass from the elements. The boxes were painted in earth tones to make them inconspicuous.

At each sandbar site, a camera box was located a sufficient distance away to allow photographing the entire beach. A single camera was used except at site 172.3L where two cameras were used to test stereographic coverage. Usually, the camera was located across, and elevated above, the river to provide a low oblique view of the sandbar. The camera box was attached with silicon sealant to a large boulder or to bedrock.

The timer was set to expose the film daily at a predetermined time selected to take advantage of local low river stage and to avoid local shading. Each camera was loaded with 36-exposure, ASA 64, color slide film, attached to the base, and sealed in the box along with a packet of desiccant. Forty-three sandbars were included in the sample, and each of the five major geomorphic reaches (Schmidt and Graf 1990) was represented (Fig. 2).

While the camera was being sited, control panels were temporarily fixed at points around the beach. A surveying crew then located the positional coordinates of the panels and the camera box using total station plane surveying techniques. Once the camera had photographed the sandbar with the control panels in place, the panels were removed. Subsequently, the film was recovered approximately monthly. Virtually no mechanical failures occurred with the cameras.

Image Processing

Film was processed conventionally and left in strips to facilitate scanning. A Nikon high-resolution slide scanner was used to convert the image to digital form. The digital tagged image format file (TIFF) created by the scanner was controlled by using Picture Publisher software. The image was imported into ERDAS V.7.5 for image rectification and analysis (Fig. 3; ERDAS 1992).

The image had to be rectified from an oblique view to a planimetric view. The pixel locations of the control panels in the image were matched with the precisely surveyed coordinates of the same panels on the ground through a transformation equation. A variety of transformation equation orders or exponential powers may be applied. The benefit of higher order equations is a reduced root mean square (RMS) error between image and ground (Fig. 4).

Each higher order equation requires an increase in the number of ground-control points. Control panels were no longer necessary once the desired transformation equation had been established. Fixed natural features in the image were used to control subsequent transformations. Typically, these natural features were chosen from the bedrock or debris fans surrounding the sandbar deposit.

Once the images were rectified to approximate the planimetric view, various area and outline shape related analyses were performed. These analyses include total area of subaerial sand cover and daily lateral erosion or deposition rates based on a comparison of sequential images (Fig. 5). Estimates of height change and sand volume cannot be made with single-camera photogrammetry. In addition to the measurements, the original oblique views or the rectified views were sequenced into high-speed video loops for improved visualization and understanding of sandbar dynamics.

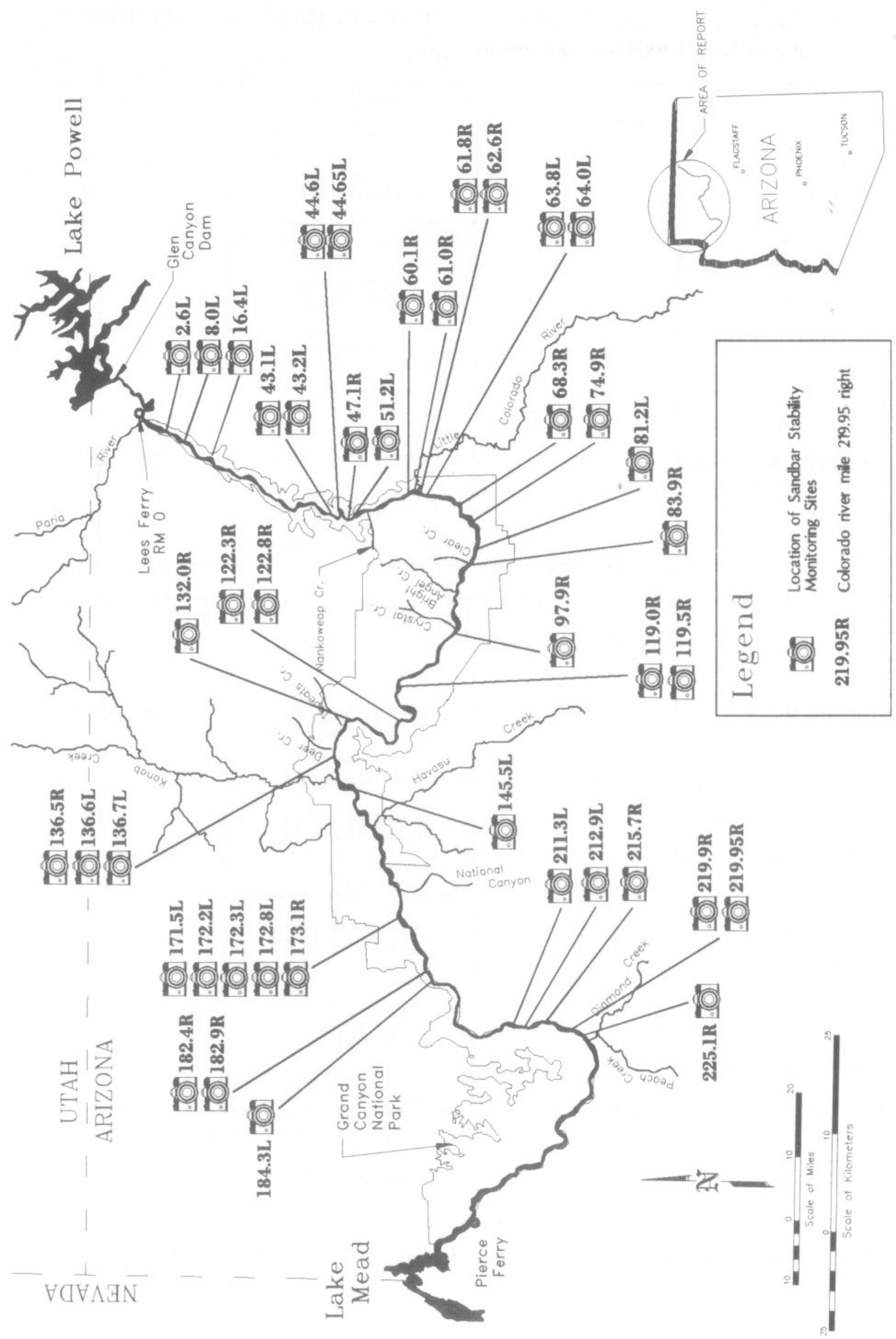

Fig. 2. Site index map for sandbars and camera stations used in this study.

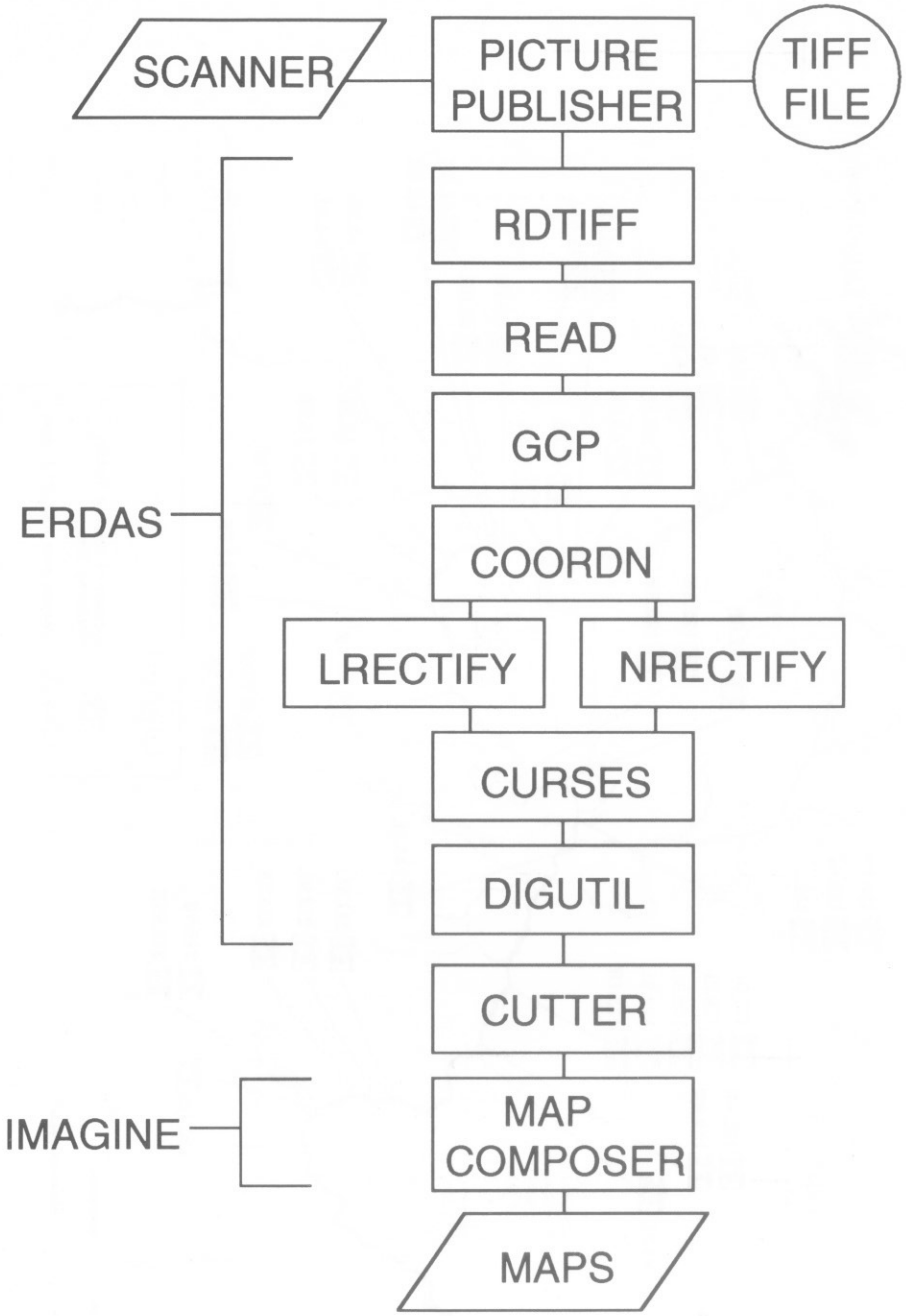

Fig. 3. Major image processing procedures and modules used in this study.

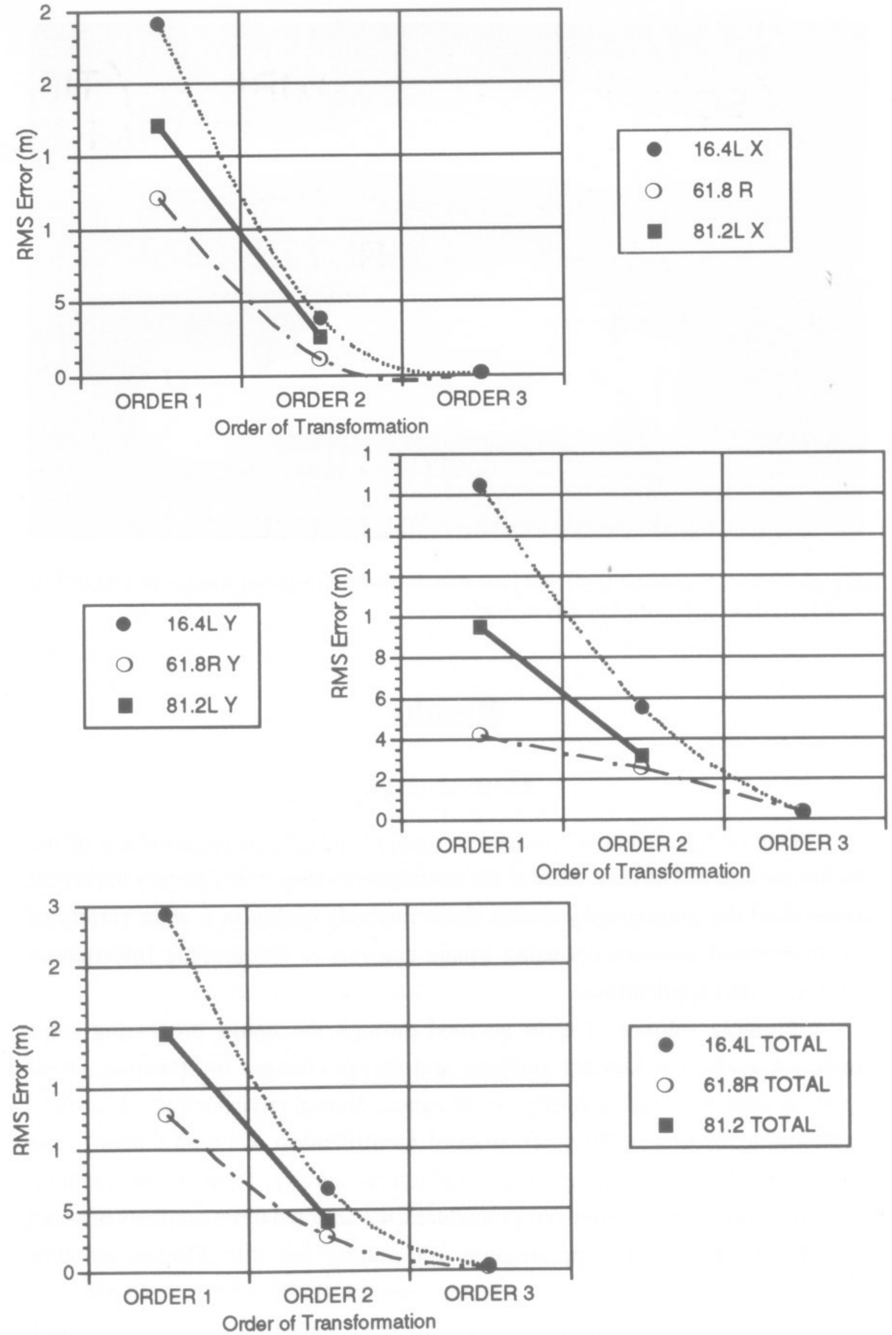

Fig. 4. Transformation order versus RMS error as reported by ERDAS.

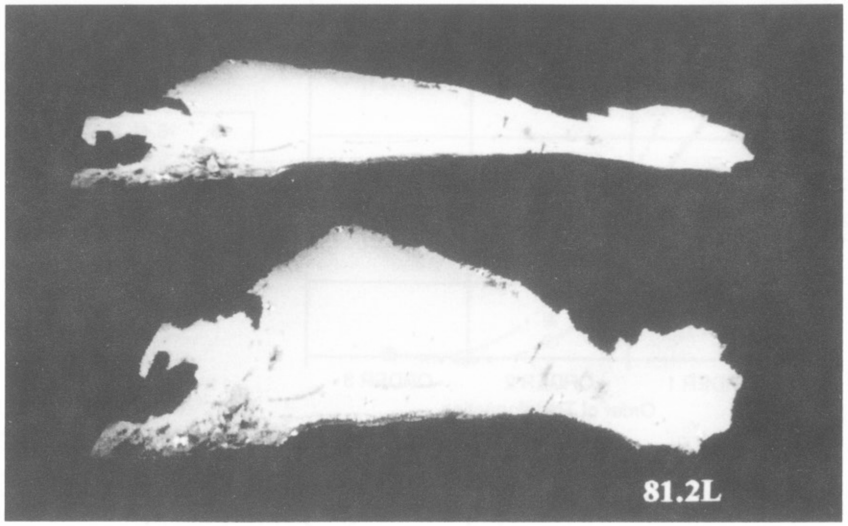

Fig. 5. Pretransformation (*top*) and post-transformation (*bottom*) images in ERDAS of 81.2L showing control panels in place.

Results

Methodologic

One of our objectives related to analysis of the spatial accuracy of the techniques used. The simplicity of the technique and the ability to vary the repeat interval of the photography makes these methods usable in a wide variety of environmental assessments using image analysis or Geographic Information System (GIS) applications.

Possible sources of error accrued through the image processing steps included nonplanar sandbar surfaces and abrupt changes in elevation, slight shifts in camera position during maintenance, diurnal environmental heat flux, scanning error (e.g., film curl); manual identification of control points, and limitations in masking target image in batch processing. To assess the cumulative spatial error involved in our procedures, we selected three sandbars of about the same linear extent (approximately 100 m long) but with different amounts of vertical relief. The sandbars selected were 16.4L (Hot Na Na), 61.8R (first site below the Little Colorado River confluence), and 81.2L (Grapevine Camp). The sandbar at 61.8 was included because of its high relief, whereas 16.4L and 81.2L represented more typical relief. We withheld several of the control panels

from the transformation, then ran the transformation operation using the remaining control points, and finally queried the transformed image for the location of the withheld panels.

The resulting queried coordinates reflected a cumulation of all errors propagated through the system when used in a manner we were likely to employ in our spatial analyses. These queried coordinates were obtained using the CURSES module of ERDAS (Fig. 3). When the queried coordinates were compared to the surveyed coordinates for the panels, a Euclidean distance error could be computed for each panel withheld.

ERDAS internally computes an RMS error for the transformed image compared to the control points used. It would be convenient if the transformation RMS value could be used as an estimate of error for any point on the transformed image. We set out to evaluate the validity of that possibility by comparing the RMS error to Pythagorean distance errors for the control points that were withheld. The salient statistics for the individual sandbar error analyses is illustrated in Table 1. When performing the error analysis, we must withhold so many points that third order transforms are not possible, so our results are derived using second order transforms and subsequently extrapolated to third order transforms (Table 2).

Results of the error analysis suggest that the RMS value is typically (but not always) a conservative estimation of Pythagorean distance error (Table 1), hence confidence intervals should be applied. Order three transforms seem to be the optimal choice considering a balance between accuracy and surveying effort.

Order three transform RMS suggests better than 1 in 100 spatial accuracy at an alpha level of 0.05 or 95% confidence (Fig. 4). Therefore, the techniques used here allow us to come within 1 m of planimetric position for 95% of the point positions sampled.

Environmental

Some initial analysis was completed but more is needed. By combining the photogrammetry from this project and the pilot project, we had usable records for selected sandbars to August 1990. Since August 1990, significant changes have occurred at least 79 times in the morphology of 28 sandbars. Two long-running records showed 10 failures from August 1990 to July 1993 (68.3R) with a mean return time of 110 days and 9 failures from January 1991 to July

Table 1. Error analysis for images of three Grand Canyon sandbars using second-order transformations.

Point number	Error in X (m)	Error in Y (m)	ΔZ[a] value (m)
16.4L Hot Na Na (approx. 100 m long)			
5 (Front)	0.17	1.10	95.98
7 (Front)	0.72	0.11	96.00
F1 (Middle)	0.31	0.44	97.31
F2 (Middle)	0.74	2.28	97.62
			ΔZ = 1.74
RMS = 0.928	$\overline{X}$ = 0.49	$\overline{Y}$ = 0.98	ΔZ all = 1.94
61.8R first sandbar below the Little Colorado River (approx. 100 m long)			
4 (Front)	0.21	0.16	101.29
7 (Back)	0.40	2.26	127.09
RMS = 4.78	$\overline{X}$ = 0.61	$\overline{Y}$ = 1.21	ΔZ = 25.80
5 (Front)	0.23	0.31	110.17
9 (Middle)	0.00	1.95	128.89
10 (Back)	2.17	6.65	166.06
			ΔZ = 55.89
RMS = 4.68	$\overline{X}$ = 0.80	$\overline{Y}$ = 2.97	ΔZ all= 77.14
81.2L Grapevine Camp (approx. 100 m long)			
3 (Front)	0.95	0.68	95.00
9 (Back)	2.44	1.38	96.97
RMS = 3.9	$\overline{X}$ = 1.70	$\overline{Y}$ = 1.03	ΔZ = 1.97
2 (Front)	1.61	0.61	95.07
7 (Back)	3.52	0.85	96.40
			ΔZ = 1.33
RMS = 1.83	$\overline{X}$ = 2.57	$\overline{Y}$ = 0.73	ΔZ all= 3.40

[a]ΔZ = Difference between minimum and maximum Z values.

1993 (172.3L) with a mean return time of 105 days. The most common morphological change was rapid erosion (complete within 1 day) followed by slow deposition (up to 2 weeks). About 50% of the documented failures followed weekend low flows.

Table 2. Summary error analysis for oblique single-point photogrammetry as used in this study.

A summary of the RMS curves presented earlier is given:

First order	20.39 m
Second order	4.44 m
Third order	0.41 m

Results of point position tests on the second order transforms from three sandbars yield the following values:

	Mean (m)	Standard deviation (m)
ΔZ[a] < 60.0 m	1.99	1.81
ΔZ < 5.0 m	1.76	1.08

Compared to the equivalent RMS values for the associated transformation:

	Mean (m)	Standard deviation (m)
ΔZ[a] < 60.0 m	4.37	1.73
ΔZ < 5.0 m	2.21	1.52

Applying confidence intervals to the reported RMS values:

Confidence	Order 2 RMS (m)	Order 3 RMS (m)
80% (a = 0.2)	6.15	0.75
90% (a = 0.1)	7.04	0.92
95% (a = 0.05)	7.78	1.07

[a]ΔZ = Difference between minimum and maximum Z values.

Figures 6 through 10 illustrate oblique views of two typical sandbar failures. Figure 6 shows 215.7R on 13 March 1993 and Fig. 7 is the same sandbar 1 day later (14 March 1993). Note the loss of several meters. Figure 8 shows 16.4L (Hot Na Na) on 22 October 1992. The same sandbar 1 day later (23 October 1992; Fig. 9) shows seepage failure with water loss in progress. The photograph for 24 October 1992 (Fig. 10) shows the full extent of the failure. Figures 11 (18 June 1991), 12 (19 June 1991), and 13 (1 July 1991) show the sandbar at 172.3L, an active bar as described above. Figures 11 and 12 reflect only 1 day of difference and are indicative of the rapid rate of failure. Two weeks after the 19 June failure, the bar was gradually rebuilding (Fig. 13).

The photogrammetry indicates more active sediment recycling than one would assume from the long term studies only. Data for a number of Grand Canyon sandbar studies (Table 3) show lateral erosion and deposition rates. As

Fig. 6. Sandbar at 215.7R on 13 March 1993, prefailure.

the sampling interval shortens, the maximum instantaneous erosion rates climb in a near-logarithmic increase (Fig. 14).

We have sequenced 200 days of oblique photographs from 68.3R, the large sandbar across the river from the bottom of the Tanner trail, into a 30-s

Fig. 7. Sandbar at 215.7R on 14 March 1993, postfailure.

Fig. 8. Sandbar at 16.4L on 22 October 1992, prefailure.

video loop for demonstration. We need to improve the registration and correction for brightness, but the pilot project allowed us to visualize the changes in an extremely dynamic geomorphic system.

Fig. 9. Sandbar at 16.4L on 23 October 1992, during failure.

Fig. 10. Sandbar at 16.4L on 24 October 1992, postfailure.

Interim Conclusions and Future Work

We conclude that terrestrial photogrammetry is a useful, economical, and minimally intrusive tool for monitoring environmental change and for verification

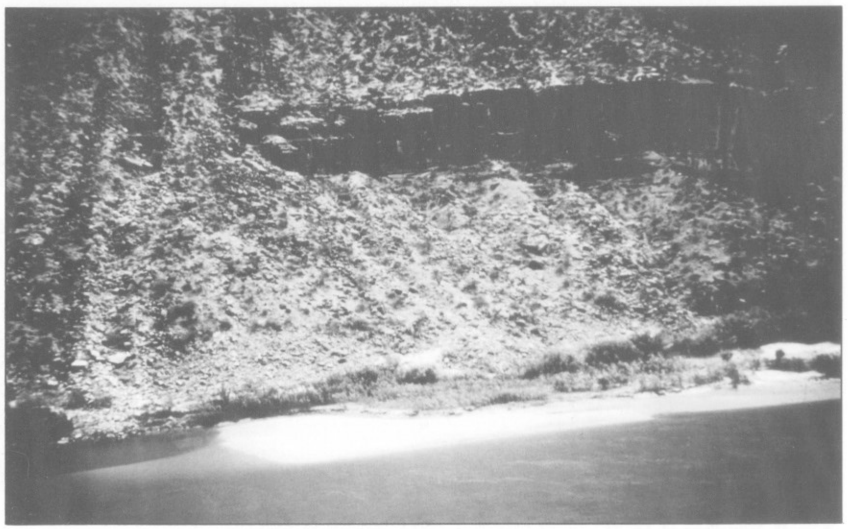

Fig. 11. Sandbar at 172.3L on 18 June 1991 prefailure.

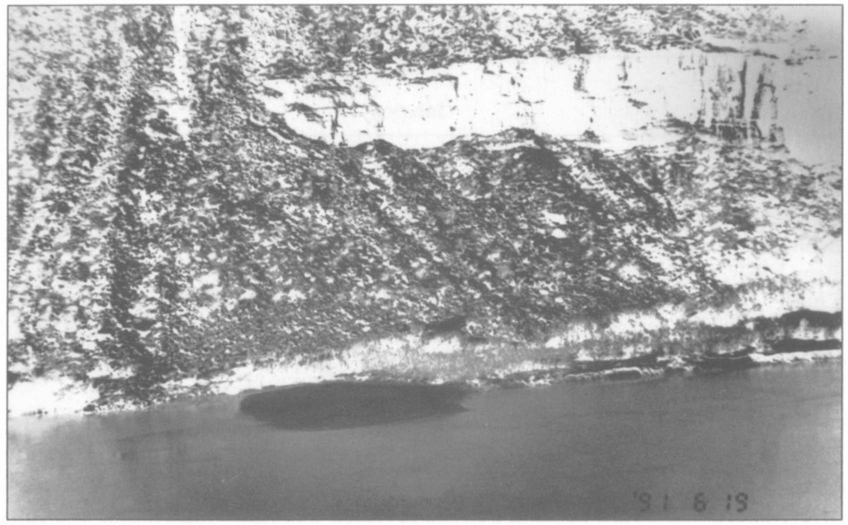

Fig. 12. Sandbar at 172.3L on 19 June 1991 postfailure.

of theoretical models. Planimetric accuracy using low-oblique, single camera, photogrammetry can approach ±1 m in a 100-m view. Sandbars in Grand Canyon often change morphology over daily and weekly time scales. Analysis of progres-

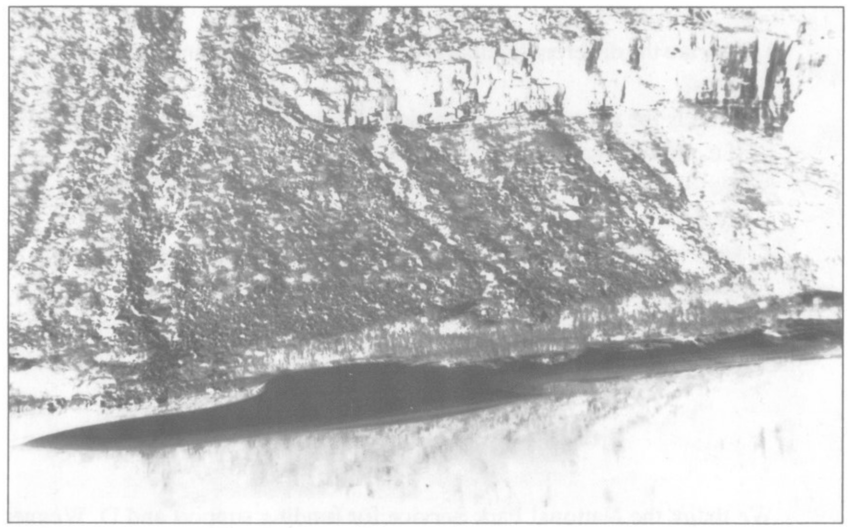

Fig. 13. Sandbar at 172.3L on 1 July 1991, approximately 2 weeks after failure and after rebuilding.

Table 3. Summary of measured lateral erosion rates versus sample frequency.

Reference	Interval	Erosion (m/yr)	Deposition (m/yr)
Beus 1992*[a]	10 years	0.8	1.7
Howard and Dolan 1979	8 years	1.15	0.7
Howard and Dolan 1979	1 year	2.45	0.7
Schmidt and Graf 1990	4.5 months	34.7	26.7
Beus 1992*	2 weeks	520	390
Cluer[b]	2 weeks	780	520
This study	daily	36,500	2,550

[a]Asterisk indicates unpublished material.
[b]Brian L. Cluer, Northern Arizona University, Flagstaff, personal observation.

sively shorter interval sampling periods revealed a roughly logarithmic increase in short term erosion and deposition rates. The highly dynamic behavior of sandbars in Grand Canyon indicates the need for short-duration sampling intervals.

The remainder of the study will focus on analysis of the effects of interim flows on sandbar stability. What effect did the spring 1993 floods down the Little Colorado River have on the mainstem sandbars? The following are potential research questions that this and future applications of this technique can address:

1. How are the different sandbar types affected by different discharge rates?
2. What is the progression of erosion and deposition both spatially (i.e., downstream) and temporally?
3. Are sandbar dynamics different above and below the Little Colorado River?
4. How do theoretical models of sandbar dynamics compare to reality? and
5. What are the sandbar conditions before and after a human-induced control flood?

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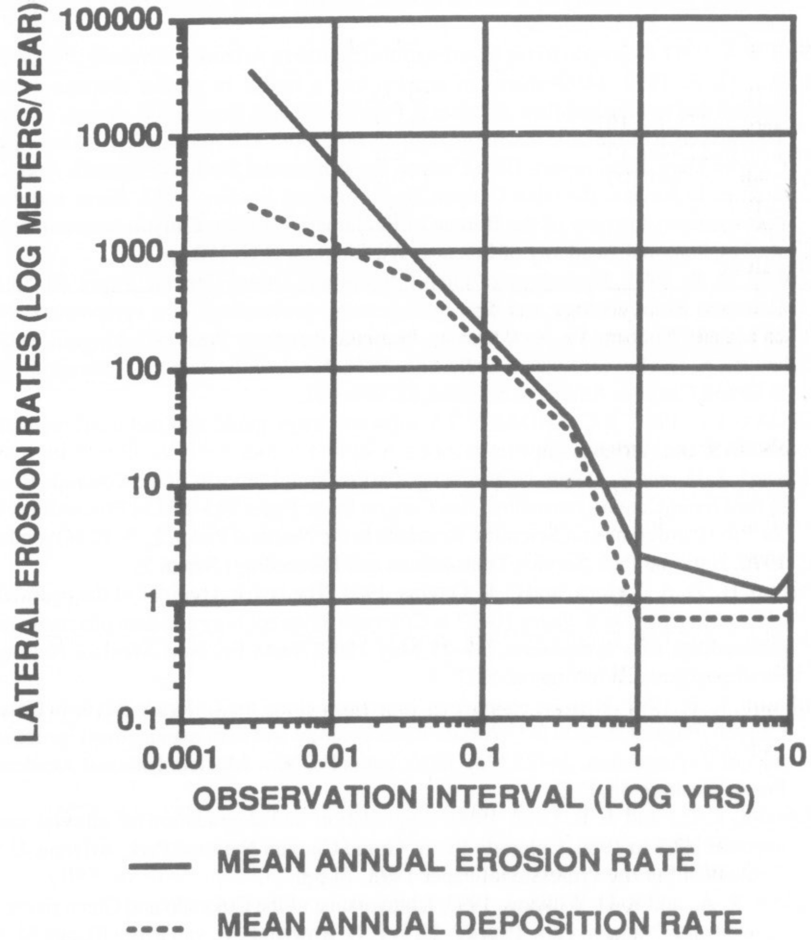

Fig. 14. Log–log scaled plot of measured lateral erosion rates versus sample frequency.

Cited Literature[1]

Andrews, E. D. 1991. Sediment transport in the Colorado River basin. Pages 54–74 *in* Colorado River ecology and dam management: proceedings of a symposium. 24–25 May 1990, Santa Fe, New Mexico. National Academy Press, Washington, D.C.

[1]Asterisk indicates unpublished material.

Bauer, B. O., and J. C. Schmidt. 1993. Waves and sandbar erosion in the Grand Canyon: applying coastal theory to a fluvial system. Annals of the Association of American Geographers 83(3):475–497.

*Beus, S. S. 1992. Colorado River investigations. Northern Arizona University, Flagstaff.

Budhu, M. R. 1992. Mechanisms of erosion and a model to predict seepage-driven erosion due to transient flow. Chapter 2. Pages 1–75 *in* S. Beus and C. Avery, editors. The influence of variable discharge regimes on Colorado River sandbars below Glen Canyon Dam. Final report. Glen Canyon Environmental Studies, Flagstaff, Ariz.

Committee to Review the Glen Canyon Environmental Studies. 1987. River and dam management: a review of the Bureau of Reclamation's Glen Canyon environmental studies. National Academy of Science, Washington, D.C. 152 pp.

Dawdy, D. R. 1991. Hydrology of Glen Canyon and Grand Canyon. Pages 40–53 *in* Colorado River ecology and dam management: proceedings of a symposium. 24–25 May 1990. Santa Fe, New Mexico. National Academy Press, Washington, D.C.

Dolan, R., A. D. Howard, and A. Gallenson. 1974. Man's impact on the Colorado River in Grand Canyon. American Scientist 62:393–401.

ERDAS, Inc. 1992. P.C. ERDAS V.7.5 software, users guide and technical manuals. ERDAS, Inc., Atlanta, Ga.

Howard, A. D., and R. Dolan. 1979. Changes in the fluvial deposits of the Colorado River in the Grand Canyon caused by Glen Canyon Dam. Pages 845–851 *in* Proceedings of the First Conference on Scientific Research in the National Parks, 2. 9–12 November 1976. National Park Service Transactions and Proceedings Series 5.

Ingram, H., D. A. Tarlock, and C. R. Oggins. 1991. The law and politics of the operation of Glen Canyon Dam. Pages 10–27 *in* Colorado River ecology and dam management: proceedings of a symposium. 24–25 May 1990. Santa Fe, New Mexico. National Academy Press, Washington, D.C.

Johnson, R. R. 1991. Historic changes in vegetation along the Colorado River in Grand Canyon. Pages 178–206 *in* Colorado River ecology and dam management: proceedings of a symposium. 24–25 May 1990. Santa Fe, New Mexico. National Academy Press, Washington, D.C.

Schmidt, J. C., and J. B. Graf. 1990. Aggradation and degradation of alluvial sand deposits 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. U.S. Geological Survey Professional Paper 1493. 74 pp.

Valdez, R. A., and R. D. Williams. 1993. Ichthyofauna of the Colorado and Green rivers in Canyonlands National Park. Pages 2–22 *in* P. G. Rowlands, C. van Riper III, and M. K. Sogge, editors. Proceedings of the First Biennial Conference on Research in Colorado Plateau National Parks. 22–25 July 1991. National Park Service Transactions and Proceedings Series NPS/NRNAU/NRTP-93/10.