Cyclic Fluvial Processes and Bias in Environmental Monitoring, Colorado River in Grand Canyon[1]

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ABSTRACT

The Colorado River in Grand Canyon is one of the most intensively studied regulated rivers in the world where discharge is controlled to optimize peak load hydropower production. Sandy channel margin deposits that occur along the Colorado River have been monitored for nearly three decades to determine the effects of flow regulation by Glen Canyon Dam. Recent results from remote daily monitoring show that it is common for large areas of fluvial sand deposits to be eroded in less than one day, followed by redeposition of the area within a few weeks or months. These remote observations were confirmed directly. A review of the maximum erosion and deposition measurements from all sources shows that the recently measured daily changes equal or exceed the magnitude of changes measured over time spans from 2 weeks to 10 years. Consequently, erosion and deposition rates are significantly greater than previously reported because erosion and deposition occur in cycles that repeat several times each year at individual sites, each with unique recurrence intervals. These findings show that monitoring environmental changes downstream of a peaking power dam such as at Glen Canyon presents temporal and spatial sampling problems that lead to data biasing. This has implications for past interpretations as well as for future investigations on this and other regulated rivers.

"Events may have progressed both faster and slower in the past than during the brief interval which we call the present."

Davis (1985)

Introduction

The Colorado River flows in the largest and most highly regulated river basin in the western United States and is one of the most highly regulated rivers in the world. Glen Canyon Dam was completed on the Colorado River 24 km upstream of Grand Canyon National Park in 1964 (figure 1). The dam altered environmental conditions downstream by: (1) reducing sediment load three orders of magnitude; (2) reducing year-round water temperature; and (3) altering the flow pattern characteristic of an annual snow-melt flood cycle to a daily "peak-load" power generation cycle (figure 2) by storing spring flood flows for power plant discharges throughout the year. The downstream hydrologic and geomorphic changes have caused various environmental stresses (e.g., Stanford and Ward 1979; Turner and Karpiscak 1980; Hirsch et al. 1990; Minckley and Deacon 1991) and threaten the ecological integrity of Grand Canyon National Park (Ingram et al. 1990).

The subjects of geomorphic investigations are the alluvial sand deposits that occur along the river banks and provide the foundation for a rich and varied riparian ecosystem in a harsh desert climate. Sand deposits commonly occur where course debris from steep ephemeral side channels and tributaries produce fans that constrict the bedrock channel and disturb normal downstream flow patterns. The fans of course debris, immobile under all but extreme discharge events (Kieffer 1985), constrict the main channel by 40 to 50% and cause lateral flow separation from the bank, thereby creating flow recirculation zones. This common geo-

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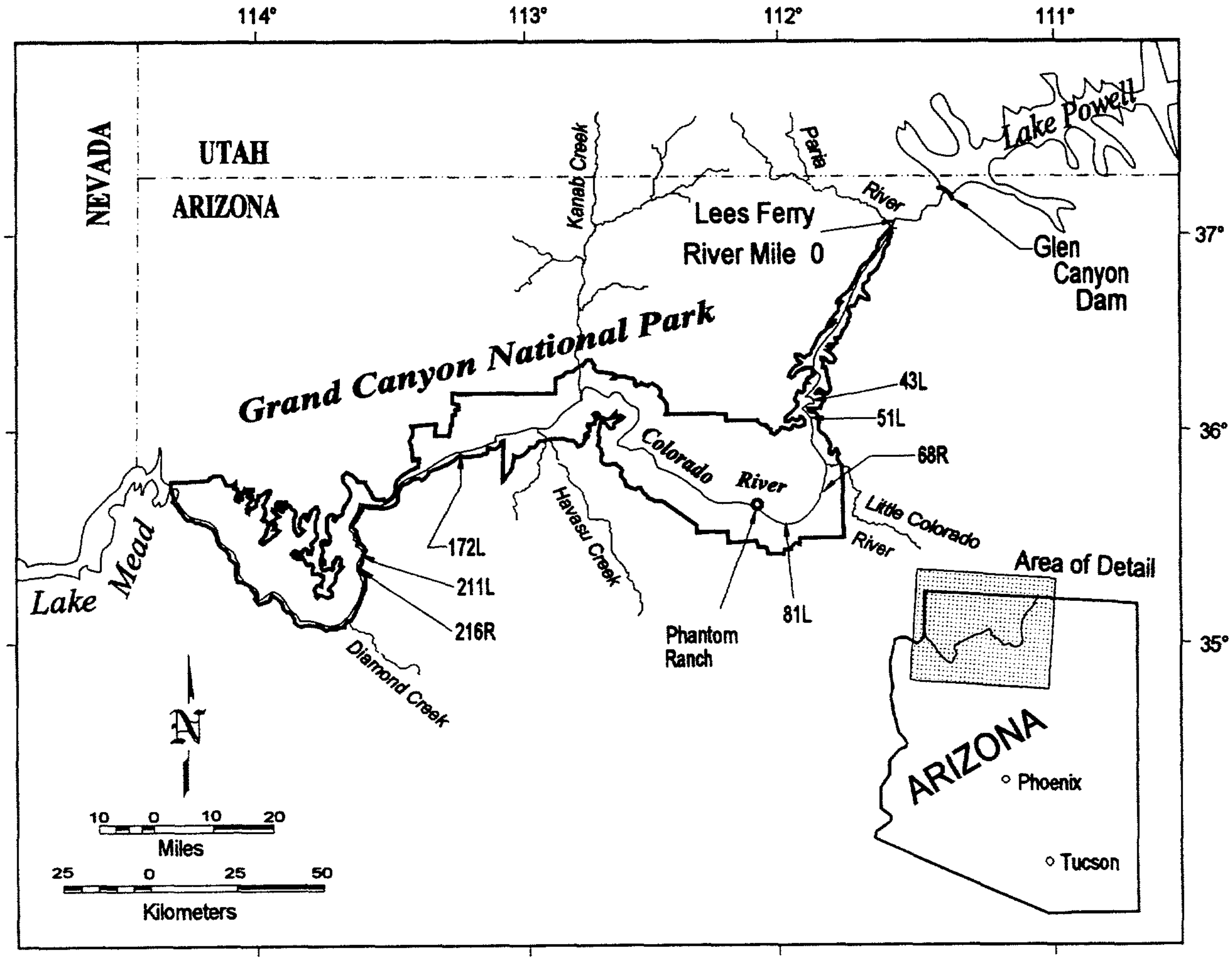

Figure 1. Geography of the Colorado River in Grand Canyon, showing impoundments upstream and downstream, time-lapse camera sites listed by river mileage downstream of Lees Ferry, and major tributaries.

morphology is responsible for the famous rapids of the Colorado (Leopold 1969), and the associated flow patterns result in characteristic alluvial sand deposits in the low velocity environments (Schmidt 1990).

There are four commonly recognized sand deposits associated with channel constriction, expansion, and lateral flow separation. A deposit type nomenclature proposed by Schmidt and Graf (1990) describes deposits with respect to the geomorphic features that control their position. The types are: upper pool, separation, eddy, and reattachment deposits (figure 3). The terms *channel margin deposit* and *sand bar* will be used as general descriptions for all of the deposits that occur along the banks of this bedrock confined river. The goals of this paper are to: (1) present new results from a daily sand bar monitoring program; (2) review the results from all previous sand bar monitoring programs; and (3) through comparing measurements obtained at vastly different time-scales, discuss some interpretive limitations of previous investigations and implications for future process monitoring.

Methods

New Data. A time-lapse camera system was deployed in August, 1990 to test the hypothesis that significantly large changes in the size of channel margin deposits might occur in periods of time much shorter than previous measurements indicated. The first roll of film recorded two events during a two-week period in which substantial erosion occurred between photographs taken every 8 hrs, during what was an otherwise depositional period for the channel margin deposits at 68R. Following this initial result six additional camera sys-

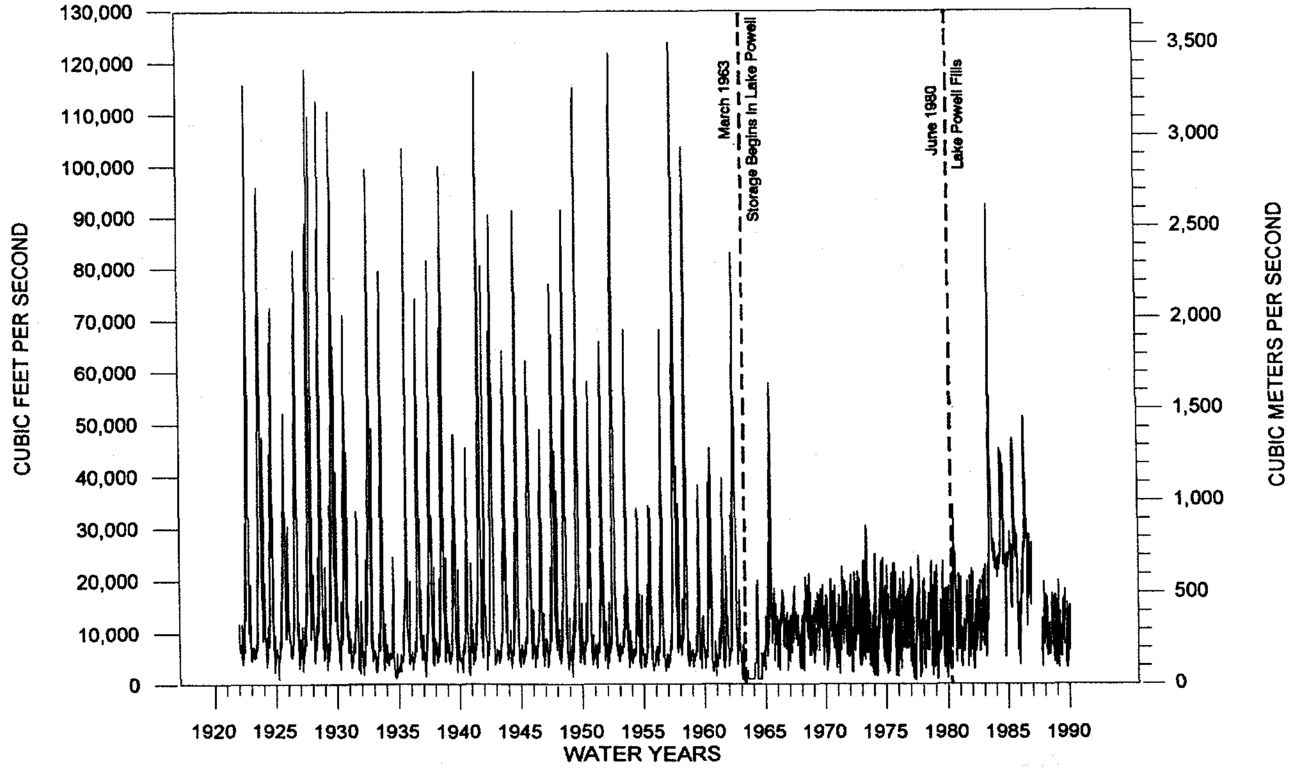

Figure 2. Daily mean discharge at Lees Ferry gage for water years 1922 to 1990. Notice annual flood pattern in the pre-dam period and regulated fluctuation patterns in the post-dam filling and post-dam full periods.

tems were deployed in November-December, 1990 to monitor seven channel margin deposits throughout the length of the Colorado River in Grand Canyon (see locations in figure 1). Sites were selected to coincide daily low stage with daylight hours and to monitor representatives of the major deposit types that occur.

The site naming convention used in this report and all previous Grand Canyon literature is by river mile downstream of Lees Ferry, and left (L) or right (R) bank when viewed downstream. The deposits chosen for this study are: 43L—an upper pool deposit; 51L, 172L, 211L, and 216R—reattachment and eddy deposits; 68R—consisting

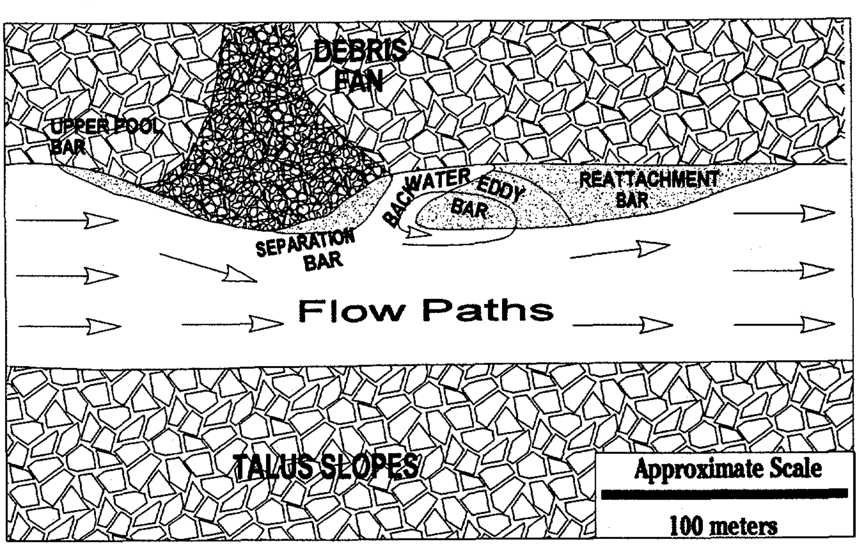

Figure 3. Sketch map of typical channel margin sand deposits and nomenclature based on geomorphic position.

of separation, eddy and reattachment deposits; and 81L—a margin deposit.

The time-lapse photography system consisted of a 35 mm camera with a date imprinting film back, controlled by a programmable intervalometer. Environmental housings for the cameras consisted of surplus steel ammunition boxes fitted with acrylic windows, fixtures to precisely align the camera body and lens, sun shades, and locking latches. The camera housings were attached to rock outcrops opposite subject deposits, providing oblique views from fixed and repeatable points. The intervalometers were programmed to take one photograph each day during the approximate low water level. Film was changed during raft trips or by helicopter approximately every 30–40 days.

Because the cameras were rigidly anchored and the image geometry precisely repeatable, any differences between successive photographs could potentially be quantified. Measurements taken from the photographs consisted of deposit width and area, resulting in rates of change for daily time-scales. An expanded ongoing monitoring program that began in March, 1992 uses geographically referenced photo control points and electronic image processing techniques to rectify the oblique images to vertical views, allowing true-scale area measurement (Manone et al. 1994). Results currently available from this study consist of event timing and overall sample statistics. Other results presented in this paper are from direct observations made between 1991 and 1993. Between 1991 and 1993, field measurements were also obtained for two large-scale rapid erosion events that occurred while the author and others were camped for several days at one sand bar.

Conversion of Existing Data. Original data from previous investigations (whether from surface profiles, topographic maps, or aerial photographs) were converted where necessary to lateral change in the width (perpendicular to main channel flow) to allow comparison of all results in common terms.

Results

Direct Observations, April 1991. A group of scientists including the author observed a rapid erosion event while camped at 172L for 9 days in April, 1991. During rising stage on the evening of April 17, the eddy bar at the upstream portion of the reattachment deposit was scoured over a period of 4–6 hrs (figure 4*a*–*b*). The event was detected after dark by audible splashing of large sandy blocks falling into the river. Closer examination revealed individual blocks approximately 1 m high, 0.5 m thick, and 1 to 3 m long, failing as recirculating current undercut the toe of the exposed deposit. Sand grains composing the non-cohesive blocks were quickly entrained and transported from the eddy into the main channel. The exposed vertical surface of the deposit was over-topped during peak discharge a few hours after the erosion event began. This resulted in recontouring the cutbank to a stable slope and obliterating the obvious signs of rapid erosion by dawn the following morning (figure 4*b*).

Direct Observations, July 1993. A more complex sequence of rapid erosion events was observed in July, 1993, at 172L (figure 5). Between July 24 and August 8, 1993, detailed bathymetry and velocity surveys were repeated twice daily (at low and high stages) along a 900 m reach that encompasses two riffle-pool sequences including the channel margin deposits at 172L. On the afternoon of July 25, 1993, approximately 5% of the separation bar area was scoured by a vortex that developed during rising stage. The vortex dissipated during peak stage a few hours later and erosion of the separation bar ceased. During the flow fluctuation cycle of July 26, the adjacent eddy bar aggraded approximately 15 cm vertically and about 1 m horizontally. During rising stage on the afternoon of July 27, rapid erosion of the eddy bar began. Within 6 hrs an area of about 2,500 m^2 had been scoured to an average depth of 5 m (approximately 12,000 m^3). Erosion ceased prior to peak stage the evening of July 27. Rebuilding of the eddy bar was measurable within 24 hrs of the scour event, and by August 8 the deposit had aggraded vertically about 3 m (figure 6).

Summary of Remote Observations. Daily photographs from an enlarged and ongoing monitoring program document that between March 1992 and December 1993 79 rapid erosion events occurred at 28 of 40 sampling sites (70%). Rapid erosion and deposition events were documented at all seven of the original study sites located throughout the Grand Canyon between January 1990 and December 1993. A total of 65 events were photographed at the seven original study sites during this period, corresponding to a subsample erosion event recurrence interval of approximately 14 days (table 1). Overall, the 40-site erosion event recurrence interval for the period March 1992 to December 1993 was approximately nine days.

Measurements from the daily photographs document that approximately 70% of all erosion during the period January 1990 to December 1993 occurred during rapid erosion events. The remaining measurable erosion was gradual, or incremental from day to day, and was dominated by traction

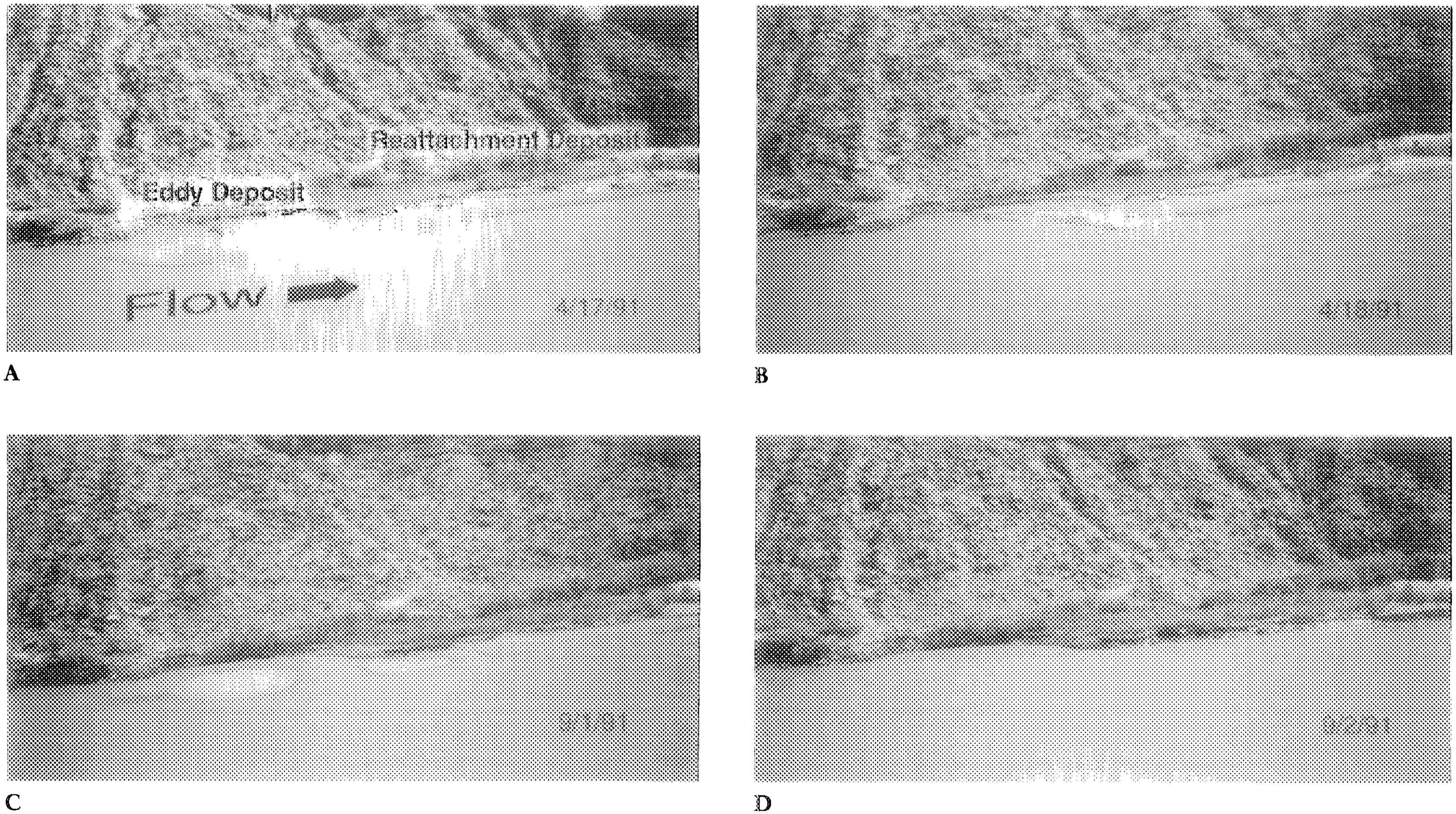

Figure 4. Selected photographs from 172L taken in 1991 during daily minimum discharge showing two of 14 typical erosion events. (*a*) April 17; (*b*) April 18; (*c*) September 1; (*d*) September 2. Flow is from left to right with counterclockwise recirculating flow over the bare eddy deposit. Image width is 180 m. Refer to figure 3 for geomorphic description.

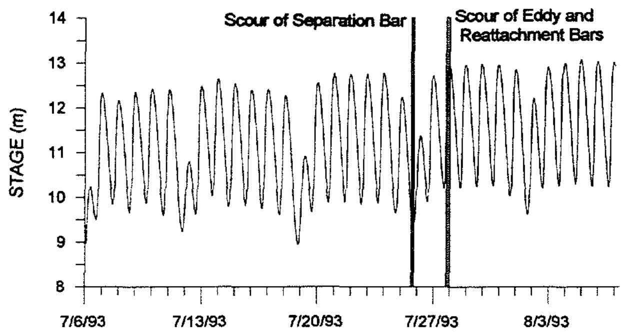

Figure 5. Instantaneous stage height from an arbitrary datum at river mile 170 for period July 7 to August 7, 1993, showing timing of July erosion events at 172L.

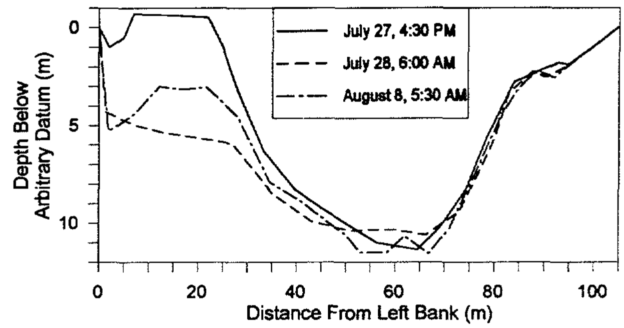

Figure 6. Topographic variation along one cross section at 172L from surveys conducted in July–August 1993. Within 6 hrs of first survey approximately 12,000 m^3 of sediment were scoured from the eddy deposit during one of 14 erosion/deposition events documented in 840 days.

processes that reshaped post-event vertical banks to more stable slopes. Comparing the minimum and maximum eroded area results in a percentage range from 1 to 51% for all rapid erosion events. In most cases, erosion events were completed in less than 24 hrs, and the areas eroded were commonly redeposited to similar size and morphology within a few weeks to two months, the rate depending primarily on the frequency and magnitude of subsequent peak discharges.

Review of Existing Data. The first monitoring program for Colorado River fluvial deposits in Grand Canyon was initiated in 1974 by Howard (1975) who established permanent benchmarks and surveyed topographic profiles on 20 channel margin deposits. Lateral erosion and deposition (changes in deposit width) were documented when the profiles were resurveyed in 1975 and 1976 (Howard and Dolan 1976). The maximum lateral erosion rate measured between 1975 and 1976 was 4.9 m (Howard and Dolan 1976).

Howard and Dolan (1976) also compared aerial photographs taken in 1965 and 1973 for the entire population of channel margin deposits along the river corridor between Glen Canyon Dam and Lake Mead. Maximum lateral erosion rates documented over this time-span were on the order of 10 m/yr (presumably determined from erosion of about 80 m between 1965 and 1973 at one deposit).

The observation of high erosion rates, made in the context of the substantial decrease in suspended sediment following construction of Glen Canyon Dam, led Howard and Dolan (1976) to predict the eventual scour of sandy banks throughout Grand Canyon, consistent with observations between 1956 and 1975 for the 24 km reach downstream of Glen Canyon Dam (Pemberton 1976). In a reversal of opinion, 20 years after the dam began trapping sediment and regulating discharge, Howard and Dolan (1981) stated that channel margin deposits had reached an equilibrium with peaking power discharge patterns by the late 1970s. They suggested monitoring a small sample of channel margin deposits at 3–6 year intervals (Howard and Dolan 1976, p. 26).

In spring 1983, high flows from the Rocky Mountains coincided with near maximum water storage in Lake Powell. These two events culminated in emergency water releases from Glen Canyon Dam in 1983 and annual flows in 1984–1986 that greatly exceeded typical post-dam flows for power production (figure 2). The floods of the 1980s renewed concerns about the impacts of Glen Canyon Dam on National Park and other resources downstream (National Research Council 1987). Short-term process-oriented studies and long-term monitoring programs were initiated following the flood releases.

Table 1. Summary of erosion events for seven sites.

Site	43L	51L	68R	81L	172L	211L	216R	Mean
Record Length (days)	887	1021	883	763	840	958	831	883
Number of Events	5	1	17	1	14	10	17	9
Recurrence Interval (days)	177	1021	52	763	60	96	49	317

Schmidt and Graf (1990) reevaluated the 1965 and 1973 photos previously analyzed by Howard and Dolan (1976) and agreed with their interpretation that initially high erosion rates in the first 10 years of river regulation were substantially reduced by the late 1970s. The effects of the 1983 flood were evaluated using aerial photographs taken in 1973 and 1984 by simply inventorying the total number of channel margin deposits within 270 km of Glen Canyon Dam. From comparing these photographs separated by 11 years, Schmidt and Graf (1990) concluded that the 1983 flood resulted in net aggradation of channel margin deposits in wide reaches and net degradation in narrow reaches.

Schmidt and Graf (1990) also surveyed a small population of channel margin deposits prior to and after the 1985 peak flow and measured approximately 12 m maximum erosion over 2.3 months. In the first attempt to determine directly the effects of fluctuating power plant discharges on channel margin deposits, they surveyed 20 sand bars in October, 1985 (four months after the 1985 flood peak) and resurveyed them in January, 1986. Over the 3.2 month fluctuating-flow period these resurveys recorded maximum lateral erosion of 13 m, as well as substantial deposition. They hypothesized that deposition measured during the fluctuating flow period was an anomaly, perhaps a local response to locally increased sediment supply. Schmidt and Graf (1990) proposed that the floods of the early 1980s caused a depositional perturbation in the previously established state of gradual erosion, a state that would return as channel margin deposits readjusted to fluctuating discharges through initially high erosion rates that would diminish with time. Year-round daily fluctuating discharges for power optimization resumed following the 1980s flood flows.

A parallel long-term monitoring program was conducted throughout the 1980s by Beus et al. (1982, 1984*a*, 1984*b*, 1985, 1986, 1987, 1988, 1989, and 1991*b*), which annually resurveyed approximately 20 sand bars established as monitoring sites in 1974 by Howard (1975). Following the 1984 surveys Beus et al. (1985) concluded that the flood of 1983 caused erosion at some sites and deposition at others, with a tendency for greater deposition at the larger deposits. In the years following the 1980s flood period Beus and coworkers measured maximum lateral erosion rates at 10 to 22 m/yr (table 2). However, maximum lateral deposition rates during the same period ranged from 5 to 26 m/yr. During this period a general response of the sample of channel margin deposits was difficult to define. From the annual data there were about equal numbers of sites showing deposition and erosion, and erosion at a site was often followed by deposition, or vice versa, from year to year.

These data are compared in table 2, which shows the sample size and time period as well as the evaluation interval and the maximum erosion and deposition measurements for all previous investigations. Also shown in table 2 are the maximum erosion and deposition measurements obtained at bimonthly, daily, and shorter time spans from recent investigations. These results are compared in the discussion section.

Discussion

The large-scale rapid erosion events documented at 172L illustrate that entirely different interpretations of a deposit's response to flow patterns can be supported by observations that are synchronous in absolute time but vary by temporal evaluation interval (figure 7). First, this deposit was topographically surveyed on February 11, 1991 and again on April 22, 1991 (Beus et al. 1991*a*). On April 22 the deposit was about 20% smaller than on February 11. The reduction in size and the contoured shapes observed on both dates (figure 4) would logically lead to the conclusion that fluvial processes gradually eroded the deposit 20% over the 60-day period between surveys. Conversely, daily photographs from this period show that the deposit was responding to the flow regime by progressive aggradation from February 11 to April 17. During this period the deposit increased in size approximately 25%, but photographs taken on April 17 and 18 show that all of the newly aggraded portion and approximately 20% of the previous eddy deposit were eroded during this 24-hr period. The daily photographs constrain the erosion interval to within 24 hrs, or within one flow fluctuation cycle. Direct field observations further constrain the erosion event to a period of approximately 6 hrs during rising stage on the evening of April 17.

The results of all repeated studies are presented in table 2. The different sample sizes and measurement intervals should be noted. One obvious trend is that rates of both erosion and deposition increased with absolute time, giving the appearance of accelerated fluvial processes (figure 8). However, repeating cycles of erosion and deposition of channel margin deposits make acceleration of processes an unnecessary explanation. Process acceleration is also physically unlikely since the forcing processes, flow fluctuation, operated throughout most of the time period and even diminished over the past 8 years.

Table 2. Lateral Erosion and Deposition Data

Reference	Study Period	Time Interval	Sample Size	Method	Erosion, Max. (m)	Deposition, Max. (m)
Howard and Dolan 1976	1965–1973	8 yr	whole population along 360 km	Aerial photography	80	15
Howard and Dolan 1976	1974–1976	1 yr	20	Surface profiles	4.9	0.7
Beus et al. 1984*a*	1974–1983	10 yr	20	Surface profiles	8.0	16.7
Beus et al. 1984*b*	1983–1984	1 yr	20	Surface profiles and topography	3.5	
——— 1986	1984–1985	"	"	"	12	5
——— 1987	1985–1986	"	"	"	12	17
——— 1988	1986–1987	"	"	"	22	8
——— 1989*a*	1987–1988	"	"	"	18	26
——— 1989*b*	1988–1989	"	"	"	10	8
——— 1991*b*	1989–1990	"	"	"	15	15
Schmidt and Graf 1990	1965–1973	8 yr	whole population along 360 km	Aerial photography	na	na
"	1973–1984	12 yr	population = 350 along 270 km	Inventory	na	na
"	1985	2.3 mo	5	Surface profiles and topography	12	
"	1985–1986	3.2 mo	20	"	13	10
Beus et al. 1991*a*	1990–1991	2 wk	30	"	20	15
Cluer (unpublished)	1990–1991	2 wk	65	Aerial photography	30	20
Cluer 1991	1990–1991	1 dy	7	Time-lapse photography	40	7
"	April, 1991	6 hr	1	Field observation	20	
Carpenter et al. 1991	1991	20–40 min	1	Water levels—Displacement of water level sensors suggests that one or more erosion events documented with time-lapse photography in 24-hr periods may have occurred in 1–2 20 min intervals.		
Cluer et al. 1993	July, 1993	6 hr	1	Bathymetric and surface topography	25	4

In light of cyclic processes, the more reasonable explanation for the apparent process acceleration involves the time interval between measurements. A plot of evaluation interval and maximum lateral change in channel margin deposits shows a logarithmic relationship (figure 9) where the greatest changes are measured at the shortest time intervals. Clearly the higher rates associated with the shortest time intervals could not persist for extended periods. The high rates are attained only for short periods of time but are repeated because erosion and deposition are cyclic processes and consequently are very difficult to measure using traditional monitoring time-scales.

The time-span bias may have been partially compensated for by large sample sizes because the probability of including the effects of rapid erosion events increases proportionally with sample size. With respect to the cyclic nature of large-scale erosion and deposition, Howard and Dolan's (1976) conclusion that equilibrium was reached following flow regulation may have been unduly influenced by comparing two vastly different sample sizes, the larger sample first and the smaller sample second. Agreement by Schmidt and Graf (1990) for the early period of flow regulation as well as their conclusions about the 1980s floods may have been similarly influenced by different sample sizes, the larger sample first and the smaller second.

The salient results derived from monitoring channel margin deposits on daily and shorter time-scales can be summarized as follows: (1) Lateral erosion occurs at magnitudes equal to or exceeding any previously measured; (2) it occurs in time spans of less than one day, resulting in (3) erosion rates orders of magnitude greater than any previ-

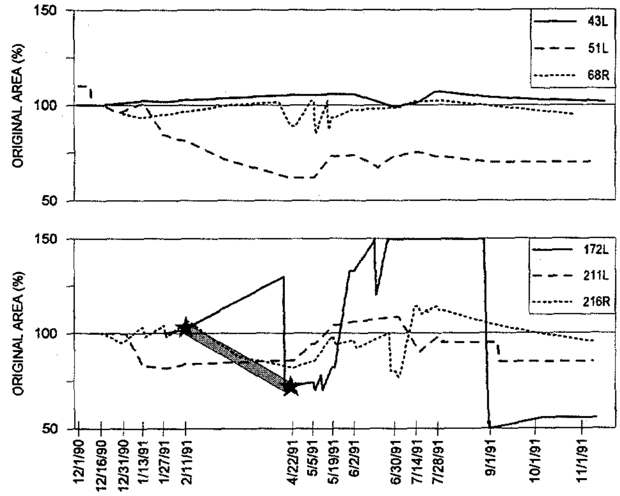

Figure 7. Time series plot of daily area for six deposits from December 1990 to November 1991. Dates correspond to simultaneous terrestrial surveys (Beus et al. 1991*b*). Stars and shaded area illustrate interpretation from surveys separated by 60 days at 172L, compared to daily response for the same period (solid line).

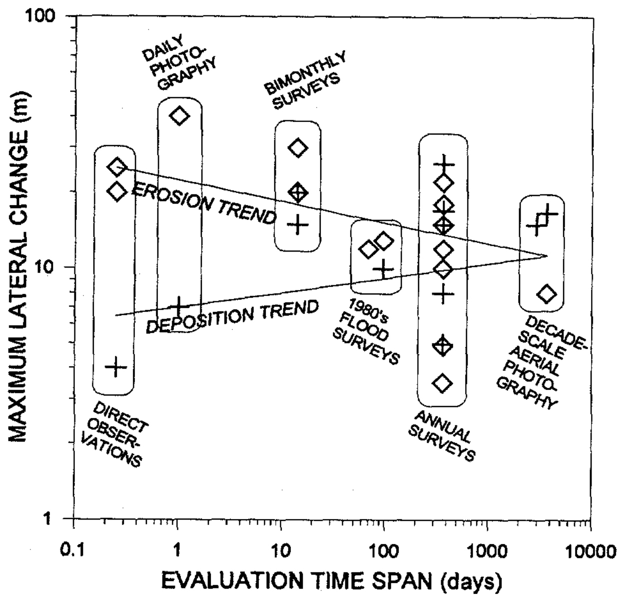

Figure 9. Log-log plot of evaluation time span and maximum measured lateral erosion (pluses) and deposition (squares). Erosion is a very rapid process easiest to detect at the shortest time-scales, while deposition is slower and easier to detect at longer time-scales.

ously reported. (4) Erosion events are followed by periods of rapid deposition, which restore original dimensions of deposits at (5) deposition rates significantly higher than previously reported. (6) Erosion and deposition are cyclic processes that occur (7) at all of the major deposit types, and (8) at a significant percentage of the deposit population, with (9) unique recurrence intervals for individual deposits.

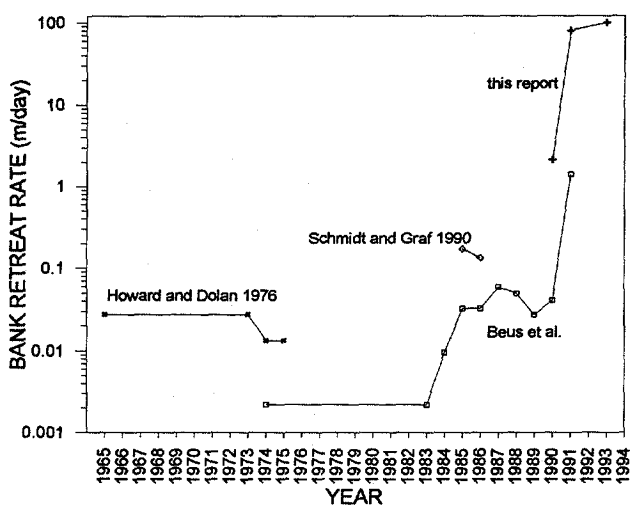

Figure 8. Log-linear chronological plot of maximum bank retreat measurements converted to daily rates. The apparent acceleration of processes is due to short evaluation intervals in latter years which lead to the detection of cyclic processes. Data symbols correspond to sources as indicated (see table 2).

Summary and Conclusions

Channel margin deposits along the Colorado River in Grand Canyon have been monitored at many temporal and spatial scales since damming and flow regulation began in 1964. The first time-scale was the 8-year period between 1965 and 1973, when the entire populations of deposits were compared. High erosion rates were documented. Between 1974 and 1976, measurements from a small number of individual channel margin deposits indicated significantly reduced rates of erosion along with deposition at similar rates. A similar diminishing linear trend was suggested following high flow events in the 1980s by Schmidt and Graf (1990) who also used an initially large sample subsequently compared to a small sample.

One common goal of the sediment research and monitoring conducted on the regulated Colorado River was to measure changes in channel margin sand storage in order to predict future trends and to help manage the fluvial resource. The results presented in this paper show that conflicting predictions for any given time period could result from, and be supported by, simultaneous data collection programs that use different time-spans or different sample sizes, because of the repeating cyclic nature of erosion and deposition. Measurements at time spans greater than the response time-span, in an attempt to determine long-term trends, only provide widely spaced points on very complex and unique response curves for deposits that are often completely reworked between annual measurements.

The results presented in this paper show that channel margin deposits continuously adjust size and morphology through the processes of rapid erosion and deposition, with daily variability equal to or greater than variability any previous longer-term measurements were capable of documenting. In fact, many deposits are completely reworked several times over the course of one year and yet retain the basic size and morphologic characteristics once redeposited. Because of repeated large scale cyclic erosion and deposition, sand bar measurements can not be considered characteristic over time spans of more than a few days or weeks.

Although not explicitly stated in the literature, it appears that the perceived general response model of channel margin deposits to flow and sediment regulation by Glen Canyon Dam was a linear or log-linear degradation diminishing asymptotically over time to some minimum erosion rate condition. This is illustrated by the time intervals used in previous and contemporary investigations. While an annual time-scale is often employed in hydrologic and geomorphic monitoring of naturally flowing rivers, such a time-scale does not characterize the inter-annual variability in channel cross section caused by scour and fill processes. Even on an unregulated stream, a very long-term record of annual measurements would be needed in order to clearly define a long-term trend of geomorphic adjustment from the inter-annual variability in the measurements. The new results suggest a general response model dominated by cyclic erosion and deposition rather than a linear erosion model, further suggesting that a very long sand bar monitoring record will be required in order to sense a long-term response to flow regulation. A more efficient means of monitoring the fluvial resources in this setting may be to monitor continuously the temporal and spatial changes in sediment transport.

Because cyclic erosion and deposition were not detected on one of the most highly studied regulated rivers in the world, perhaps the processes operate but are as yet undetected on other regulated rivers that are also monitored less frequently than the dominant geomorphic response frequency. The results presented suggest that fluvial geomorphic process rates and magnitudes of change are biased by the temporal and spatial components of the measurements, which are functions of the perception of change manifest in research and monitoring designs. These conclusions may apply globally, because it is predicted that by the year 2000 over 60% of the world's rivers will be regulated (Gore and Petts 1989).

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REFERENCES CITED

Beus, S. S.; Avery, C. C.; and Cluer, B. L.; 1991*a*, Beach erosion studies under discrete controlled releases: Colorado River through Grand Canyon National Park: EOS (Trans. Am. Geophys. Union), v. 72, p. 223.

———; Biddle, J. W.; Iaquinto, P.; Lojko, F. B., and McAfee, B., 1982, Study of beach profiles as a measure of beach erosion on the Colorado River: Colorado River Investigations I, Northern Arizona University/Museum of Northern Arizona, p. 16–19.

———; Bogart, R.; Flick, L.; Brinkhuif, S.; Possen, B.; Ringhiser, S.; and Kuhl, M., 1988, Chapter IV—topographic changes on selected beaches in the Grand Canyon, 1986–1987: Colorado River Investigations VI, July–August 1987, Northern Arizona University/Museum of Northern Arizona, p. 16–41.

———; Burmaster, B.; Byars, B.; Dancis, D.; Hasenbuhler, P.; and Pauls, J., 1984*a*, Changes in beach profiles along the Colorado River in Grand Canyon 1974–1983: Colorado River Investigations II, July–August 1983, Northern Arizona University/Museum of Northern Arizona, p. 85–105.

———; Cardon, R.; Fulton, F.; Pastrick, A.; and Stock, M., 1987, Chapter II-beach profile data from July–August 1986 surveys in Grand Canyon: Colorado River Investigations, V, July–August 1987, Northern Arizona University/Museum of Northern Arizona, p. 3–33.

———; Carothers, S. W.; and Avery, C. C., 1985, Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon: Jour. Ariz.-Nev. Acad. Sci., v. 20, p. 111–120.

———; Coffin, J.; Doty, A.; Messina, P.; and Mail, D., 1986, Chapter II-changes in selected beach profiles along the Colorado River, Grand Canyon, 1984–1985: Colorado River Investigations II, July–August 1983, Northern Arizona University/Museum of Northern Arizona, p. 3–69.

———; Lojko, F.; Holmes, M. F.; Penner, D.; and Renken, S., 1984*b*, Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon: Colorado River Investigations II, July–August 1983, Northern Arizona University/Museum of Northern Arizona, p. 23–84.

———; Stevens, L. E.; and Lojko, F., 1989, Chapter II-topographic changes on selected beaches in the Grand Canyon, 1988–89: Colorado River Investigations VII, July–August 1989, Northern Arizona University/Museum of Northern Arizona, p. 35–61.

———; ———; and ———, 1991*b*, Chapter II-topographic changes on selected beaches in the Grand Canyon, 1989–1990: Colorado River Investigations VIII, July–August 1990, Northern Arizona University/Museum of Northern Arizona, p. 25–50.

Carpenter, M. C.; Carruth, R. L.; and Cluer, B. L., 1991, Beach erosion and deformation caused by outward flowing bank storage associated with fluctuating flows along the Colorado River in the Grand Canyon: EOS (Trans. Am. Geophys. Union), v. 72, p. 222.

Cluer, B. L., 1991, Catastrophic erosion events and rapid deposition of sandbars on the Colorado River, the Grand Canyon, Arizona: EOS (Trans. Am. Geophys. Union), v. 72, p. 223.

———; Carpenter, M. C.; Martin, L. J.; Wondzell, M. A.; Dexter, L. R.; and Manone, M. F., 1993, Rapid erosion and slow redeposition of sand bars along the regulated Colorado River in the Grand Canyon: EOS (Trans. Am. Geophys. Union), v. 74, p. 321.

Davis, W. M., 1895, Bearing of physiography on uniformitarianism: Geo. Soc. America Bull., v. 7, p. 8–11.

Gore, J. A., and Petts, G. E., 1989, Alternatives in Regulated River Management: CRC Press, 344 p.

Hirsch, R. V.; Walker, J. F.; Day, J. C.; and Kallio, R., 1990, The influence of man on hydrologic systems, *in* Wolman, M. G., and Riggs, H. C., eds., Surface Water Hydrology (The Geology of North America: Volume 0-1), Boulder, Geol. Soc. America, p. 329–359.

Howard, A. D., 1975, Establishment of benchmark study sites along the Colorado River in Grand Canyon National Park for monitoring of beach erosion caused by natural forces and human impact: University of Virginia Grand Canyon Study Tech. Rept. 1, 182 p.

———, and Dolan, R., 1976, Alterations of terrace deposits and beaches of the Colorado River in the Grand Canyon caused by Glen Canyon Dam and by camping activities during river float trips: summary, management implications, and recommendations for future research and monitoring: University of Virginia Grand Canyon Study Tech. Rept. 7 (Grand Canyon National Park Colorado River Research Series Contribution Number 36), 29 p.

———, and ———, 1981, Geomorphology of the Colorado River in the Grand Canyon: Jour. Geology, v. 89, p. 269–298.

Ingram, H.; Tarlock, A. D.; and Oggins, C. R., 1990, The law and politics of the operation of Glen Canyon Dam, *in* Proc. Nat. Research Council, Symposium (May 24–25, 1990, Santa Fe, New Mexico), Colorado River Ecology and Dam Management: Washington, DC, National Acad. Press, p. 10–27.

Kieffer, S. W., 1985, The 1983 hydraulic jump in Crystal Rapid: implications for river-running and geomorphic evolution in the Grand Canyon: Jour. Geology, v. 93, p. 385–406.

Leopold, L. B., 1969, The rapids and the pools-Grand Canyon: U.S. Geol. Survey Prof. Paper 669-D, 000 p.

Manone, M. F.; Cluer, B. L.; and Dexter, L. R., 1994, Monitoring Sand Bar Stability in Grand Canyon on a Daily Time-Scale: Am. Assoc. Geographers, Abs. (90th Ann. Meeting, San Francisco), p. 234.

Minckley, W. L., and Deacon, J. C., 1991, Battle against Extinction: Tucson, University of Arizona Press, 517 p.

National Research Council, 1987, River and Dam Management, A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies: Washington, DC, National Acad. Press, 152 p.

Pemberton, E. L., 1976, Channel changes in the Colorado River below Glen Canyon Dam, *in* Proc. Third Federal Inter-Agency Sedimentation Conf. (1976): Water Res. Coun. Sed. Comm., v. 5, p. 61–73.

Schmidt, J. C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona: Jour. Geology, v. 98, p. 709–724.

———, and Graf, J. B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geol. Survey Prof. Paper 1493, 74 p.

Stanford, J. A., and Ward, J. V., 1979, Stream regulation in North America, *in* Ward, J. V., and Stanford, J. A., eds., The Ecology of Regulated Streams: New York, Plenum Press, p. 215–216.

Turner, R. M., and Karpiscak, M. M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geol. Survey Prof. Paper 1132, 125 p.