Bridging the Gap to Long-Term Monitoring: Transitional Monitoring of Sand Bars along the Colorado River during Fiscal Year 1996

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INTRODUCTION

Sand-sized sediments are stored in sand bars along the banks of the Colorado River in Grand Canyon National Park. These bars are deposited in areas of reduced flow velocity , particularly in recirculation zones associated with channel constrictions (Schmidt and Graf, 1990). Sand bars are important resources in Grand Canyon, providing habitats for endangered and native fish species, surfaces for riparian vegetation establishment and areas for marsh and wetlands development, and recreational camp sites (Bureau of Reclamation, 1995a). The operation of Glen Canyon Dam (GCD) has altered the pattern of sand bar deposition and erosion and directly influences the stability of fluvial sediment deposits in Grand Canyon (Schmidt and Graf, 1990; Water Science Technology Board 1987; Beus et al. 1992; Kaplinski et al., 1995). Because sand bar stability underlies all aspects of ecosystem maintenance and development, sand bars are recognized by the National Park Service (NPS) as a primary natural and recreational resource in Grand Canyon National Park.

This report presents the results from survey studies designed to monitor the effects of the current dam operating strategy (interim flows) on Colorado River sand bars. These surveys allow us to test the hypothesis that interim flows have not changed the condition of the sediment resources in downstream reaches of Glen and Grand Canyons. The results from monitoring during fiscal year 1996 are compared to the results and analyses of previous monitoring conducted between 1991 and 1995 (Kaplinski et al., 1995; Hazel et al., 1996). In this report we also examine impacts from the relatively constant medium/high flows (18,000 to 20,000 ft^3/s) that occurred from 6/95 to 10/95. This sand bar study involves: 1) comparison of topographic and bathymetric surveys of bar and channel morphology at 32 sites located in each of the 11 geomorphic reaches of the Colorado River corridor, as defined by Schmidt and Graf (1990), 2) analyses of daily photographs at 30 of the 32 study sand bars for short-term bar failure frequency, 3) the collection of surveyed transects across important marsh areas for other related investigations (Kearsley and Ayers, 1995), and 4) producing GIS coverages of the topographic surveys for inclusion into the GCES/NPS GIS database.

For an "online" project overview and study site information, readers are referred to the NAU sandbar survey World Wide Web (WWW) homepage located at URL: ***http://vishnu.glg.nau.edu/gces/index.html.***

Objectives

To determine the effects of interim flows on the sediment resources within Grand Canyon National Park, the following objectives were established:

Objective 1: The topography and bathymetric surfaces of 32 Colorado River sand bars were monitored using standard ground survey techniques and methodologies developed during GCES Phase II (Figure 1; Table 1; Beus et al., 1992).

Objective 2: The results from the above objective were used to compare topographic change between previously reported survey data (Beus et al., 1992; Kaplinski et al., 1995; Hazel, et al., 1996) and assess whether sand bar deposits have been affected by flows from Glen Canyon Dam (GCD), tributary influences, local surface runoff, and vegetation growth.

Objective 3: Continue to monitor short-term bar failure frequency using daily photogarphy and identify the timing of erosional/depositional events to supplement interpretation of sand bar survey results (Table 2).

Objective 4: Continue the marsh transect surveying utilized by the Vegetation Monitoring Project (Stevens and Ayers, 1993; Kearsley and Ayers, 1996) to determine the relationship between sand bar geomorphology and spatial scale of marsh development.

Objective 5: For data management and archival purposes, we will include our data in the GCES/NPS GIS database at the NAU Department of Geology (Kaplinski et al., 1994) and assist in the process of integrating related studies into the existing centralized database at the GCES office in Flagstaff, Arizona.

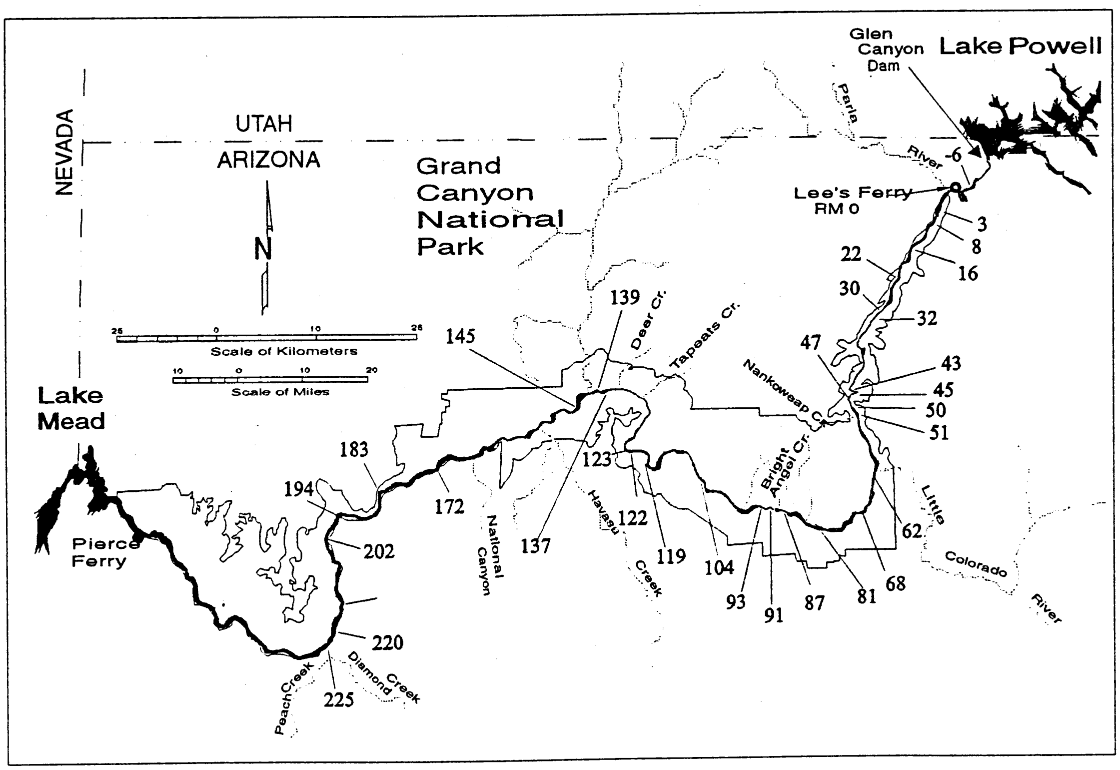

Figure 1. Location map showing study site locations.

Table 1. Sand Bar Survey Sites

Site Ref.#	River Mile (RM)*	River Side	Site #	Site Name	Deposit Type	Reach/ Relative Width
-6**	-6.5	Right	2	Hidden Sloughs	R	0W
3	2.6	Left	3	Cathedral Wash	R	1W
8	7.9	Left	4	Lower Jackass	S	1W
16	16.4	Left	5	Hot Na Na S		2N
22	21.8	Right	6		R	2N
30	30	Right	7	Fence Fault	R	3N
31**	31.6	Right	8	South Canyon	S	3N
43	43.1	Left	10	Anasazi Bridge	R/UP	4W
45	44.6	Left	11	Eminence Break	S	4W
47	47.1	Right	12	Lower Saddle	R	4W
50	50	Right	13	Dino	R/S	4W
51	51.2	Left	14		R	4W
62	62.4	Right	34	Crash Canyon	R	5W
68	68.2	Right	15	Upper Tanner	R/UP	5W
81	81.1	Left	16	Grapevine	R/S	6N
87	87.5	Left	17	Cremation	R/UP	6N
91	91.1	Right	18	Upper Trinity	S	6N
93	93.3	Left	19	Upper Granite	R/UP	6N
104	103.9	Right	20		R/UP	6N
119	119.1	Right	21		R	7N
122	122.2	Right	22		R	7N
123	122.7	Left	23	Upper Forster	R/UP	7N
137	136.7	Left	24	Middle Ponchos	R	8N
139	139	Right	25	Upper Fishtail	R/UP	8N
145	145	Left	26	Above Olo	R	9N
172	172.2	Left	27		R	10W
183	182.8	Right	28		R	10W
194	194.1	Left	29		R	10W
202	202	Right	30		S	10W
213	212.9	Left	31	Pumpkin Spring	R/UP	10W
220	219.9	Right	32	Middle Gorilla	R/UP	11N
225	225.3	Right	33		R	11N

*** Distance downstream from Lees Ferry in Stevens (1983) river miles (RM). Deposit type from Schmidt and Graf (1990): R- reattachment deposit, S - separation deposit, UP - upper pool deposit. Reaches (0-11) and channel width (W-wide, N-narrow) from Schmidt and Graf (1990).**

**** Sites not used for daily photographic monitoring.**

Previous Work

Historical and concurrent studies of sand bar dynamics, morphology, and sedimentology that pertain to this study can be separated into research conducted prior to initiation of the Bureau of Reclamation's Glen Canyon Environmental Studies (GCES) program in 1982 (National Resource Council, 1987); publications from GCES Phase I and II investigations, the latter of which was intended to be used for the GCD-EIS (Bureau of Reclamation, 1995a); and ongoing monitoring during the Interim Flow period.

Adverse downstream impacts from GCD were first recognized by Dolan et al. (1974) and early work that first quantified dam induced changes on sand deposits was based on analysis of aerial and ground photography since 1965 (Laursen and Silverston, 1976; Turner and Karpiscak, 1980) and topographic profile surveys of about 20 sand bars since 1973 (Howard, 1975; Howard and Dolan, 1981; Beus et al., 1985). These studies documented slight to insignificant instability and erosion of sand bars under the post-dam fluctuating flow regimes, with bar building and rapid erosion observed during the high flows of 1983-1986. Erosional patterns were described as being obscured by variability in reach characteristics, local channel geometry, poorly developed stage/discharge relationships, unknown antecedent conditions, and survey accuracy.

Public concern over dam operations culminated with the proposal by the Bureau of Reclamation in the early 1980's to revise and possibly increase the peaking power generation at GCD. This led the Department of the Interior, under pressure from the concerns of the public and other government agencies, to direct the Bureau of Reclamation to initiate the GCES Phase I program, the results of which are included in the GCES Final Report (U.S. Department of Interior, 1988) which was subsequently reviewed by the Water Science and Technology Board (1987). Several studies that were part of the Phase I program were the first to carefully describe the general hydraulic and sedimentologic characteristics of recirculation zones and associated bars. Schmidt and Graf (1990) developed a classification and description of alluvial sand deposits in Grand Canyon, a reach-length classification of the river corridor, and documented the history of bar aggradation and degradation at several study sites. Schmidt (1990) described the general association of sand bars with recirculating flow. Bar sedimentology and morphology were examined by Rubin et al. (1990). These studies greatly increased our understanding of the effects of fluctuating flows on sand bar stability.

Increased public environmental concern initiated another phase of multidisciplinary research (GCES Phase II) in 1990 (Water Science and Technology Board, 1991) to provide information for the GCD-EIS. As part of this research, the Bureau of Reclamation conducted a series of discrete research flows from June 1990 through July 1991 to determine the impacts of specific flow regimes on sand bar stability (Beus and Avery, 1992). The test flows lasted a minimum of 11 days and included a variety of both steady and fluctuating releases. Fluctuating releases were either uniform (same daily pattern) or varied in response to changes in electrical load (normal releases). Each flow was preceded by 3 days of 142 m^3/s (5,000 ft^3/s). Important studies contained within Beus and Avery (1992) and other investigations conducted as part of the GCES Phase II program that are relevant to this report include bank stability changes related to groundwater fluctuations (Carpenter et al., 1991; Budhu, 1992; Werrel et al., 1993), the importance of surface-gravity waves on sand bar stability (Bauer and Schmidt, 1993), modeling of recirculating flow (Nelson, 1991). daily photography detailing short-term topographic changes (Cluer, 1992; Dexter et al., 1994), repeated surveying of topographic changes (Beus et al., 1992), and analysis of long-term trends in sediment storage (Clark et al., 1991; Schmidt, 1992; Webb et al., 1991).

The results from the GCES Phase II research flows, and the absence of a Record of Decision for the GCD-EIS, led the Bureau of Reclamation to examine the effectiveness of the Interim Operating Criteria. Monitoring studies related to this investigation during the Interim Flow period are repeated inventories of campsite size (Kearsley et al., 1994; Kearsley, 1995), sedimentologic investigations (Rubin et al., 1994), the importance of seepage erosion (Budhu and Gobin, 1994), daily eddy dynamics (Dexter et al., 1994), semi-annual assesment of sand bar volume/area change (Kaplinski et al., 1995), and long-term history of sediment storage change (Schmidt, 1994; 1995).

Important conclusions from the sand bar monitoring projects of Beus and Avery (1992), Dexter et al. (1994), and Kaplinski et al. (1995) include: 1) sand bar topography is affected by discharge, local geomorphology, sediment supply, and antecedent condition; 2) major periods of erosion follow periods of aggradation suggesting that antecedent conditions influence subsequent changes in bar topography; 3) Interim Flows have significantly eroded sand bars; 4) deposition is occurring below the maximum Interim Flow stage elevation, while erosion is dominating at, and above Interim Flow stage elevations; 5) occasional flood flows near, or in excess of GCD power-plant capacity, are necessary to redistribute sediment from river-storage to bar elevations not reached by Interim Flows and to maintain sand bar volume; 6) semi-annual sand bar surveys can detect system-wide changes in sediment storage; and 7) erosional events continue at similar frequencies and magnitudes during Interim Flows.

Modern Alluvial Deposits of the Colorado River

The characteristic channel unit of bedrock canyon rivers with abundant debris fans has been termed the fan-eddy complex (Schmidt and Rubin, 1995). This is a geomorphic assemblage of river constricting debris fan, backwater (pool) above the debris fan constriction, associated eddies with debris fans, and downstream gravel bars. At nearly all tributary junctions, debris fans locally constrict the main river channel (Figure 2; Howard and Dolan, 1981; Schmidt and Graf, 1990). In the channel expansion above and below the narrowed channel, a recirculation zone (eddy) forms where flow separates from and then reattaches to the bank (Schmidt, 1990). In reaches dominated by debris fans, as much as 75% of the sand-sized sediment load of the Colorado River is deposited within these debris fan-eddy complexes (Schmidt and Rubin, 1995). Water velocities within eddies are much lower than velocities in the main channel and therefore are sites of potential sand deposition by a variety of bar forms (Schmidt et al., 1993). Deposition is typically localized near the separation point, reattachment point, and eddy center (Schmidt, 1990).

Schmidt and Graf (1990) described and categorized several different types of alluvial sand deposits in Grand Canyon. These are:

Reattachment deposits form near the reattachment point of large primary eddies (Rubin et al., 1990). These bars are typically deposited along the downstream regions of the eddy by sediment swept across the eddy toward the shore, perpendicular to the main river current. This type of bar is characterized by a broad platform that extends upstream into the eddy. Return current channels form along the shoreward side of the reattachment bar platform where the eddy current is redirected along the shoreline. When a recirculation zone is present in the pool above the constriction an *upper pool deposit* is deposited that is similar to reattachment bar morphology or exists as a linear deposit along and parallel to the shoreline.

Separation deposits typically form immediately downstream of the debris fan constriction. They commonly mantle the downstream portion of the debris fan and are deposited in secondary eddies upstream of the larger primary eddy associated with the debris fan. This type of bar is typically steeper and of higher elevation than reattachment bars.

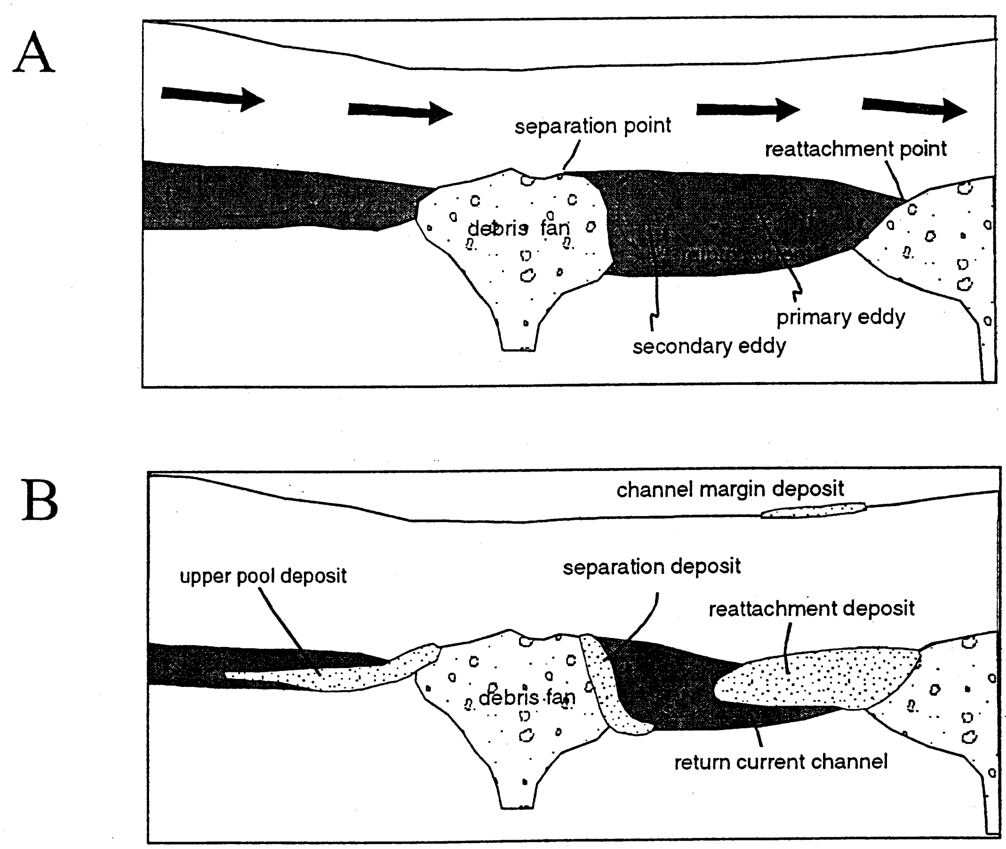

Figure 2. Schematic diagram showing flow patterns and configuration of bed deposits in a typical recirculation zone. A) flow patterns during higher volume flows. B) configuration of bed deposits during lower volume flows. Modified from Schmidt and Graf (1990).

Channel margin deposits are those that parallel the shoreline in areas not specifically related to recirculation zones or separation points. This type of deposit was not examined in this study.

In addition to the above, *main-channel sediments* are transported and locally deposited along the channel bottom and in pools above constrictions.

The morphology and sedimentology of sand bars in recirculation zones is closely associated with changing flow patterns in the recirculating eddy (Rubin et al., 1990; Schmidt, 1990). During increasing discharge, recirculation zones expand as more bar area is inundated, and secondary eddies or low velocity zones develop upstream of the return current channel. This results in downstream migration of the reattachment point and upstream migration of the separation point onto the debris fan (Schmidt, 1990). Deposition rates also increase (Andrews, 1991). The reattachment deposit may fill much of the recirculation zone beneath the primary eddy. During periods of low discharge recirculation zones generally consist of a smaller, primary eddy and large areas where both the reattachment and separation bars are exposed (Schmidt and Graf, 1990).

Flow Regimes During Study

The discharge of the Colorado River in Grand Canyon has been regulated by GCD since its completion in 1963. GCD has substantially reduced the sediment load, sediment concentration, duration of high flows, and peak-flow rates compared to the unregulated streamflow of the pre-dam era. The annual flood from spring runoff is contained by Lake Powell. Only under extreme circumstances such as the extended periods during 1983-86 when spillway releases were necessary, has discharge exceeded maximum powerplant capacity of 940 m^3/s (33,200 ft^3/s). The other important flow exception during the post-dam era occurred in 1965 and 1980 for reservoir balancing and spillway tests, respectively, and when discrete research flows were conducted from June 1990 through July 1991 to provide data for the GCD-EIS. Prior to these test flows and until Interim flows were implemented, the previous range of discharge fluctuation was 85 m^3/s (3,000 ft^3/s) to 892 m^3/s (31,500 ft^3/s), with no limitations on maximum daily change and the rate of change in powerplant output discharge (ramp rate).

When interim flows began at the conclusion of the 1990-1991 test flow period the maximum discharge was limited to 566 m^3/s (20,000 ft^3/s), the minimum discharge to 142 m^3/s (5,000 ft^3/s), with up- and down-ramp rates of 57 $m^3/s/hr$ (2,000 $ft^3/s/hr$) and 42.5 $m^3/s/hr$ (1,500 $ft^3/s/hr$), respectively (Figure 3). In addition, normal dam operations that have continued during interim flows are low-, medium-, and high-volume months, with low flows during the late spring and late fall, moderate flows in May and September, and high flows during mid-summer and mid-winter (Figure 3). Interim flow criteria specify that daily change cannot exceed 142 m^3/s (5,000 ft^3/s) during low volume months, 170 m^3/s (6,000 ft^3/s) during medium volume months, and 227 m^3/s (8,000 ft^3/s) during high volume months. Flows are reduced on weekends as the demand for electricity decreases.

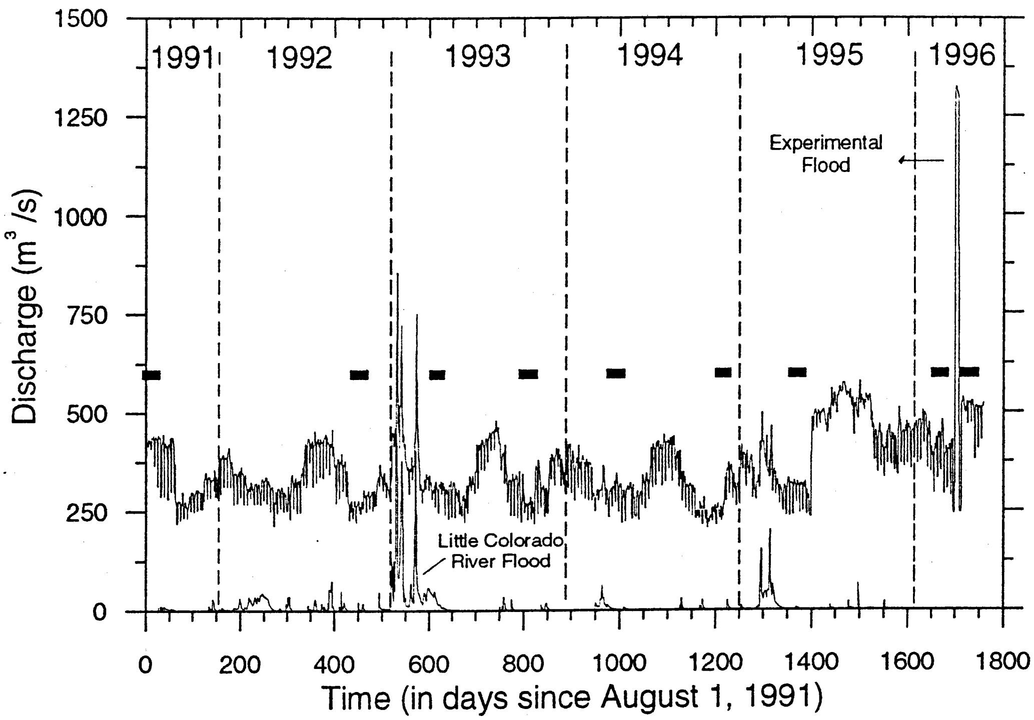

Figure 3. Interim Flow discharge hydrograph from U.S. Geological Survey streamflow gages 09402500 *Colorado River near Grand Canyon* and 09401200 *Little Colorado River at Cameron*. Survey trip dates are highlighted by short horizontal bars.

Tributary flooding from the Little Colorado River (LCR) caused significant deviations from regulated flows during the winter of 1993 (Figure 3). Three separate floods, January 12-16, January 19-23, and February, 23-26, 1993, raised flows that peaked at Phantom Ranch (RM88) to approximately 966 m^3/s (34,120 ft^3/s), 793 m^3/s (28,016 ft^3/s), and 824 m^3/s (29,100 ft^3/s), respectively. By raising mainstem flows to slightly above powerplant capacity and delivering a significant amount of sediment, the 1993 winter floods provided an unexpected test-case of a bar-building flow event (Hazel et al., 1993).

Unusually high surface runoff throughout the upper Colorado River basin caused abnormally high flow releases beginning in June (Figure 3). Flows from GCD between June and October, 1995 have averaged 523 m^3/s (18,520 ft^3/s), compared with averages of 350 m^3/s (12,390ft^3/s), 363 m^3/s (12,882ft^3/s), 375 m^3/s (13,286ft^3/s), and 412 m^3/s (14,599 ft^3/s) for the same period of time during 1991, 1992, 1993 and 1994, respectively. This report addresses the effects of this change in flow regime on the sediment resources of the river corridor.

METHODS

Sand Bar Monitoring

Study Site Selection

Thirty-two eddy sand bars, approximately 15% of all large sand deposits between GCD and Diamond Creek, were selected for repeated surveys of bar topography during the GCES Phase II test flow series. These bars were selected by Beus et al. (1992) on the basis of: 1) distribution throughout the geomorphic reaches identified by Schmidt and Graf (1990); 2) sufficient size to guarantee persistence through the period of study; 3) geomorphic diversity within and between sites; 4) availability of historical topographic data; 5) variation in recreation use intensity and vegetation cover; and 6) access limitations downstream of Diamond Creek. Site selection, baseline surveys, and protocol development were accomplished during June and August, 1990. The Interim Flow Sand Bar Monitoring Project (Kaplinski et al., 1995; Hazel et al., 1996) utilized these same sites and added one, RM62. The number and distribution of these sites provide adequate spatial coverage of the entire river corridor and proportionate numbers of each geomorphic sand bar type are sampled.

Topographic Surveys

Survey trips consisted of two ground-based survey teams, a bathymetry team, and a sedimentology/stratigraphy team. Each ground-based team completed one survey per day using Leitz Set4c and Set3c total stations equipped with digital data collectors. Site size and topographic complexity determined the point density needed to form proper topographic models. Smaller sites (~2000 m^2) typically require 200-400 points and larger sites (~10,000 m^2) require 750-1000 points. Points are also collected offshore to depths of approximately 1 m to provide overlapping coverage with the bathymetry survey. Survey protocol was developed during the GCES Phase II test flows (Beus et al., 1992) and documented according to standard survey practices for ground surveying. Benchmark and backsight relationships were verified at all sites during March, 1991. Priority was placed on completing surveys within the zone of dam fluctuation, then expanding coverage to the higher elevations. Terrestrial survey coverage has typically extended from the 142 m^3/s (5,000 ft^3/s) stage elevation to slightly above the 850 m^3/s (30,000 ft^3/s) stage elevation contour, and in preparation for the 1996 experimental flood was extended to the 1742 m^3/s (45,000 ft^3/s) stage elevation. Bathymetric data collection expanded ground-based coverage to include the entire river channel and recirculation zone surrounding the sand bar. Upon completion of each survey, field data was transferred to micro-computers and edited.

The bathymetric survey technique used during the course of this study was the GCES "Hydrographics Survey Package" (HSP) that consists of a shore-based total station, a boat-mounted transducer, a digital/analog receiving unit, and a computer that controls the digital data collection process. The shore station data is radio-telemetered to the boat computer where depth-position data is calculated and automatically stored. Since April, 1993 the HSP has been used by bathymetry crews to survey two sites per day. Point density needed to form proper topographic models of the entire recirculation zone and surrounding river channel typically requires 1000-3000 points.

Topographic Model Formation

The ground-based and bathymetric survey points are combined and used to form a Triangulated Irregular Network (TIN) model of the sand bar surface using Sokkia Mapping Software (Datacom Software Research Limited, 1992). Breaklines are coded during ground-based data collection along lines known to have a constant grade, such as cutbanks, water surface lines, slope breaks, etc. Breaklines are used in TIN model formation to force individual prism sides along the proper grade breaks and stop the program from making incorrect interpolations across the surface (Datacom Software Research Limited, 1992). Topographic maps of the sites were prepared with a 0.2 m contour interval to insure proper model formation. The surface model, not the topographic map, is used to generate profiles at predetermined locations, and determine volumes and areas within a boundary we term the "hydrologically active zone" (HAZ).

The HAZ boundary formed around a subset of the survey area that encompasses the elevation range of dam operations (142-850 m^3/s). The HAZ boundary provides a consistent, repeatable region, within which to quantify changes in sand bar volume and area due to dam operations (Beus et al., 1992, Kaplinski et al., 1995; Hazel, et al., 1996). We determined the total volume and area within the HAZ zone above the 142 m^3/s elevation contour, and partitioned volumes from a lower HAZ section (between the 142 m^3/s and the 410 m^3/s elevation contour), and an upper section (above the 410 m^3/s elevation contour).

Short-Term Bar Failure Frequency Monitoring

Study Sites

Fourteen daily monitoring cameras were installed at existing sand bar topographic survey sites in addition to cameras already in-place to provide nearly 100% overlap with the topographic study sites at 30 of the 32 monitoring sites. Cameras were not installed at the -6R and 31R study sites due to logistical constraints (Table 1).

Field Procedures

The land-based time-lapse camera system was built from relatively inexpensive off-the-shelf products. The core of the system is the Pentax IQZ 105 programmable camera. The microprocessor controlled camera allows the intervolometer to be set for repeat exposures once every 24 h at a pre-set time of day. Each camera was secured to an alignment base which was then fastened snugly inside a surplus military ammunition can. A large, round hole was cut into the side of the box congruent with the position of the camera lens and fitted with acrylic windows. A small metal gable was fashioned to protect the camera/window from dust, dirt and insolation and locks have been added for protection. The camera housings were attached to rocks or outcrops opposite subject deposits, providing a fixed point for repeatable oblique photography. The intervolometers are programmed to acquire one photograph each day during or approximately during the daily low water level. The film was changed during cooperating research raft trips approximately every 30-35 days and was immediately processed and scanned onto Photo CD.

Image Processing and Analysis

Because the cameras are rigidly anchored and the image geometry is precisely repeatable, any differences between successive photographs can potentially be quantified. Upon installation of remote camera stations aerial photography control panels were temporarily fixed at points around the field of view. A surveying crew then located the position coordinates of the panels and the camera lens/film plane using total station plane surveying techniques. Once the camera had photographed the area with the control panels in place, the panels were removed. Hard points such as rock features were also used to strengthen control. A technique has been developed using ERDAS image processing software (ERDAS Inc., 1992), to rectify these oblique images to vertical perspectives so that true scale area measurements may be made (Manone et al., 1994). Digital images are then imported into ERDAS v.7.5 software and rectified from an oblique view to a planimetric model. The resulting planimetric models are screen digitized to determine area change at each site.

Short-term sandbar erosion, or bar failure, was recognized as an important aspect of sand bar dynamics by Cluer (1992). We documented the frequency of these bar failure events at fifteen study sites where sufficient coverage existed. Due to logistical constraints beyond our control, a three month gap exists in the coverage, from October through December 1995. Failure events may have occurred during this time interval that could have influenced the results of our observations. In addition, cameras were not completely installed at all sand bar monitoring sites until January, 1996. Images from these sites were examined for substantial decreases in sand bar area. Images in which an event was observed to have occurred were rectified photogrammetrically and considered "bar failures" if the planimetric area decrease was greater than 5% of the exposed sand bar. Bar failure frequency was then compared to the frequency of events documented by Dexter et al. (1994) from 1992 through 1995.

Marsh Topographic Surveys

The areas on sand bars that are favorable to marsh development have historically been a component of typical survey coverage for the NAU Sand bar Monitoring Project. We used the aforementioned surveying techniques and obtained precise marsh transect locations from the Vegetation Monitoring Project prior to the FY 96 river trip so that coverages were precisely duplicated.

GCES/NPS GIS Database

Survey and photographic data will be converted to ARC/INFO format and incorporated into NAU Geology sand bar survey database, a subset of the overall GCES/NPS GIS database. Methodologies for this aspect of the study, including data conversion and analysis AML's, have been developed by Kaplinski et al. (1995).

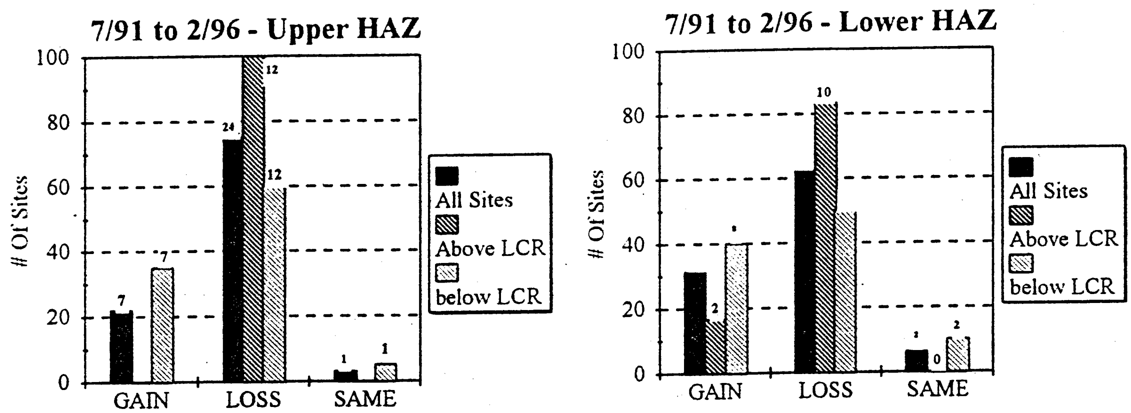

Figure 5. Histograms of site response to interim flow period for both the upper and lower HAZ sections.

The trend of decreasing sand bar size and volume, as reported by Kaplinski et al. (1995) and Hazel et al. (1996), continued during this monitoring period (Figure 6). When compared to all survey runs conducted during interim flow monitoring (n=7), volumes in the upper HAZ section show a steady rate of decline, while the those in the lower HAZ fluctuate. We performed linear regressions of the upper HAZ volume curves that yield erosion rates of -6.8% (Y = -0.0187153 * X + 7.29368, R^2 = 0.94) for sites above, and -4.5% (Y = -0.0123828 * X + 21.324, R^2 = 0.83) for sites below the LCR confluence over the five years of monitoring (Figure 6a). Volume changes within the lower HAZ fluctuated over this same time interval and did not yield significant correlations (Figure 6b). This suggests that the area of sand bars subject to daily or monthly inundation by the river is being reworked and sediment is transported into and out of the lower HAZ section. Daily photographs of these and other study sites in Grand Canyon show that the portion of the eddy sand bar that is daily inundated is inherently unstable because erosion and deposition occur in cycles that continuously adjust bar size and morphology (Dexter et al., 1994; Cluer, 1995). However, these are relatively small-scale changes when compared to the magnitude of erosion that has occurred in the subaerially exposed portions of sand bars during interim flows (Figure 6a). This large-scale geomorphic response to change in release pattern is not due to the variability in response of different sites. Although none of the study sand bars have been completely eroded, the rate of erosion has not declined during interim flow monitoring.

RESULTS

Topographic, bathymetric, and marsh transect surveys were collected at each study site on a research river trip conducted from February 13 to March 3, 1996. Film from the cameras at each site was changed and images processed to encompass the fiscal year 1996 monitoring period.

To examine the status of sand bar size and morphology in 1996 we compared volumes measured from within the HAZ boundary (see methods for explanation of HAZ boundary and volume calculations) prior to the implementation of interim flow criteria (7/91) to this latest survey (2/96). Figure 4 shows that interim flows have greatly decreased the volume of bar stored sand at 26 of the 32 study sand bars during this 55 month period (Figure 4). A volume loss is considered significant if it is greater than 3% (Beus et al., 1992). The upper elevations of sand bars, those areas above the maximum stage levels of interim flows, show the most significant losses. For example, within the upper section of the HAZ boundary, 100% of the sites above the LCR confluence and 60% of all study sand bars have decreased in sand volume (Figure 5). The lower HAZ section, areas of the sand bar subjected to daily inundation by interim flows, also showed a similar pattern of sand volume decrease as 83% of the study sites above and 50% below the LCR confluence lost volume, respectively (Figure 5a).

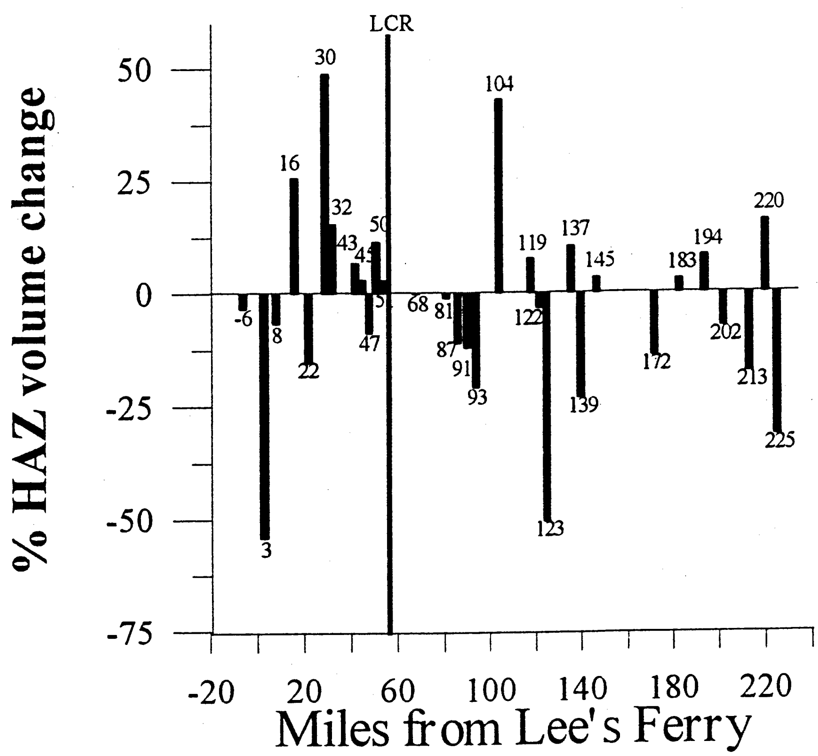

Figure 4. Percent volume change for each study site versus distance downstream of Lee's Ferry, AZ. Comparison is between volumes measured in July 1991 to February/March 1996.

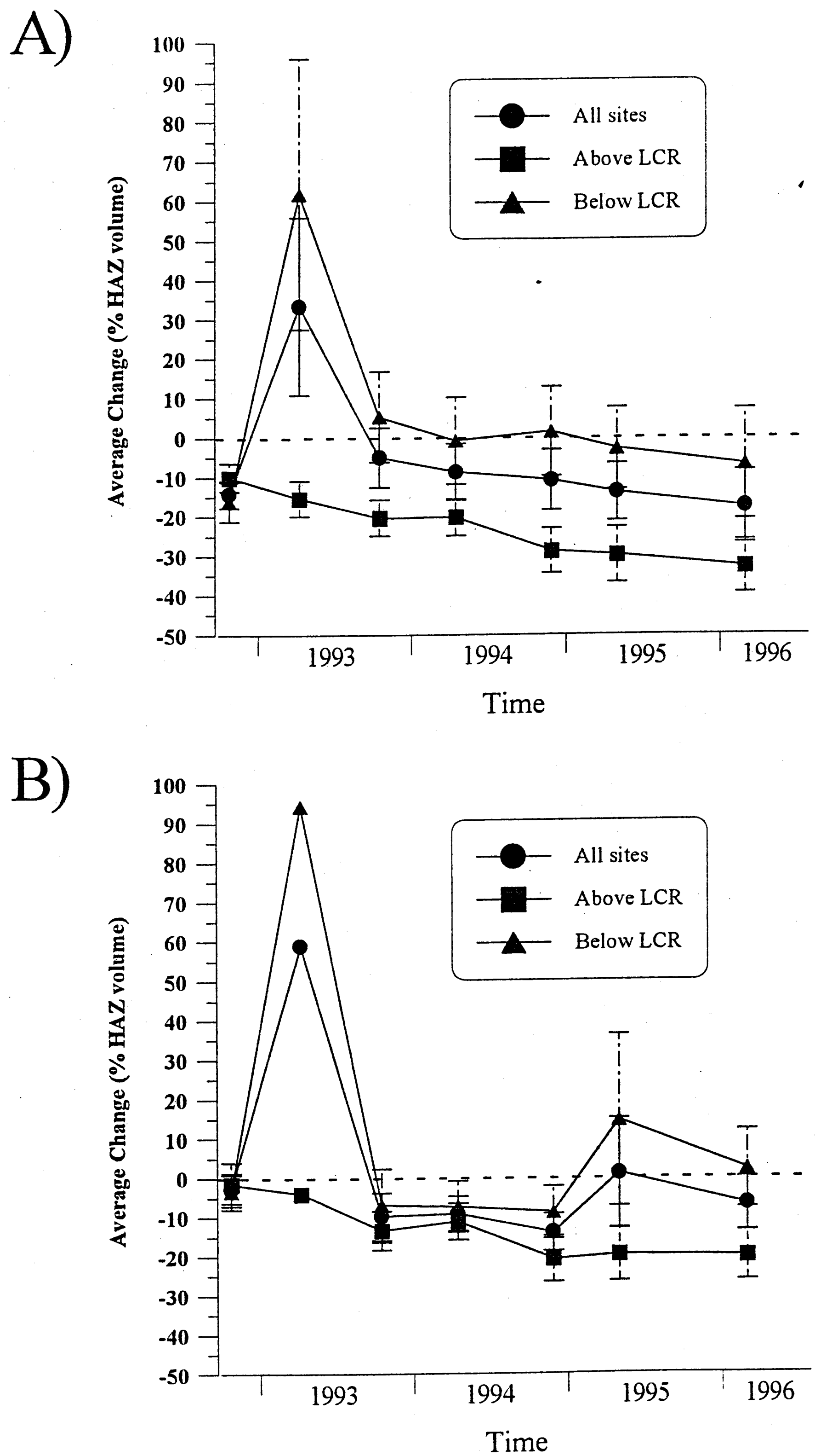

Figure 6. Averaged percent change for each survey run (standard error about the mean error bars) vs. time for A) upper HAZ section, and B) lower HAZ section.

The 1993 winter floods from the LCR remain the most significant event during the 5 years of interim flow monitoring (Figure 6). These floods resulted in deposition of high elevation sand in nearly all eddies downstream of the LCR confluence (Hazel et al., 1993; Kaplinski et al., 1995). Erosion rates of bars downstream from the confluence were initially high but declined with time. However, sediment remained available for erosion in the next 3 years of interim flow monitoring as evidenced by the average percent change for subsequent surveys (Figure 6a). Thus, the 1993 LCR floods caused only temporary storage of sand-sized sediment at high elevations. These results demonstrate that high flow events, in excess of the maximum interim flow levels, are necessary to maintain sediment volume in the upper areas of sand bars. High flows, whether natural or controlled dam releases, are the only mechanism that we have observed that will increase the amount of sediment at the higher elevations of sand bars.

Short-term Bar Failure Frequency

Short-term bar failure frequency at fifteen study sites appears to have decreased during the interim flow period (Figure 7). "Bar failures", or short-term degradational events greater than 5%, were only observed at two of the sites. Short-term degradational events of 2-5% were observed at eleven of the sites.

These results contrast with the frequency of bar failure events observed during the 1990-1991 test flows (Cluer, 1992) and the beginning of interim flows (Dexter et al., 1994) where larger magnitude (20-50%) "bar failures" had higher rates of occurrence. Interim flows appear to have decreased both the magnitude and frequency of short-term bar failure events.

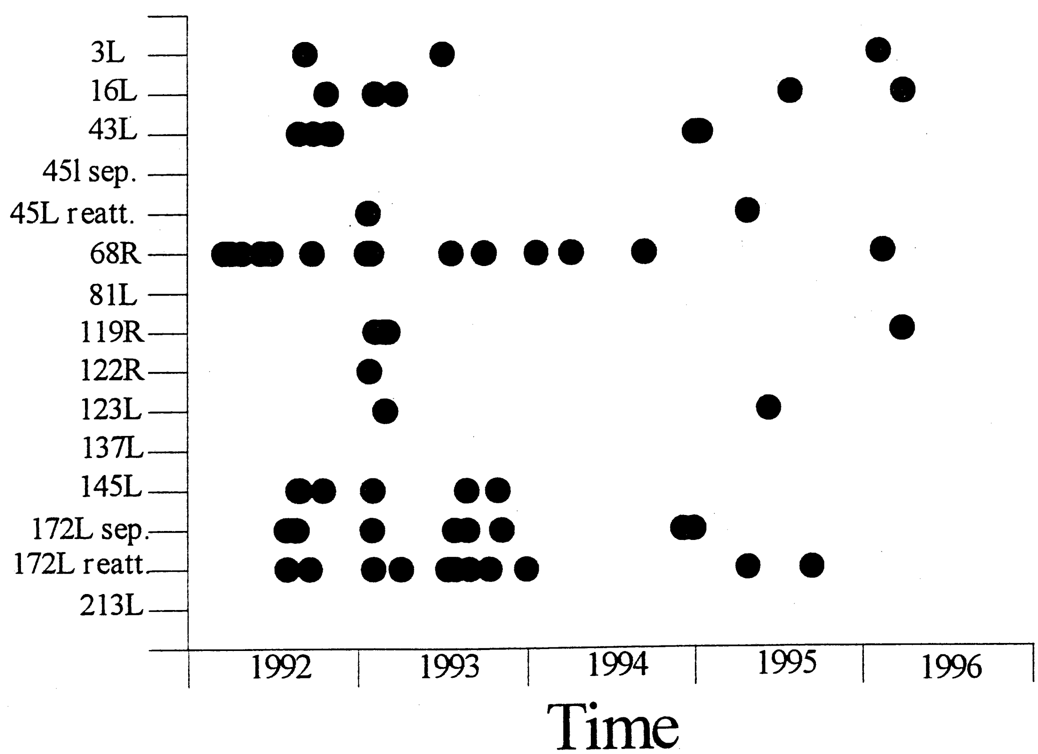

Figure 7. Occurrences of short-term "bar failure" throughout the interim flow period.

SUMMARY

The following patterns of erosion and deposition of sand bars along the Colorado River have been observed during the 5 years that interim flow criteria has existed. The beginning of interim flows was characterized by system-wide erosion of both the upper and lower HAZ sections as the sand bars, following a year of test flows (see Beus and Avery, 1992), adjusted to the new, lower volume flow regime. Surveys conducted in April 1993 indicated that winter floods from the LCR tributary a significant amount of sediment at topographic levels not reached by interim flows. Sand bars above the LCR confluence were not affected by the high flow events and continued to erode. Following the 1993 LCR high flow events, erosion rates increased significantly at bars affected by the flood, then decreased to "normal" rates within approximately nine months. After the LCR events, a consistent, system-wide pattern of erosion developed. The upper elevations of the study bars lost HAZ volume as sediment was distributed within and out of the lower HAZ zone. The sand storage capacity of eddys was lessened by interim flows because recirculation zones are smaller during low flows. Without restoration of sediment to the upper elevations of sand bars, the pattern of interim flow erosion will continue to adversely sediment resources criticial to the riverine ecosystem and area available for recreational camp sites.

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