THE EFFECTS OF THE 1996 GLEN CANYON DAM BEACH/HABITAT-BUILDING TEST FLOW ON COLORADO RIVER SAND BARS IN GRAND CANYON

FINAL REPORT

By
Joseph E. Hazel, Jr., Matt Kaplinski, Mark F. Manone, Roderic A. Parnell, Alan R. Dale, James Ellsworth, Leland Dexter

Department of Geology
Northern Arizona University
Box 4099
Flagstaff, AZ 86011

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ABSTRACT

In Spring 1996 the U.S. Bureau of Reclamation released an experimental beach/habitat-building flow from Glen Canyon Dam into Grand Canyon. A major objective of the test flow was to rebuild eroded Colorado River sand bars by transfer of sediment accumulated in eddy and mainstem locations to the channel margin. We surveyed bar and channel topography at 34 fan-eddy complexes before, after, and six months following the test flow to measure the amount and style of deposition and erosion, and to assess the longevity of rebuilt deposits.

Analyses of topographic survey data, daily photographs, and bar sedimentology show that the 7 day steady release of 1,274 m^3/s significantly increased the volume of sand stored in recirculation zones by redistributing stored sediment from the river bed to eddy sand bars. Areas of deposition typically exceeded 1 m in thickness. Sand bar volumes increased by an average of 49%, while area change increased only 7%. The higher elevations of sand bars, where the greatest amount of erosion had occurred during Interim Operating Criteria, gained an average of 176%. A Friedman Test of sand bar volume and area shows that the change in volume was significant, while the change in area was not. In general, the test flow resulted in sand bars that were higher, not wider.

Sediment was mobilized from the main channel as well as from the upstream areas of larger recirculation zones at each fan-eddy complex. The volume of stored sand from the channel bed decreased by 16% as an estimated 222,100 m^3 of sediment was scoured from the bed. The volume of stored sand in recirculation zones, particularly eddies >5,000 m^2 in plan area, decreased by 7%, as an estimated 82,700 m^3 sediment was scoured from the upstream, low elevation areas of large reattachment bars.

A normalized index of the volume change within the recirculation zone (eddy + bar volume) was determined to examine the role of eddy systems in trapping and storing sediment during the test flow. The NVC indices from the pre- to post-test flow comparison are normally distributed around a positive system-wide mean. The NVC distribution shows that, while some eddy systems lost sediment, the average response of eddy systems was to gain sediment during the test flow.

Six months after the test flow, sandbars still retained approximately half of the sediment deposited during the test flow. Sand bar volumes decreased from 47% to 23% larger than the pre-test flow condition. Upper sand bar volumes decreased from 176% to 97%. Erosion rates of the upper bar zone averaged 13% during the first six months following the test flow. Eddy systems rapidly filled with sediment that was eroding from sand bars and channel margin deposits. The main channel remained relatively scoured. Until tributary sediment delivery, eddies and sand bars are the primary storage location of sediment within the system.

The success of the 1996 test flow was largely dependent on the antecedent conditions of sediment storage in the system. If the supply of sediment in Grand Canyon is depleted, then bar-building flows have the potential to be net erosive. However, beach/habitat-building flows are needed to remove sediment from mainstem transport, to maximize the residence time of sediment at a particular site, and to minimize the eventual transport of sediment out of the system.

Acknowledgements

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INTRODUCTION

Problem Statement

Scientific research conducted during the U.S. Bureau of Reclamation's Glen Canyon Environmental Studies (GCES) program has led to a consensus that floods are necessary to maintain the Colorado River's geomorphic structure and related ecosystems downstream from Glen Canyon Dam (Bureau of Reclamation, 1996). Ecosytem diverisity is intimately related to the natural disturbance of flooding and a beach/habitat-building flow was included in the Preferred Alternative recommended in the Glen Canyon Dam Environmental Impact Statement (GCD-EIS) (Bureau of Reclamation, 1995a). An experimental controlled flow release with a high steady discharge of 1,274 m^3/s, hereafter referred to in this report as the "test flow", was released from GCD for seven days between March 26 and April 3, 1996 (Fig. 1). The test flow was conducted to provide resource managers with detailed information so that ecosystem benefits of future intentional and unplanned releases greater than GCD powerplant capacity will be maximized.

The test flow was designed to test the predictions stated in the GCD-EIS and verify certain hypotheses concerning the role of controlled flooding as a vital part of resource management (Patten et al., written communication, 1994). Several management

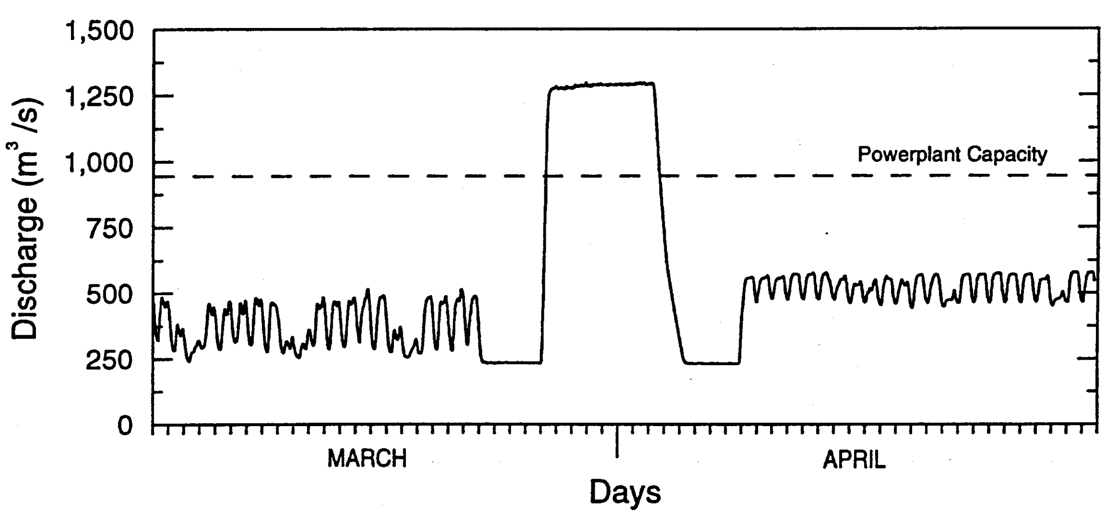
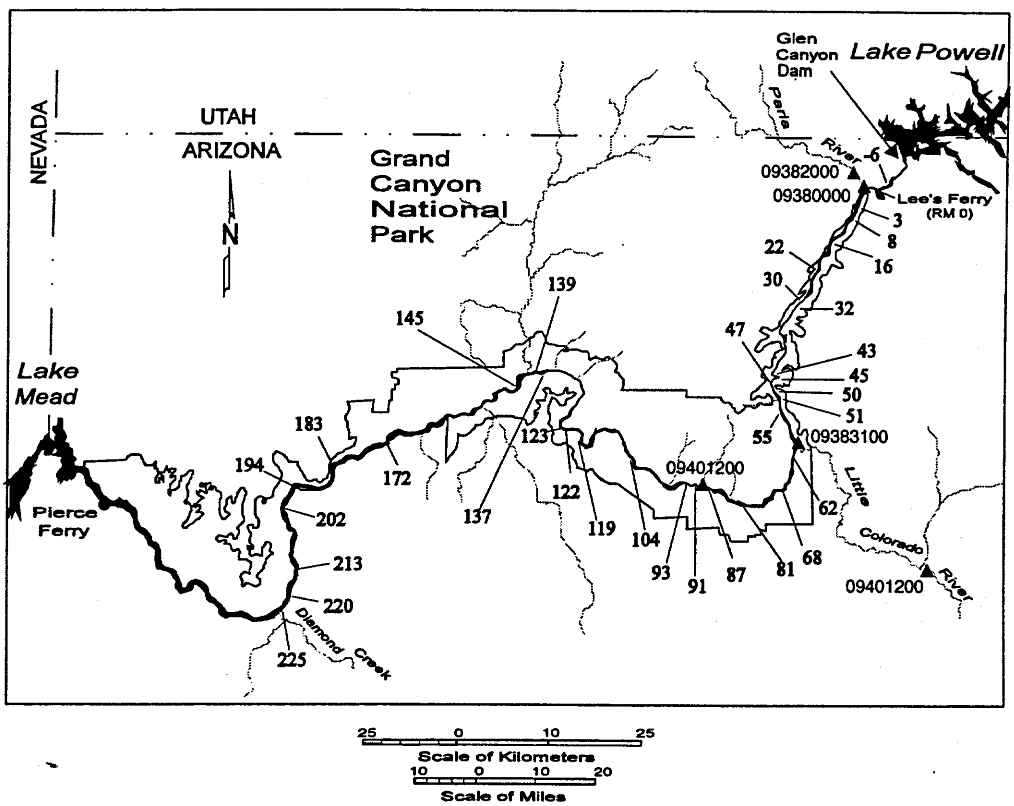


Figure 1. Hydrograph of the test flow at USGS streamflow-gaging station, Colorado River at Lees Ferry (09380000). Note that this level of release is about 334 m^3/s (11,800 ft^3/s) greater than powerplant capacity and more than 566 m^3/s (20,000 ft^3/s) above the maximum discharge allowed under the Interim Operating Criteria.

objectives were related to sediment resources because sand bar stability is linked to nearly all aspects of ecosystem maintenance and development (Bureau of Reclamation, 1996). Recent work on sand bar dynamics and sediment transport indicate that, during the previous Interim Operating Criteria and the now implemented GCD-EIS Preferred Alternative operating regime, sand was accumulating on the channel bed but the higher elevations of sand bars continued to erode (Graf et al., 1995; Kaplinski et al., 1995; Schmidt and Leschin, 1995; Wiele et al., 1995). One of the major objectives of the test flow was to transfer sediment accumulated in eddy and mainstem locations to the channel margin, thereby increasing the total number and size of sand bars along the river corridor (Patten et al., written communication, 1994). As part of this experiment, we conducted sand bar survey river trips before, after, and six months following the test flow to document and record changes at thirty-four eddy complexes (EC) in Glen and Grand Canyons (Figs. 2 and 3; Table 1). This report presents (1) description of sand bar dynamics and changes in pool sand storage at the selected eddy complexes, (2) stratigraphic information from the flood deposits, and (3) daily photographic analyses of post-flood erosion rates.



EXPLANATION

▲ **09383100** USGS STREAMFLOW-GAGING STATION-Number is station identifier

145 STUDY SITE-Number is in Stevens (1983) River Miles

Figure 2. Location map showing Colorado River, major tributaries, Grand Canyon National Park, study locations, and USGS streamflow-gaging stations.

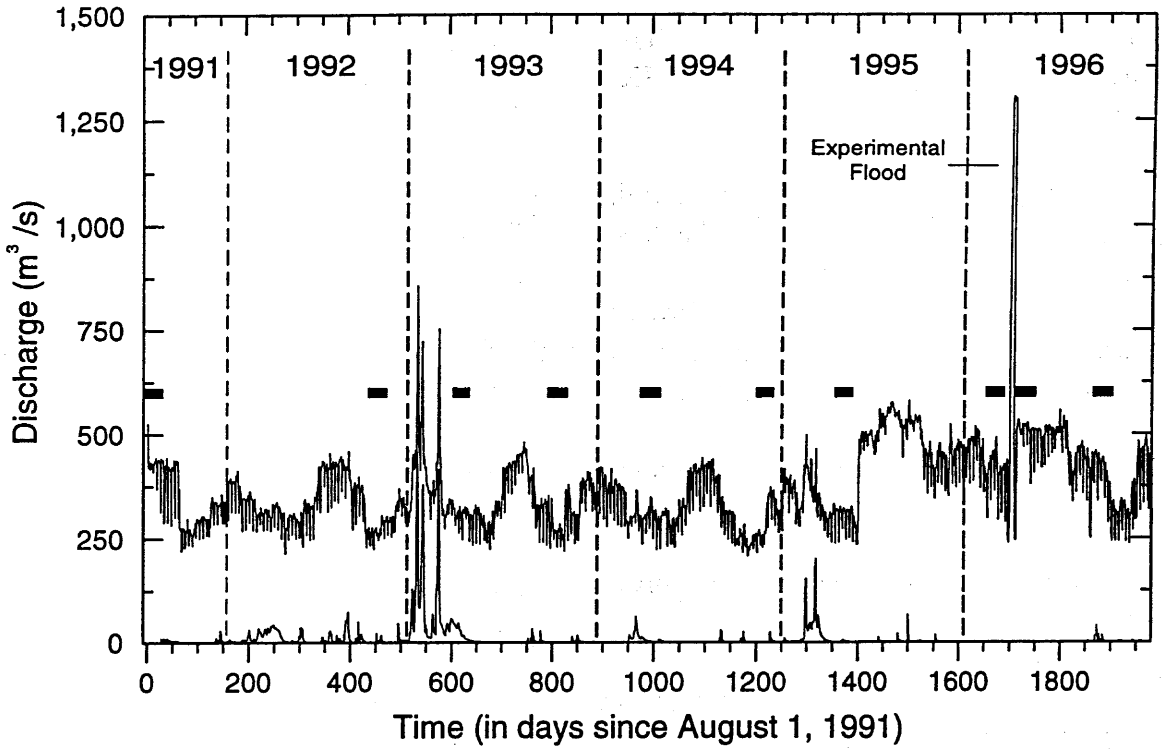


Figure 3. Daily mean discharge from USGS streamflow-gaging stations, Colorado River near Grand Canyon (09402500) and Little Colorado River at Cameron (09401200). Survey trip dates are highlighted by short horizontal bars.

Objectives and Associated Hypotheses

The following objectives were set and hypotheses tested by monitoring and recording changes in sand bar morphology before and after the test flow:

Objective 1) Monitor the topography and bathymetry of thirty-two eddy complexes during three survey trips; one before, one after, and one six months following the test flow.

Objective 2) Compare topographic changes at the study sites before and after the test flow to quantify changes in sand bar morphology and eddy/channel sediment storage.

H0.1: There will be no net change in the size and morphology of eddy sand bars following the test flow.

HA.1: Following the test flow, there will be a net increase in the size and morphology of channel-margin alluvial deposits along the river. Well-defined return current channels (eg., backwaters) will exist at reattachment bars.

Objective 3) Compare topographic changes six months following the test flow to assess how the eddy complexes were affected by "normal" Glen Canyon Dam operations.

H0.2: There will be no net change in the size and morphology of sand bars six months following the test flow and the deposits will resemble a size and shape similar to that existed prior to the flood.

HA.2: Deposition from the test flow will persist for a long enough time to benefit the riparian ecosystem and recreational resources of the river corridor. Re-excavated return current channels will exceed the size and number that existed prior to the flood.

Objective 4) Collect daily photography at thirty two study sites before, during, and after the test flow.

Objective 5) Use the daily photographs to document erosion patterns following the test flow.

Objective 6) Use the daily photographs in conjunction with post-test flow topographic surveys to determine erosion rates following the test flow.

Objective 7) Sequence daily photographs from 2 or 3 sites into short digital video loops for use in documentary and interpretive programs being developed by the National Park Service and the Grand Canyon Monitoring and Research Center.

H0.3: There will be no net change in the rate of erosion following the test flow.

HA.3: Following the test flow, erosion rates will initially be high and then decline with time.

Objective 8) Conduct a stratigraphic investigation at selected sites to determine if sand bars were scoured.

H0.4: The test flow will not scour sand bars during the rising limb of the test flow.

HA.4: The use of an intentional flood in habitat reconstruction will scour and rework sediments and kill or damage established riparian vegetation.

Objective 9) Conduct topographic transects along existing long-term marsh vegetation monitoring sites to assist in determining the relationship between sand bar morphology and spatial scales of marsh development.

H0.5: The test flow will not alter marsh development or productivity on reattachment bars through scouring or aggradation in return current channels.

HA.5: Marsh area and vegetation will be significantly altered by the test flow.

Table 1. Sand Bar Monitoring 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
55	55.5	Right	35	Kwagunt Marsh	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@	139.0	Right	25	Upper Fishtail	R/UP	8N
145@	145.1	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	201.9	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). @Denotes site monitored with photogrammetry.**

Background

Investigators have been studying impacts to the river corridor downstream from GCD since the mid 1970's. Thorough reviews of the findings from these studies are included in the GCES Phase I and Phase II final reports (U.S. Department of Interior, 1988; Beus and Avery, 1992) and reviews of the GCES program by the Water Science and Technology Board (National Research Council, 1987; 1991; 1996).

The results from the GCES Phase II research flows, and the absence of a Record of Decision (ROD) for the GCD-EIS, led the Bureau of Reclamation to examine the effectiveness of the Interim Operating Criteria that was implemented in 1991. Studies related to this investigation that were conducted during Interim Flow monitoring (1991-present) 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), bi-annual assessment of sand bar volume/area change (Kaplinski et al., 1995), surficial mapping of alluvial deposits from aerial photographs (Leschin and Schmidt, 1995; Schmidt and Leschin, 1995), and field-measured cross-sections combined with flow and sediment-transport models (Graf et al., 1995; Wiele et al., 1996; Wiele and Smith, 1996).

Important conclusions from these investigations are: (1) sand bar topography is affected by discharge, local geomorphology, sediment supply, and antecedent condition, (2) major periods of erosion follow post-dam events that deposit sediment in eddies, (3) Interim Operating Critera have significantly eroded sand bars, (4) deposition during Interim Operating Critera occurs within the range of discharges but erosion dominates at and above the maximum stage elevation, and (5) occasional high releases, at or in excess of GCD powerplant capacity, are necessary to redistribute sediment from river-storage to bar elevations not reached by Interim Operating Criteria.

Deposit Morphology and Processes

The characteristic channel unit of bedrock canyon rivers with abundant debris fans has been termed the fan-eddy complex (Fig. 4) (Schmidt and Rubin, 1995). Debris fans locally constrict the main river channel at nearly all tributary junctions (Howard and Dolan, 1981; Webb et al., 1989; Schmidt and Graf, 1990). In the channel expansion upstream and downstream from the constricted channel, a recirculation zone (eddy) forms where mainstem flow separates from and then reattaches to the bank (Schmidt, 1990). 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). Examples of deposits from each of these depositional areas are discussed in this report. We use the nomenclature of Schmidt and Graf (1990) who described and categorized four major bar types. *Reattachment bars* form near the reattachment point of the primary eddy. 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 (Rubin et al., 1990). 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 bars* are deposited in secondary eddies upstream of the primary eddy associated with the debris fan. They typically mantle the downstream portion of the debris fan. This type of bar is typically steeper and of higher elevation than reattachment bars. *Channel margin* deposits are those that parallel the shoreline in areas not

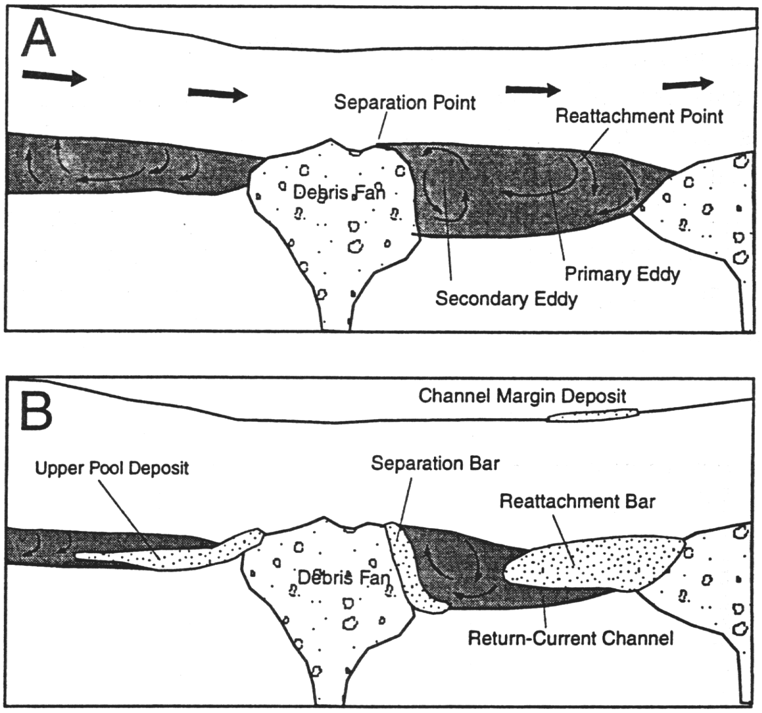


Figure 4. Schematic diagram showing flow patterns and configuration of bed deposits in a typical fan-eddy complex. (A) Flow patterns during higher volume flows. (B) Configuration of bed deposits during lower volume flows. Modified from Schmidt and Graf (1990).

specifically related to recirculation zones. This type of deposit was not examined in this study. In addition to the above, *main-channel sediments* are transported and locally deposited within or near the thalweg on the channel bed.

The morphology and sedimentology of eddy sand bars 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 (Fig. 4). 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, 1991a). The reattachment deposit may fill much of the recirculation zone beneath the primary eddy (Fig. 4). 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).

Main Channel Transport and Storage

Sediment accumulation on the channel bed can vary widely because of sediment mass-balance in the reach, sediment-transport capacity, and dam operations (Randle and Pemberton, 1987; Randle et al., 1993; Schmidt, 1992; Wiele et al., 1996). Large tributaries, such as the Little Colorado and Paria Rivers, provide the primary sources of sediment to the post-dam Colorado River below Glen Canyon Dam (Fig. 2). These perennial streams drain relatively low, semi-arid parts of the Colorado River basin (Hereford, 1984; Graf et al., 1991) and provide a highly variable average of 2.3×10^6 Mg/yr of sand-sized sediment to the mainstem Colorado River, particularly during winter or mid-late summer storms (Fig. 5). Sediment contribution from these tributaries has decreased in the 20th century as a result of a change in the frequency of large floods (Andrews, 1991b).

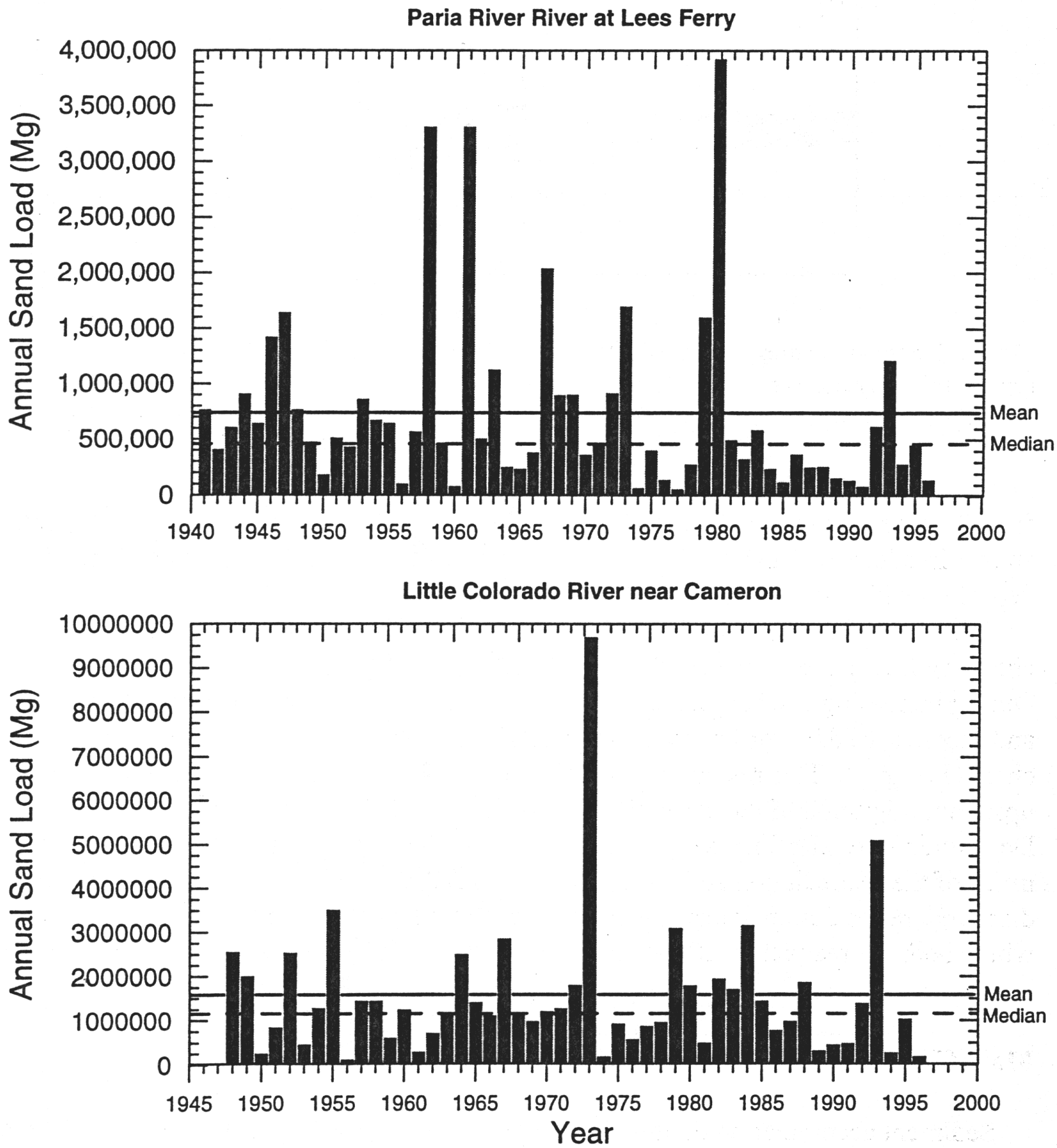


Figure 5. Annual sand inputs from the Paria and Little Colorado Rivers.

Previous mass-balance calculations have shown that sediment accumulates during years when dam releases are less than powerplant capacity, but is removed and transported downstream to Lake Mead when releases exceed powerplant capacity (Howard and Dolan, 1981; Schmidt, 1992; Randle et al., 1993; Smillie et al., 1993). Low releases between 1963 and 1982 as Lake Powell filled after dam closure, allowed accumulation of tributary-derived sediments (Fig. III-15; Bureau of Reclamation, 1995). However, flows exceeded powerplant capacity by 2 - 3 fold for 1 - 3 months/yr during the high inflow years of 1983 to 1986, removing this accumulated sediment (Schmidt, 1992; Randle et al., 1993).

Interpretations of bar stability and history of aggradation and degradation, whether it is the effects of dam operating criteria or flow exceptions such as the 1996 test flow, need a detailed understanding of the volume of sand in storage in Grand Canyon. Prior to Interim Operating Criteria, the last major change in flow regime was the high discharges that occurred annually between 1983-1986. In this report we present a calculated sediment budget of the Interim Operating period (1991-1997) for the Colorado River in Grand Canyon. In this way our measurements of eddy and channel topography are made within a historical context that takes into account the degree of accumulation after this change in flow regime to help explain impacts from the test flow, subsequent reworking by dam operations, and depositional or erosional trends.

METHODS

Study Site Selection

Thirty-two fluvial sand deposits (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 (Figs. 2 and 3). These sand 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, and (5) variation in recreation use intensity and vegetation cover. Site selection, baseline surveys, and protocol development were accomplished during June and August, 1990. Our monitoring project (Kaplinski et al., 1995) utilized these same sites and added one, RM62 (Fig. 2; Table 1). An additional site, RM55, was added for the test flow to assist the "Backwater Rejuvenation" study (Stevens et al., 1996).

Forty-three sand bars were originally selected by the Photogrammetry Project for daily monitoring using oblique photography (Dexter et al., 1994). The Photogrammetry Project and sand bar survey investigations were integrated into a combined Sand Bar Monitoring Project (Parnell, et al., 1995). Remote camera systems were installed at sites that did not have cameras resulting in nearly 100% overlap of the study sites. The number and distribution of these sites provides adequate spatial coverage of the entire river corridor and samples proportionate numbers of each geomorphic sand bar type.

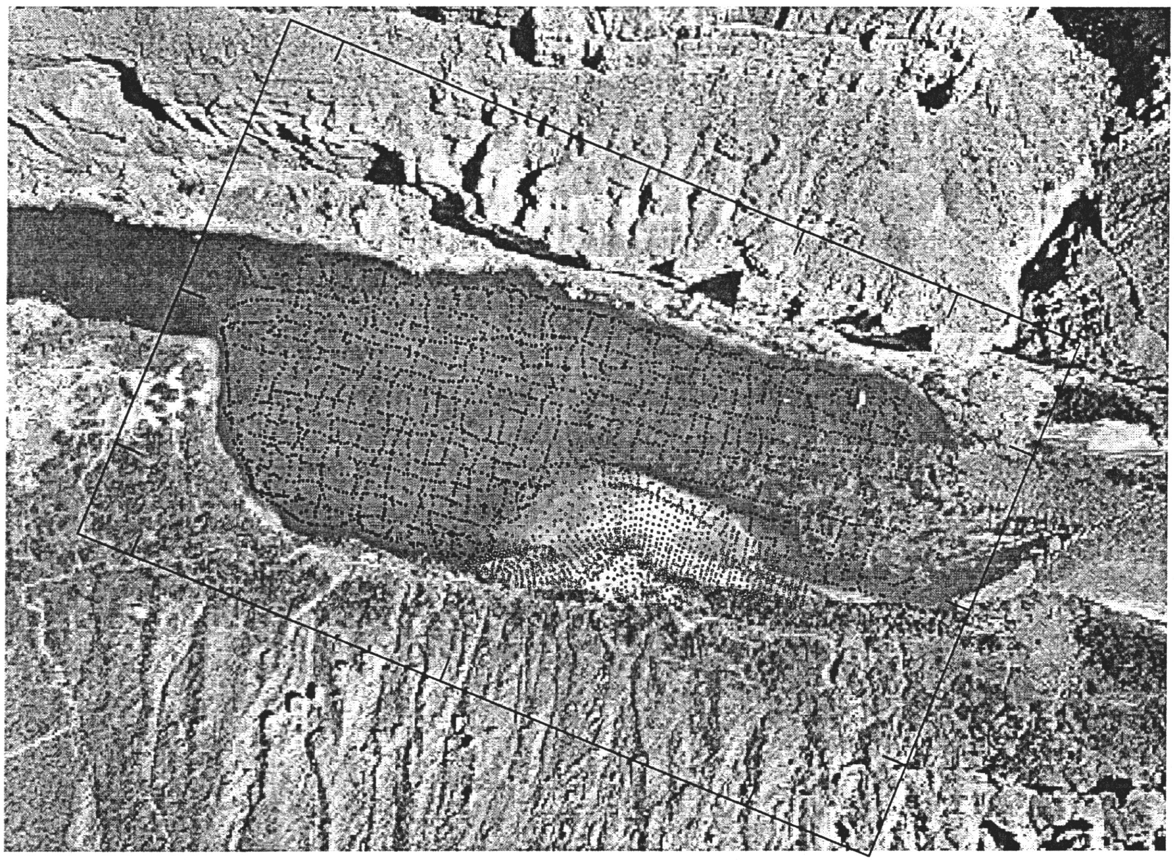


Figure 6. Combined ground-based and hydrographic data points collected at the RM47 study site on April 19, 1996. This coverage (1,225 ground-based points and 3,170 bathymetric points, respectively) was collected in approximately three hours.

Topographic Surveys

Topographic mapping was accomplished using Leitz total stations equipped with digital data collectors. Site size and topographic complexity determined the point density needed to form proper topographic models (Fig. 6). Smaller sites (~2000 m^2) typically require 200-400 points and larger sites (~10,000 m^2) require 750-2000 points. Points were 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. Terrestrial survey coverage typically extends from the 142 m^3/s (5,000 ft^3/s) stage elevation to slightly above the 1,274 m^3/s (45,000 ft^3/s) stage elevation. Bathymetric data collection, using a Hydrographics Survey Package (HSP), expanded ground-based coverage to include the entire river channel and recirculation zone of each fan-eddy complex. The HSP consists of a shore-based total station, a boat-mounted transducer, a digital/analog receiving unit, and a computer that controls the

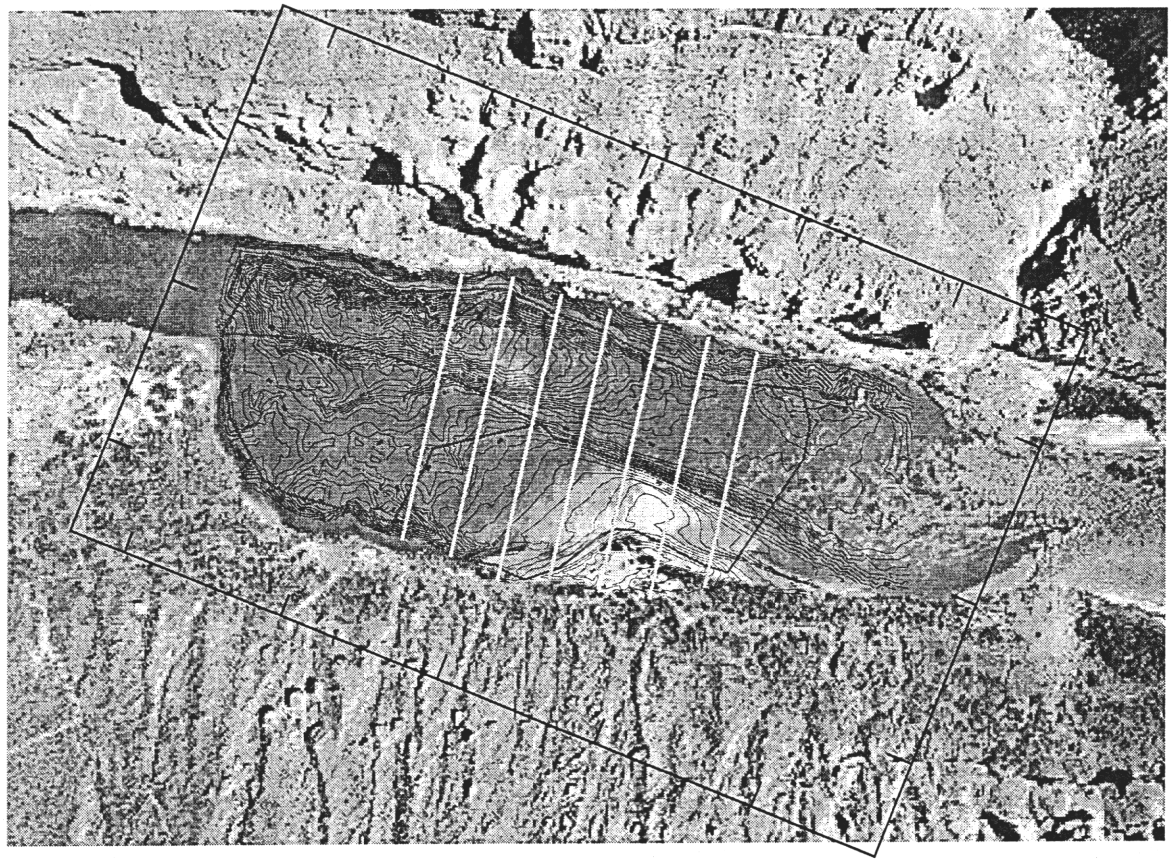


Figure 7. Topographic map and volume calculation boundaries at the RM47 study site.

digital data collection process. The shore station data is radio-telemetered to the boat computer where depth-position data is calculated and automatically stored. The location of the boat is determined by targeting a reflective prism mounted directly above the transducer. Digital depth records are checked by comparison with the analog sonar recording. Channel and eddy surveys were made by crossing the river at 10 m intervals combined with upstream and downstream longitudinal lines to form a grid.

Topographic Model Formation

The ground-based and bathymetric survey points were combined and used to form a Triangulated Irregular Network (TIN) surface model of channel, eddy, and sand bar topography (Fig. 7) using Sokkia Mapping Software (Datacom Software Research Limited, 1992). Breaklines were coded during ground-based data collection along identifiable features (ie. cutbanks, water surface lines, slope breaks, etc.) Breaklines are used in TIN model formation to force individual triangle sides along the proper grade breaks in order to prevent incorrect interpolations across the surface. The topographic models are edited with a 0.2 m contour interval for the ground-based survey area and a

0.5 m contour interval for the HSP data to insure proper model formation. Results from the GCES Phase II test flows showed that survey accuracy using the aforementioned total station survey procedures was less than three percent (Beus et al., 1992). Therefore, for this analysis, sand bar changes greater than three percent are considered significant. Eddy and channel volumes were determined from the section of the topographic model created from HSP collected data. Verification of x,y position and depth data found that HSP coordinate data have a horizontal error of <1 m and z elevation data < 0.5 m. We determined that volumes computed from surface models using HSP data vary from five to ten percent. Therefore, eddy and channel volumes presented here, and used in our analysis, were rounded to reflect these errors.

Plan area and volume were determined from each surface model within three distinct boundaries (bar, eddy, and channel) that enclose three distinct geomorphic regions within the complex (Fig. 7). Bar volumes were calculated from a subset of the survey area that encompasses the elevation range of dam operations (142-850 m^3/s). The elevation range at each site was determined from empirically derived stage-discharge relations (Kaplinski et al., 1995; Appendix A). These were constructed by compiling water surface elevations during a series of test flows within powerplant capacity between 1990-1991, the 1996 test flow, several periods of constant flow, and daily high and low flows. Discharges were assigned to each elevation by using the flow recorded at the nearest USGS streamflow-gaging station. By only using values measured during test flows, constant flows, and daily high and low discharges, the attenuation of the daily, peak-power production flood wave described by Wiele and Smith (1996) was minimized.

In order to assess changes to different topographic levels of each bar we determined the total volume and area within the boundary above the 142 m^3/s elevation contour, and partitioned volumes from a lower section (between the 142 m^3/s and the 410 m^3/s stage elevations), and an upper section above the 410 m^3/s elevation contour (Fig. 8). Subaqueous sediment storage within the eddy was determined within a boundary that encompasses the dimensions of the eddy (up to the 142 m^3/s elevation contour) and by estimating the location of the dividing streamline between downstream flow and recirculating flow (eddy fence), assuming this zone is vertical at a discharge of 566 m^3/s (20,000 ft^3/s) (Fig. 7). The eddy volume and area boundary was only created at twenty three of the thirty four sites because several sites (e.g. RM 81L Grapevine) are characterized by poorly-developed circulation during Interim Operating Criteria and thus do not have a distinct eddy that is a discernable feature separate from the bar itself. Sediment volume on the channel bed was determined within a boundary (Fig. 7) that approximates main-channel, downstream-directed flow outside of the eddy fence at a discharge of 566 m^3/s (20,000 ft^3/s). In order to compare sites of varying dimensions, volumes and areas were expressed as a percentage of the pre-flood surveys, conducted in February, 1996.

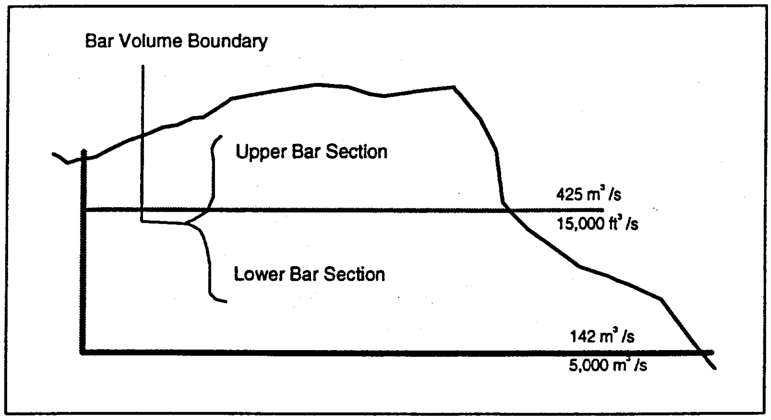


Fig. 8. Schematic topographic profile illustrating the upper (> 425 m^3/s stage elevation) and lower (142-425 m^3/s) sections of the sand bar volume and area boundary.

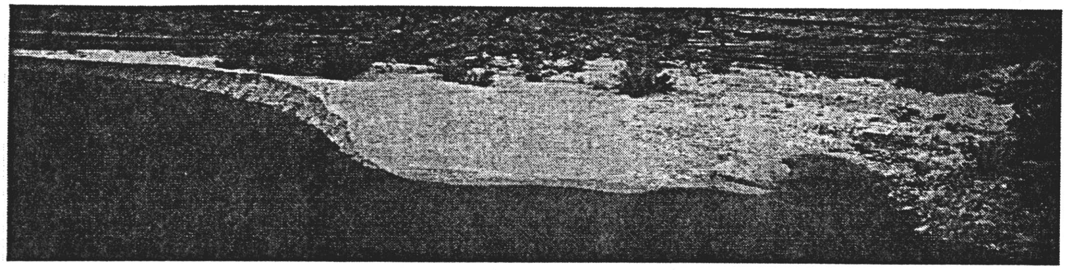
Sediment Transport Capacity

Methods for computing riverbed sand storage were developed to compare field measurements against tributary sand delivery and potential transport capacity during Interim Operating Criteria and the 1996 test flow. The sand-transport relations of Randle and Pemberton (1987) were used to construct a sand mass-balance model similar to that developed by Randle et al. (1993) for the GCD-EIS (Bureau of Reclamation, 1995). This budget was calculated by multiplying mean daily discharge data from selected USGS streamflow-gaging stations for each day between August 1, 1991-December 31, 1996, by the appropriate sediment rating relation. The Paria and Little Colorado Rivers were assumed to be the only sources of sand (Fig. 5). For example, the cumulative storage of sand between Lees Ferry and the LCR and Phantom Ranch was calculated as the sum of computed inputs from the Paria and Little Colorado Rivers minus the computed transport past the USGS streamflow-gaging station, Colorado River near Grand Canyon (09402500) (Fig. 2). The sand-transport relations were derived by Randle and Pemberton (1987) from measured values collected in 1983 and between 1985 and 1986 at this and several other USGS streamflow-gaging stations by Garrett et al. (1993). Error in this type of analysis results from possible shifts in rating relations (Bureau of Reclamation, Appendix D, 1995). The mass-balance model presented here is not intended to represent actual transport in the system but only to compare field results against potential sediment transport and tributary sediment delivery.

Daily Photogrammetry

The land-based time-lapse camera system consists of a Pentax IQZ 105 programmable camera mounted inside of a surplus ammunition can with a round, acrylic-covered window cut into the side. The camera housings were attached to rocks or outcrops

A)



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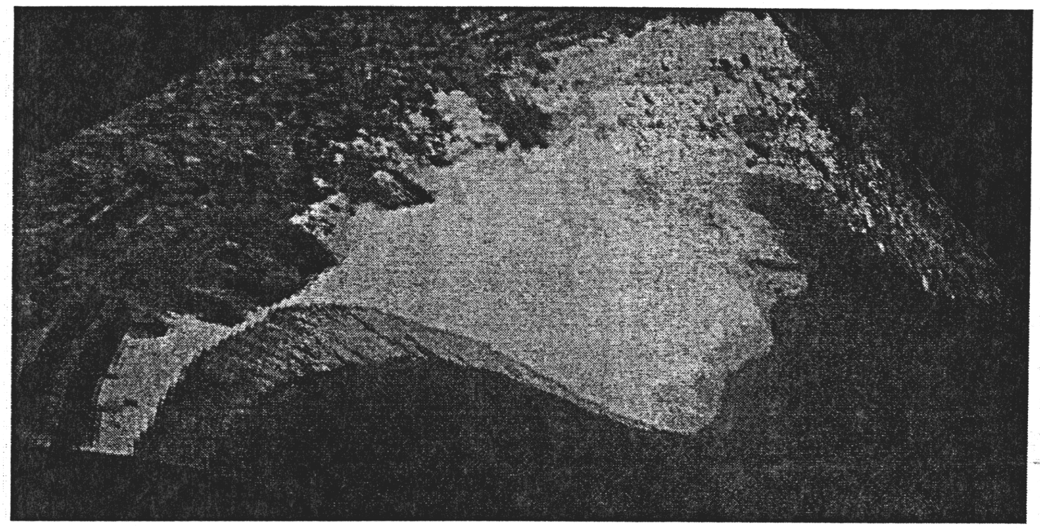


Fig. 9. Example of photogrammetric techniques. A) Oblique image obtained at RM122 on April 7, 1996 during the constant 227m^3/s flow that followed the test flow. B) Rectified planimetric model.

opposite the study sites to provide a fixed point for repeatable oblique photography. An exposure was taken every 24 hr at a pre-set time of day, approximately during the daily low water level. Film was changed during cooperating research raft trips approximately every 30-35 days and was processed and scanned onto Photo CD. Oblique images were rectified to vertical perspectives and planimetric models with ERDAS image processing software (ERDAS Inc., 1992) using methods documented by Manone et al. (1994) (Fig. 9). Planimetric models were digitized to determine area change at selected sites (Table 1).

Stratigraphy of High Flow Deposits

Stratigraphic investigations were conducted to determine the amount of initial flood scour and thickness of subsequent deposition. Scour chains or other markers were implaced on the pre-test flow survey trip. These were recovered after the test flow by utilizing a stake-out routine on the total station to locate the buried chain. Small pits were excavated to determine depositional contacts, measure thickness of high-flow deposition, and describe sedimentary structures. Initial scour was measured by noting the difference between the starting and ending elevation of the contact between test flow deposition and the pre-existing sand bar surface. Sedimentary structures exposed along cutbanks were photographed and described in order to interpret the internal structure of bar platforms.

RESULTS AND DISCUSSION

The hypotheses listed above were tested with data collected during ten survey trips between 1991-1996. The pre-high flow topography was measured during February 1996 and the post-test flow topographic measurements and stratigraphic observations were made in April, 1996. The third survey trip (Sept. 14-30, 1996) measured topography six months following the flood to examine the longevity of re-built sand bars and the channel bed condition. Daily photographs were collected throughout the reporting period.

Effects of the Test Flow

Sediment Storage Changes

Sand Bars. The test flow resulted in a net increase in the volume of sand stored in channel-margin alluvial deposits, or sand bars. During the seven day duration of this event sediment was successfully redistributed from the channel bottom to higher elevation sand bar locations (Fig. 10, Appendix A). Fig. 11a shows the percent change of the study sand bars versus distance downstream and demonstrates that the high flows resulted in a system-wide increase in sand bar volume, regardless of geomorphic reach or deposit type. Volume measurements within the sand bar boundary increased an average of 48% (Fig. 12a). Deposition in the upper sand bar boundary resulted in an average volume gain of 176% (Fig. 12b). Deposition of sand to the upper boundary was critical because this section had the highest erosion rates during interim flows (5-7%/yr.; Parnell et al., 1996). Twenty nine of the thirty four study sites (85%) increased in volume, three (9%) decreased in volume, and three (9%) maintained the same volume (Fig. 13a). In contrast to the large volumetric increase, the plan area of the bars increased only slightly by an average of 7% (Fig. 12a). Comparison of area change to the pre-flood condition shows that twenty (59%) of the sites gained area, twelve (35%) lost area, and two (6%) remained the same (Fig. 13b). This marked difference between changes in sand bar volume and area indicates that, in general, the test flow resulted in bars that were higher, but not necessarily wider.

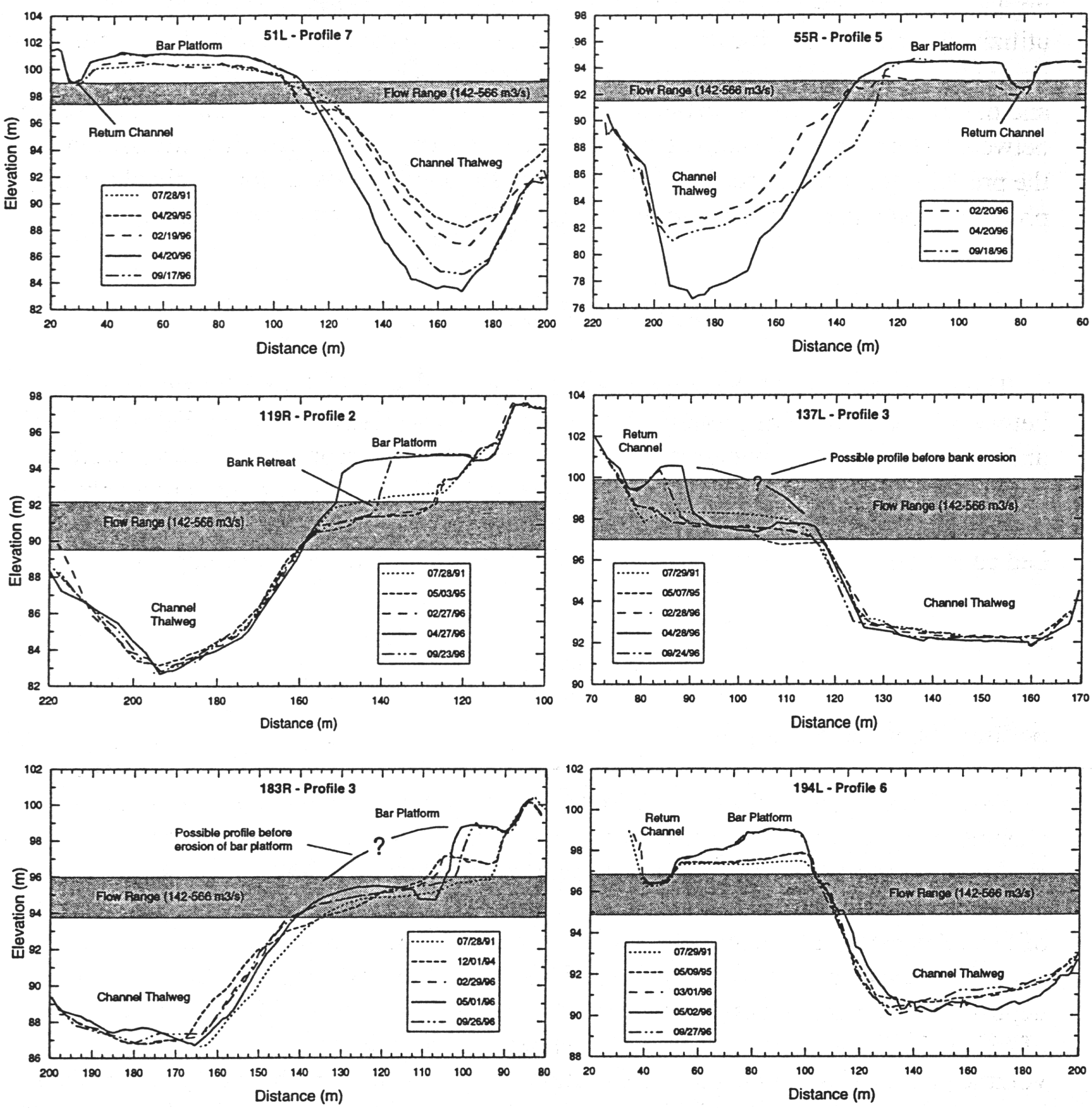


Figure 10. Cross-channel profiles from selected study sites. See Kaplinski (1995; Appendix A) for profile location information. Depicted profiles show a baseline, typically 1991 or 1992, and the last 4 surveys, 1994-1996.

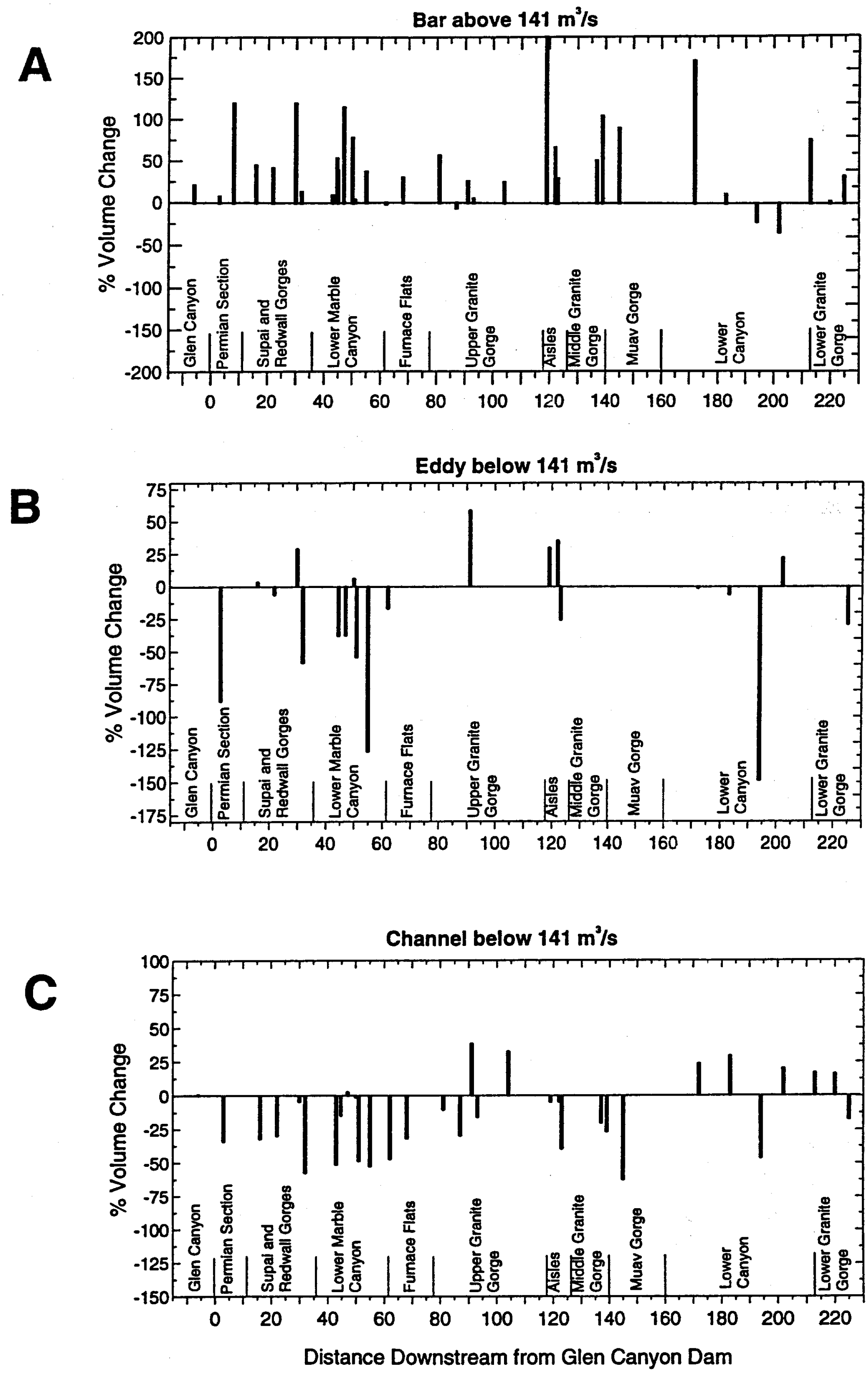


Figure 11. Graphs showing percent change in sediment volume for each survey run relative to values measured in February/March 1996. Geomorphic reaches within Grand Canyon from Schmidt and Graf (1990). A) sand bar, B) eddy, and C) channel boundaries versus distance downstream from Glen Canyon Dam.

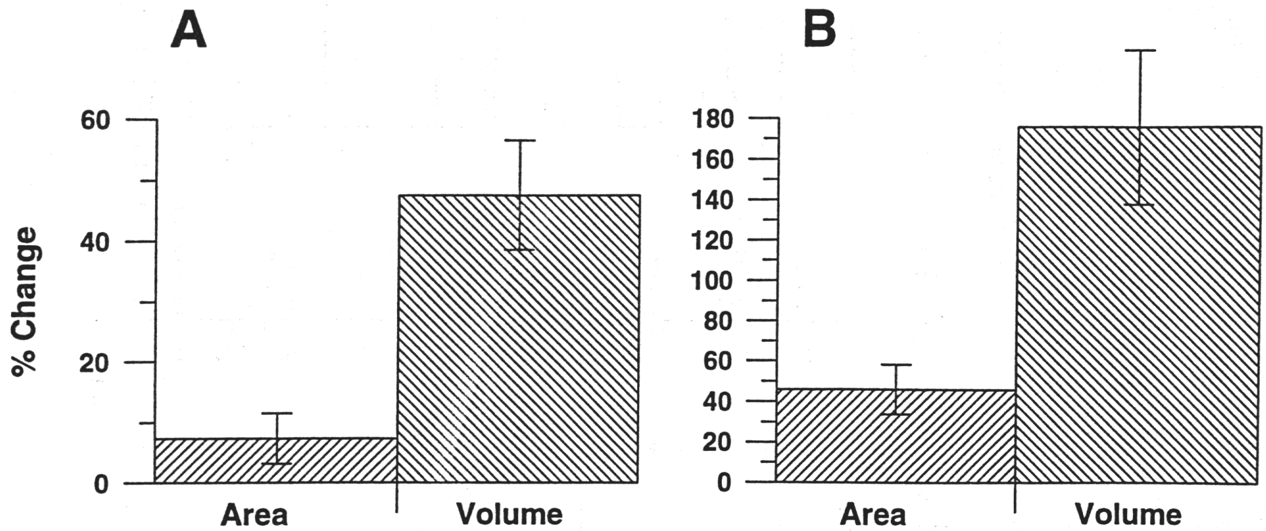


Figure 12. Average % change of sand bars from February-April, 1996 for A) total bar zone and B) upper bar zone.

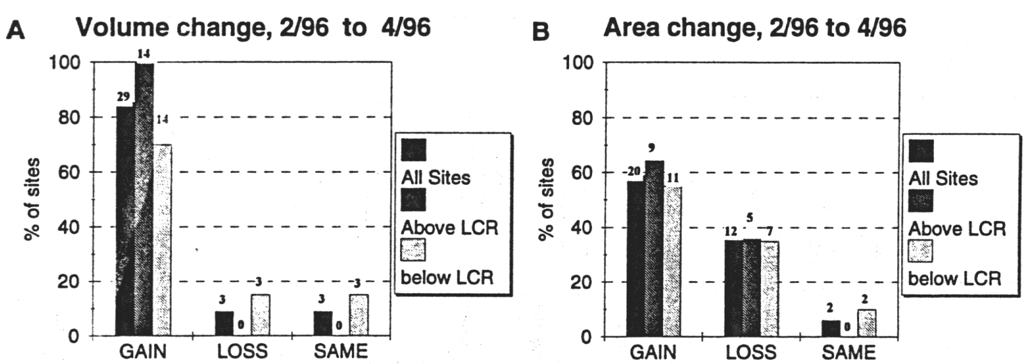


Figure 13. Histograms of site response from February-April, 1996 for A) volume change, and B) area change.

Eddies. The fan-eddy complex at "normal" flow regimes (142-556 m^3/s (5,000-20,000 ft^3/s)) consists of both an exposed sand bar and submerged areas within the zone of recirculating current (Fig. 4). In order to determine volumetric changes in sand storage within the entire recirculation zone (sand bar + submerged eddy areas), we measured changes from within an eddy boundary, below the 142 m^3/s (5,000 ft^3/s) elevation contour, in addition to bar changes. These eddy measurements were calculated at a subset of the study sites (Table 2). Recirculation zones that do not have an eddy volume

Table 2. Summary of volume changes between surveys

Site	FEBRARY – APRIL, 1996 in m^3			APRIL – SEPTEMBER, 1996 in m^3		
	Bar	Eddy	Channel	Bar	Eddy	Channel
-6	670		200	-130		-2400
3L	120	-8300	-8400	-810	2000	-3300
8L	690			-400		
16L	640	700	-9100	-30	-400	1400
22R	1420	-600	-5300	-790	-3500	100
30R	5000	2700	-500	-1720	-500	-500
32R	290	-8300	-11200	-340	800	2300
43I	310		-30400	-140		23300
45L	3910	-14300	-8000	-1250	5900	-12900
47R	4610	-17300	1500	-4820	9700	-13400
50R	2320	300	-200	-330	100	-1200
51L	190	-14100	-46600	-910	21400	5500
55R	4680	-18800	-54900	-1180	5800	12600
62R	-20	-10200	-18100	-20	-1500	-1300
68R	1470		-7300	-1330		-4500
81L	1350		-500	-590		300
87L	-40		-5300	30		-2000
91R	50	4400	3900	-50	-100	-4600
93L	90		-2600	50		-2700
104R	170		1800	-120		-1700
119R	6400	2600	2600	-3210	-2000	-2000
122R	3130	1900	-300	-330	1800	-200
123L	840	-3600	-9100	280	3800	2500
137L	2020		-900	-800		400
139R	2210		-4800	-1340		3600
145L	830		-500	-290		100
172L	2170	-100	4400	-620	100	-4300
183R	450	-300	2600	-80	300	-3000
194L	-1430	-6100	-17900	-100	2000	8500
202R	-760	8200	4100	80	5500	-4900
213L	2190		2400	-2020		-2900
220R	30		800	40		0
225R	1230	-1500	-4500	700	3400	-2900
Total	47230	-82700	-222100	-22570	54600	-10100

boundary either have subaerial bars that fill the upstream parts of the recirculation zone (e.g. RM 137, RM 145) or an eddy could not be differentiated from the channel boundary at flows approximating or less than 566 m^3/s (20,000 ft^3/s) such that meaningful measurements could be obtained (e.g. RM 81, RM 43). In this case, the total change in sediment volume from the recirculation zone was assumed to equal the change in bar volume only.

A normalized index of the volume change (NVC) within the recirculation zone (eddy + bar volume) was determined to examine the role of eddies in trapping and storing sediment during the test flow (Fig. 14). This index was determined for each eddy system by dividing the total volume gain (eddy + bar) by the total area (eddy + bar). An NVC value greater than zero shows that the eddy system had a net gain in sediment, while a negative value indicates a net loss of sediment from the eddy system.

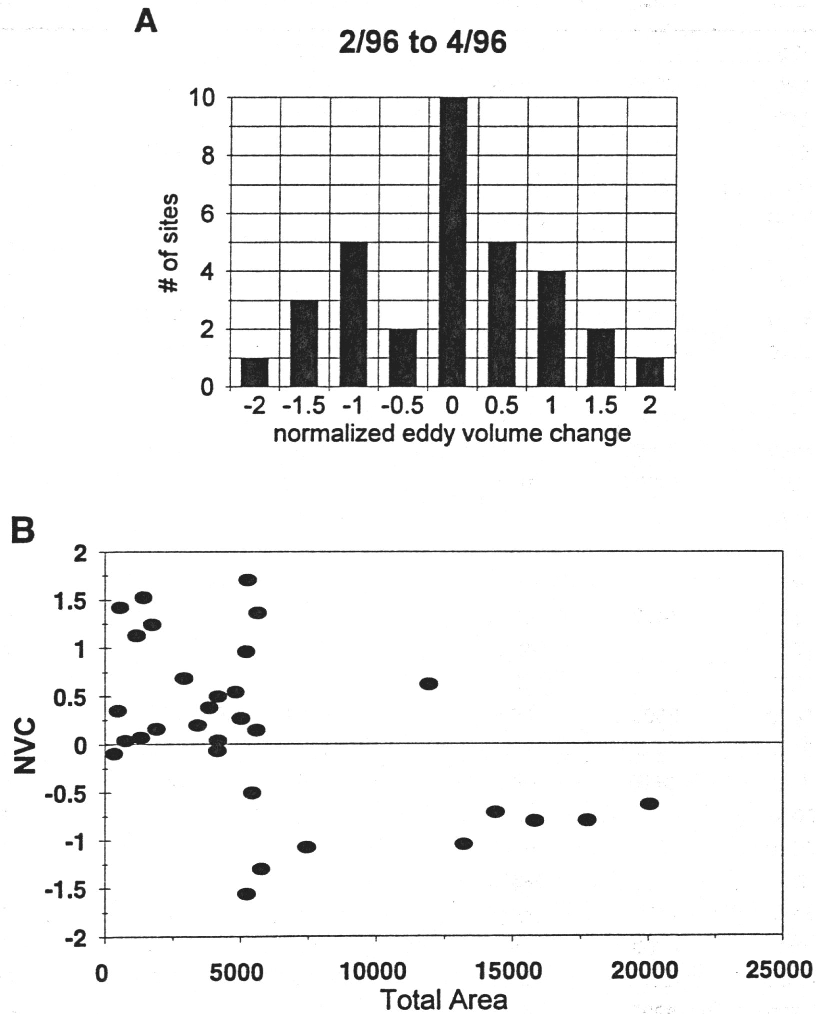


Figure 14. Normalized recirculation zone index (NVC) comparison between 2/96- 4/96. A) Histogram of NVC distribution, and B) NVC index versus eddy size.

The NVC indices of the study sites are normally distributed and show that eddy systems gained or lost sediment around a system-wide mean of 0.23 (Fig. 14a). A positive mean NVC value suggests that the net system-wide response of fan-eddy complexes was to gain sediment. Large eddies show a net loss in sediment while small eddies showed a net gain (Fig. 14b; Table 2). The slightly negative kurtosis of the NVC distribution is due to eddies larger than 5,000 m^2 and indicates that the larger eddies comprise a separate population (Fig. 14a). However, the sum of the computed eddy volumes show a net loss of 35,470 m^3 from the fan-eddy complexes (Table 2). These data suggest that the larger eddy systems, primarily in the wide reaches (Fig. 11b) may not be indicative of the average response, but were a source of large amounts of sediment during the test flow. Schmidt and Leschin (1996) developed a similar, normally distributed eddy deposition index from detailed, reach-scale mapping of alluvial deposits using aerial photographs. The agreement between these independent studies suggests that eddy systems along the river corridor behave in a predictable manner over a broad range of flow regimes. This correlation between eddy size and degree of filling or removal of sediment should be the focus for future study and integration.

Isopach maps from the large fan-eddy complexes show that scoured areas were located in the upstream parts of recirculation zones (Fig. 15). Volume measurements from this example, RM 47, indicate that 4,611 m^3 was deposited within the bar boundary and 17,300 m^3 was lost from the eddy boundary, resulting in a net loss of sediment from the eddy (Fig. 15; Table 2). Cross-channel profiles at the upstream parts of several recirculation zones show up to 10 m of scour (Fig. 16). Although the majority of the scoured eddies occurred at large reattachment bars within wide reaches of the river (eg. The Lower Marble Canyon Reach), scour was not limited to one geomorphic reach and both wide and narrow reaches were affected (Fig. 11b).

Main Channel Bed. Channel geometry was distinctly altered by the test flow, suggesting that the bed had been scoured (Fig. 17). Volume measurements of channel bed topography indicate that a total of 222,100 m^3 of sediment was scoured from the channel expansion portion (pool) of the fan-eddy complexes (Table 2). This sediment was either transported downstream or into adjacent eddies. Fig. 11c shows that a volumetric decrease in sand storage occurred at all sites between Lees Ferry and the LCR confluence. Below the LCR confluence, variability between aggradation and degradation increased. There was no distinct pattern of change between wide and narrow reaches. The site in the Glen Canyon Reach, RM -6, was not significantly scoured and suggests that the channel bed in this reach had previously established a degraded condition (Fig. 17; Table 2). Sand stored in pools was scoured from depressions in the main channel just downstream from channel constricting debris fans and from broad flat areas in the widest part of the channel expansion at the downstream end of the pool (Figs. 16 and 17).

Differences in main channel sand storage between sites depends on channel morphology (Wiele et al., 1996). Although both wide and narrow reaches were

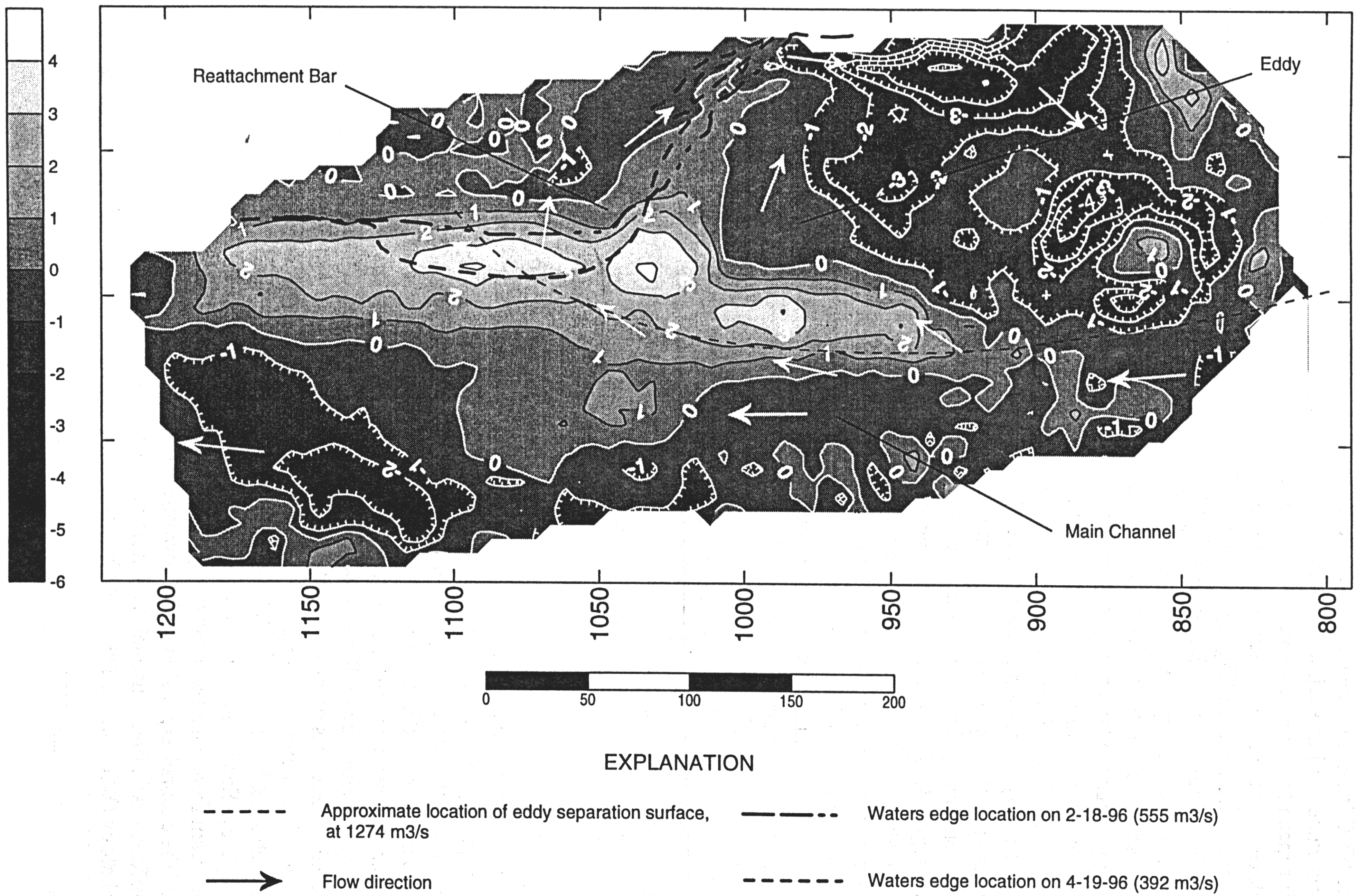


Figure 15. Isopach map of the pool and eddy at the Saddle Canyon fan-eddy complex (RM 47R) constructed from the 2-18-96 and 4-19-96 surveys. Note the bed scour in the upstream portion of the eddy.

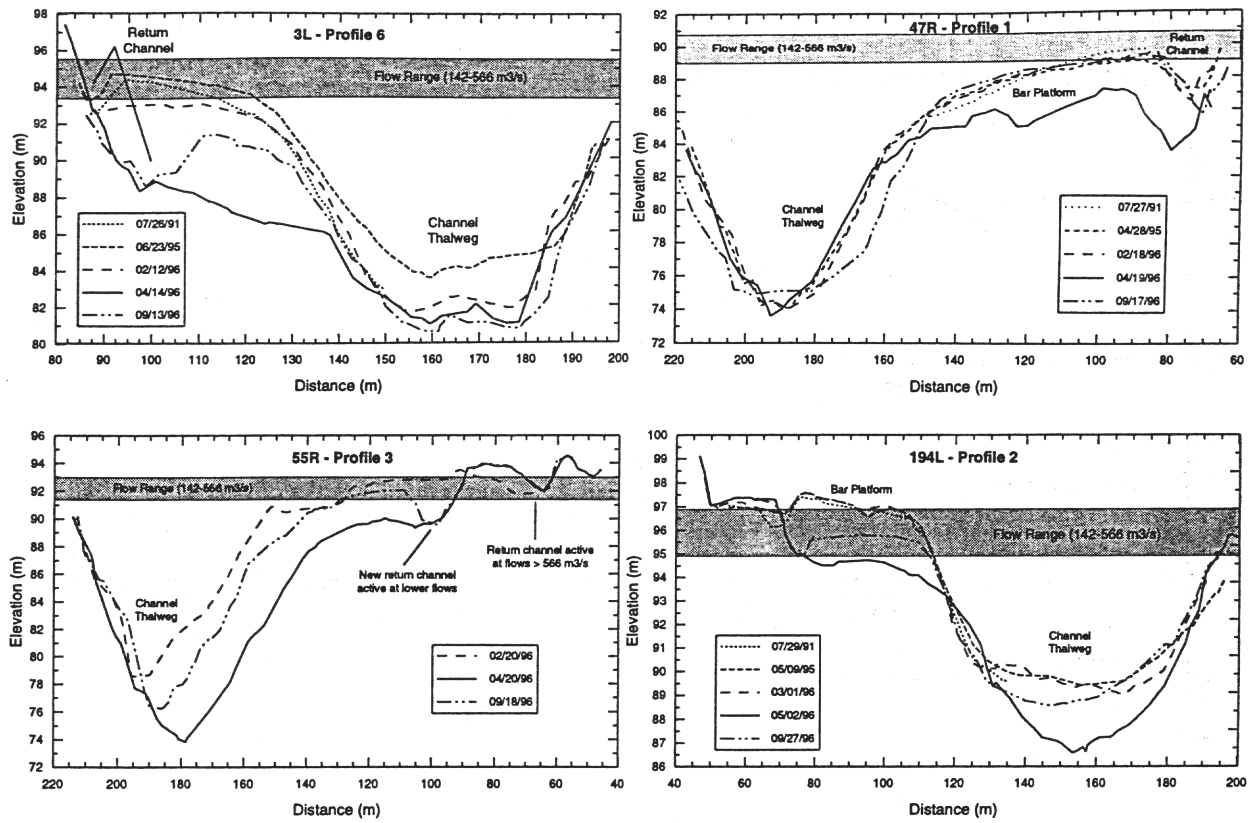


Figure 16. Cross-channel profiles from selected study sites. See Kaplinski (1995; Appendix A) for profile location information. Depicted profiles show a baseline, typically 1991 or 1992, and the last 4 surveys, 1994-1996.

scoured, the largest main channel volume loss occurred in wide reaches where channel width and expansion ratio are conducive to large fan-eddy complexes with well-formed eddies. These fan-eddy complexes are characterized by expansion ratios greater than 2.8, a value similiar to the average ratio of 2.9 calculated by Schmidt and Graf (1990). The net effect of the test flow at sites with expansion ratios less than 2.8 ranged from net erosive to net aggradational. The magnitude and pattern of change in stored sand at the study sites depends on pool morphology. During higher flows, wide reaches of the river provide a greater proportion of the sediment used to build sand bars, than is supplied from narrow reaches.

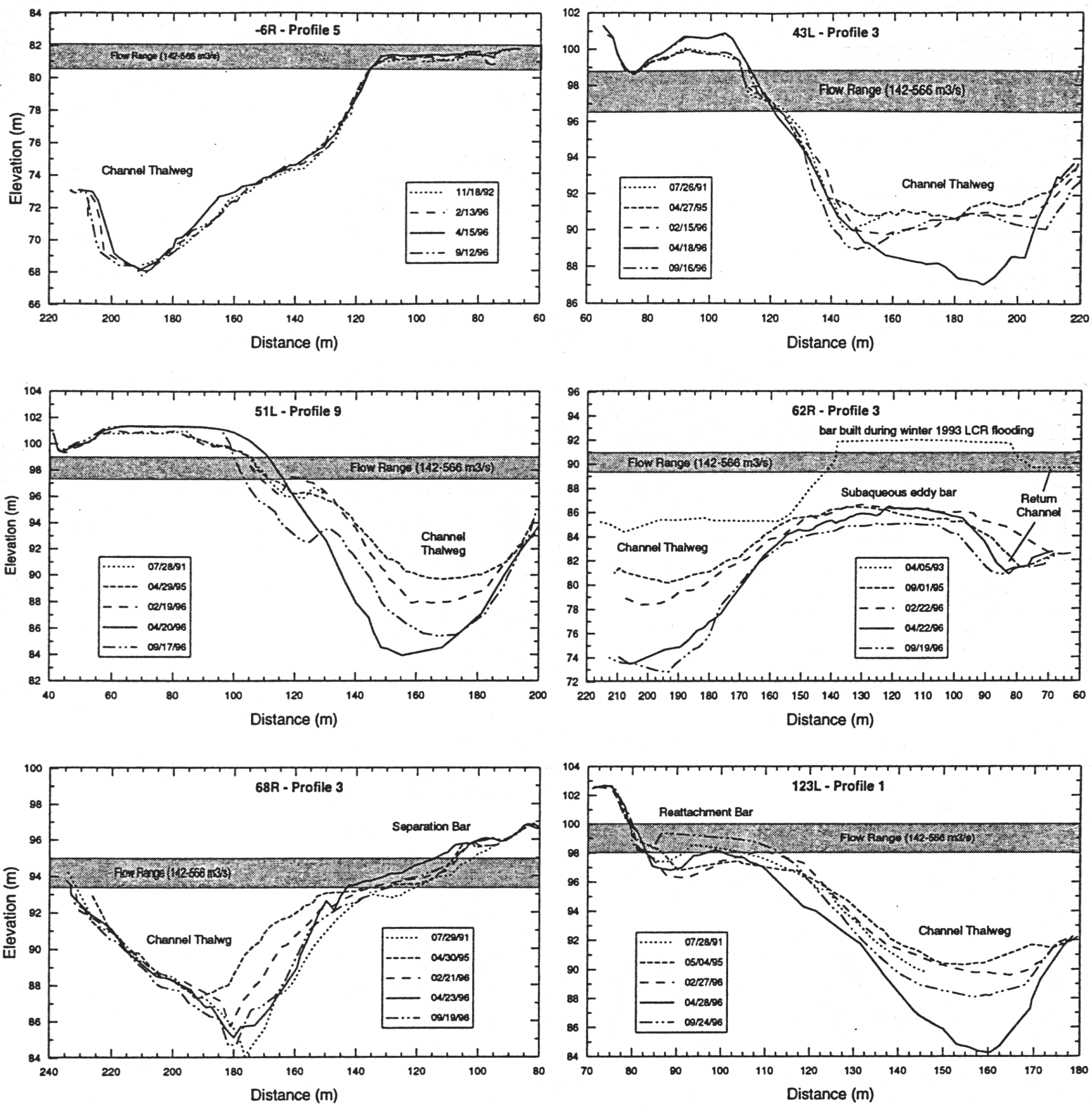


Figure 17. Cross-channel profiles from selected study sites. See Kaplinski (1995; Appendix A) for profile location information. Depicted profiles show a baseline, typically 1991 or 1992, and the last 4 surveys, 1994-1996.

Stratigraphy of Test Flow Deposits

Excavations of trenches and scour chains, and sedimentologic interpretation of cutbank exposures, in combination with topographic measurements, were used to determine rates and style of scour and fill. In cooperation with Utah State University and the U.S. Geological Survey (J. Schmidt and D. Rubin, written communication, 1996), scour chains were implaced at our study sites to assist in their test flow hypothesis that portions of sand bar deposits scour and then fill during high flow events. Approximately half of the scour chains or other markers were recovered on the post-test flow trip (Table 3). Chain recovery was dependent on depth of burial, location of implacement, and logistical constraints.

Table 3. Scour and fill chain observations

SITE	CHAIN	SCOUR, in m	NET DEPOSITION, in m
RM 8	CE2	0.09	0.18
	CE3	0.06	0.22
RM 16	CE1	0.00	0.32
	S3	0.45	0.10
RM 22	S3	0.00	3.20
	S4	0.00	2.25
	S5	0.00	0.46
RM 30	CE1	0.00	1.19
	CE2	0.00	0.69
RM 32	CE1	0.00	0.14
	CE2	0.00	0.22
	S1	0.00	0.27
	S3	0.15	0.12
	S4	-0.00	0.24
RM 55	CE6	0	1.06
	CE7	0	0.93
	CE9	0	0.48
	CE10	0	0.13
RM 81	CE1	0.00	0.99
	CE2	0.25	-0.31
	S5	-0.02	0.47
RM 93	S3	0.00	0.37
	S4	0.07	0.63
RM 119	S5	0.04	0.31
RM 137	S4	0.00	1.77
RM 183	S4	-0.02	0.55
RM 202	S4	0.03	0.20
	S6	-0.09	1.10
AVG.		**0.04**	**0.65**

Recovered scour chains and other markers indicate that sediment was deposited on bars with little associated scour (Table 3). This is due in part to chain location. Topographic survey data indicate that large amounts of scour, depending on location in the eddy, accompanied the test flow (Figs. 15 and 16). In general, the vertical sequence in excavated pits consisted of the old bar surface overlain by ripple strata composed of reddish, silty to fine-grained sand (0.04-0.15 mm) and then by ripple strata and dune foresets composed of clean, fine- to medium-grained sand (0.15-0.30 mm). The contact with the old bar surface showed little evidence of scour and was often demarcated by buried vegetation or pre-flood beds with trampled-structures (D. Rubin, USGS, personal communication, 1997). Organic debris was ubiquitous in dune troughs and on the lee side of migrating ripples (Fig. 18). Grain size coarsened upward as ripples were replaced by larger bedforms.

Seven of the study bars were examined by photographing and describing sedimentary structures exposed along eroding cutbanks (Fig. 19). Separation bars were not examined in this manner. A general sequence of reattachment bar deposition during the test flow was identified. The lowermost beds along cutbanks were not easily observed but internal structures examined in trenches and pits indicate that the early phases of deposition was not accompanied by extensive scour. Large-scale cross-beds were deposited by dunes migrating out of the channel and into the eddy in the vicinity of reattaching flow (Fig. 20). Dunes are characterized by asymmetric, trough shaped sets of cross-beds as thick as

Figure 18. Organic debris entrained by migrating bedforms and deposited in dune troughs.

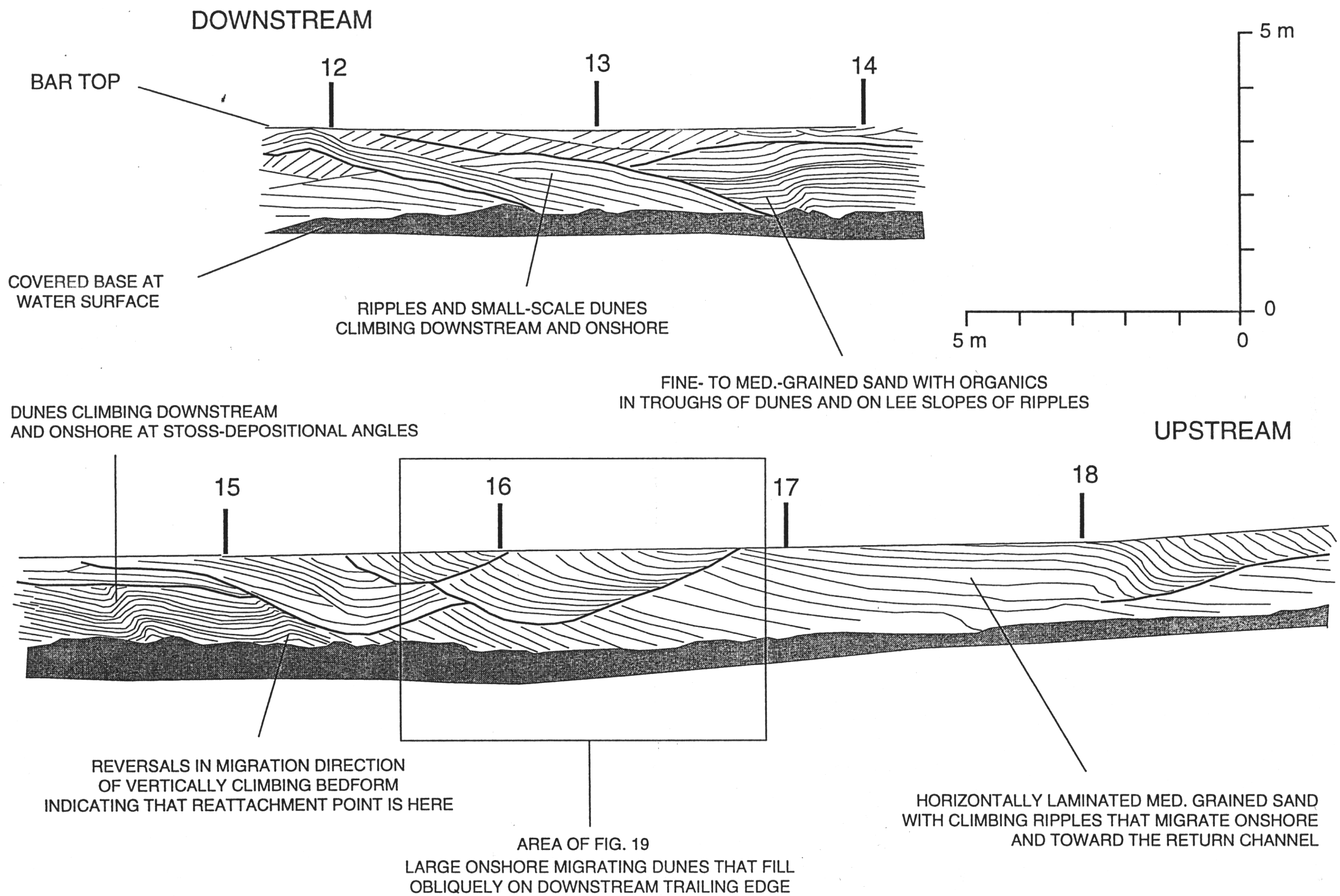


Figure 19. Portion of a 110 m cutbank profile exposed along river edge at the RM 119 reattachment bar. Numbers correspond to surveyed locations that are 5 m apart.

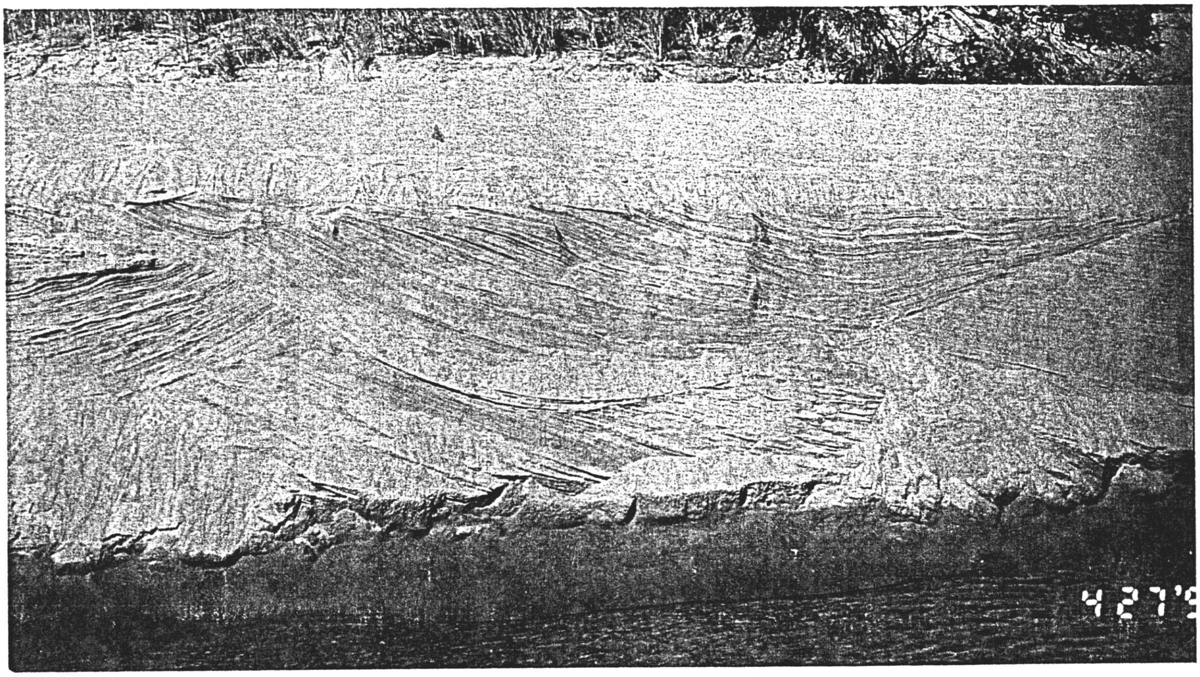


Figure 20. Large-scale, trough-shaped bedforms asymmetrically filled with cross-beds. Location is shown on Fig. 19.

2 m. This type of bedform has been interpreted to form by migration of the leading (erosional) side and scour of a trough-shaped bounding surface. Migration of the bedform trailing edge deposits the overlying cross-beds (Rubin, 1987). Upstream and downstream from the reattachment point smaller-scale dunes replace climbing ripples as the dominant bedform in the vertical sequence (Fig. 19). Extensive cross-beds were formed in upstream areas as bars and superimposed dunes migrated toward the return-current channel. As eddies filled, flow over bar surfaces weakened and/or sediment supply decreased and the depositional sequence at the top is characterized by reworking of smaller-scale bedforms and ripples. The reader is referred to descriptions of depositional processes and details of structures in these bars published previously (Rubin et al., 1990) and related studies in progress (D. Rubin, personal communication, 1996) for a more complete model of bar-building during the test flow.

Sedimentary structures are useful indicators of flow conditions and rates of aggradation (Rubin, 1987). Since discharge was steady during the test flow and the deposits represent one depositional episode, controls of bedform climb and orientation are inferred to be related to sediment supply. The internal structure of bar platforms examined in this study indicate high deposition rates. Evidence for rapid deposition includes large bedforms (dunes), scour pits, stoss-depositional bedforms and climbing ripples, and ubiquitous organics. Stoss-depositional climb of bedforms and ripples requires relatively rapid rates of deposition where the rate of sand supply approaches or exceeds the rate of bedform migration (Rubin, 1987). Floating mats of vegetation and organic matter were mainly observed in the first 2 days of the flood. This material was entrained by migrating bedforms and deposited in dune troughs and on the lee side of migrating ripples throughout the entire depositional sequence (Fig. 18), suggesting either rapid deposition in the first few days of the test flow, or the supply of organic material was continuous over the duration of the experiment. Coarser grain sizes and dunes, rather than ripples, were found at the tops of reattachment bars, the reverse of the idealized fining-upward sequence described by Rubin et al. (1990). Ripples did not replace dunes as the dominant bedform, and grain size did not become finer as eddies filled, which suggests that the only sediment available towards the end of the depositional event was coarser-grained sand. The coarsening upward sequence in the test flow deposits is attributed to initial deposition of finer-grained sediment that had accumulated during Interim Operating Criteria and, as sediment supply became depleted, increasingly coarser-grained sediment was entrained from the channel bed.

Post-Test Flow Effects of GCD Operations

Sediment Storage Changes

Sand Bars. Following the test flow, the newly aggraded sand bars eroded as the system adjusted to GCD operations (Fig. 21a; Table 2). Dam operations following the test flow were constrained to the GCD-EIS Preferred Alternative, which is similiar to Interim Operating Criteria. However, GCD flows fluctuated from 453-566 m^3/s (16,000-20,000 ft^3/s) in the first two months following the test flow, well above the 8-13,000 ft^3/s fluctuations typical for spring releases. The volume of sediment stored in sand bars above the 142 m^3/s (5,000 ft^3/s) stage elevation decreased an average of 13% during from April-September, 1996 (Fig. 22a). Five of the thirty-four study sites (15%) gained volume, twenty-four (71%) lost volume, and five (15%) maintained the same volume (Fig. 23a). The net loss of sand from within the bar boundary (-22,570 m^3) was slightly less that half of the volumetric increase measured after the test flow (Table 2). After 6 months of dam operations sand bars still contain an average of 97% more sediment than was stored before the test flow. The volumetric decrease corresponded with a negligible decrease in bar plan area above the 142 m^3/s (5,000 ft^3/s) stage elevation (Fig. 22a). However, erosion from the upper sand bar boundary (above the 410 m^3/s stage elevation) decreased the area by an average of 18% (Fig. 22b). Comparison of area change from April-September, 1996 shows that fourteen (41%) of the sites gained area, fourteen (41%) lost area, and five (15%) remained the same (Fig. 23b).

Daily photographs shows that erosion at several sites began immediately following the test flow (Appendix A). However, other sites were relatively stable until the Labor Day weekend (August 31-September 2, 1996) constant 227 m^3/s (8,000 ft^3/s) flow (Appendix A). Profiles from the RM 55R, 119R, 137L and 183R show that has much as 25 to 30 m of bank retreat occurred in 6 months (Fig. 10). The decrease in area and volume from the upper sand bar zone is attributed mainly to the shoreward retreat of cutbanks.

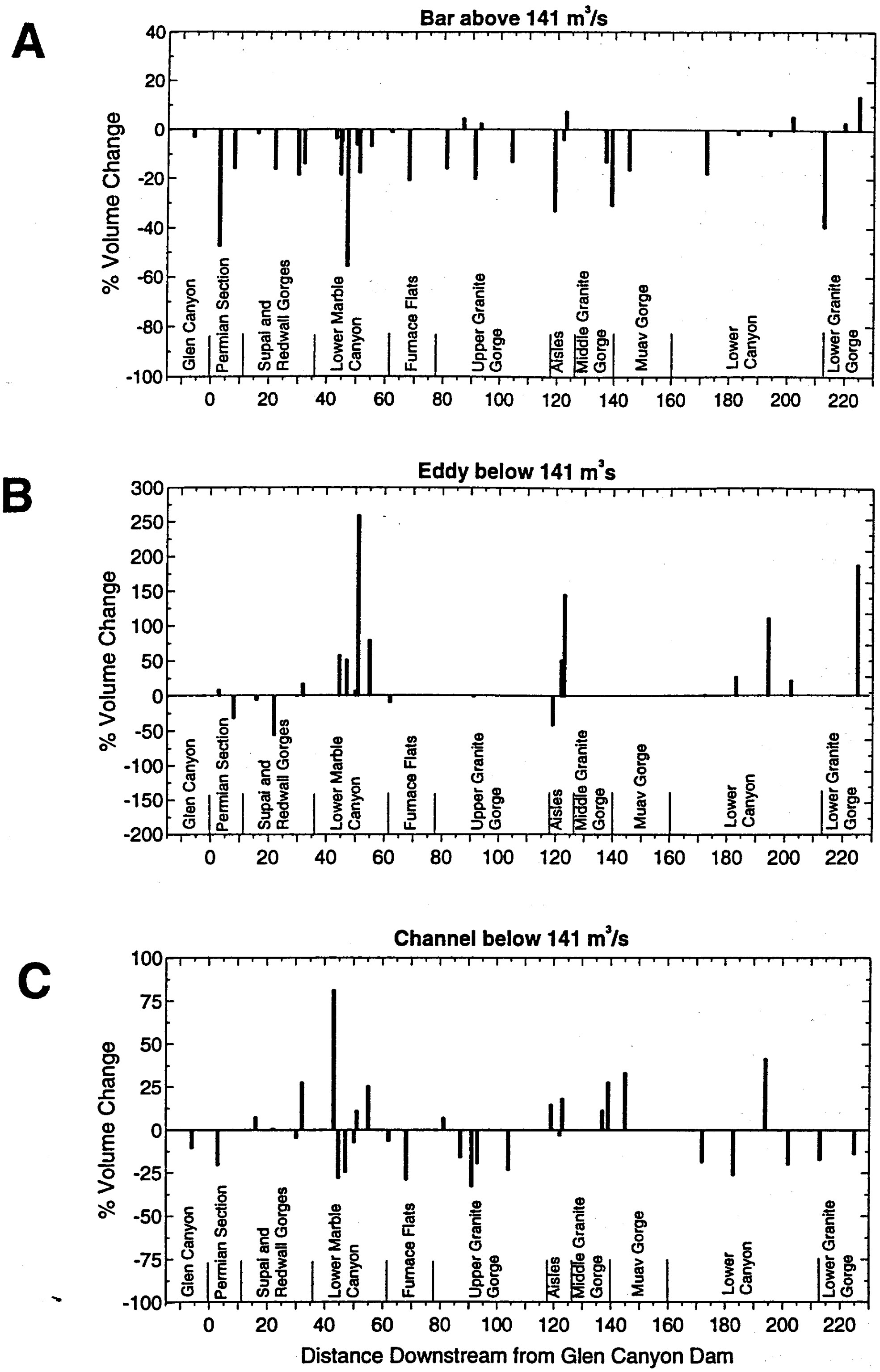


Figure 21. Graphs showing percent change in sediment volume from April-September, 1996 relative to values measured in February/March, 1996. Geomorphic reaches within Grand Canyon from Schmidt and Graf (1990). A) sand bar, B) eddy, and C) channel boundaries versus distance downstream from Glen Canyon Dam.

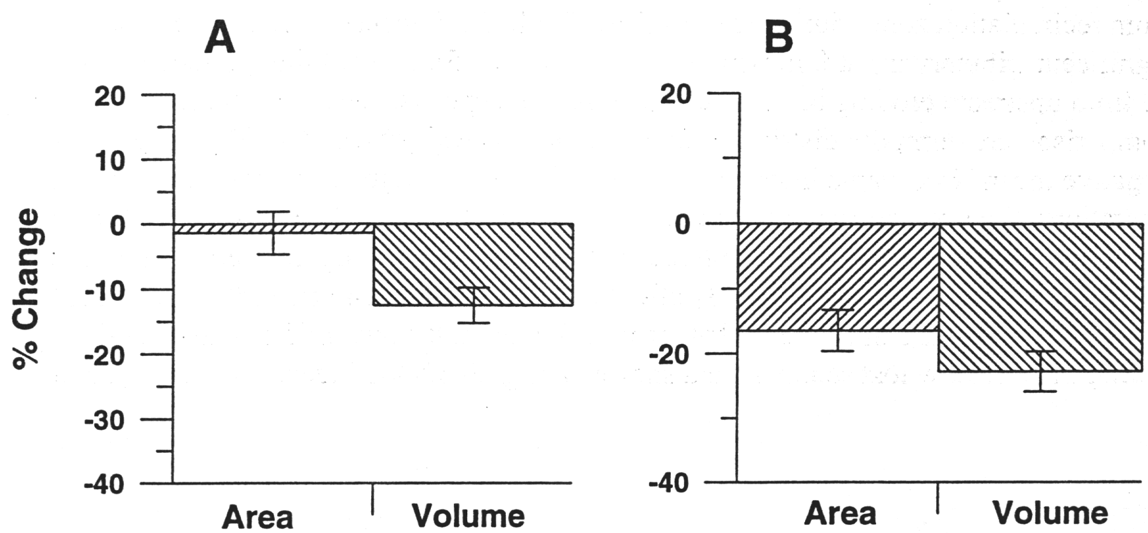


Figure 22. Average % change of sand bars from April-September, 1996 for A) total bar zone and B) upper bar zone.

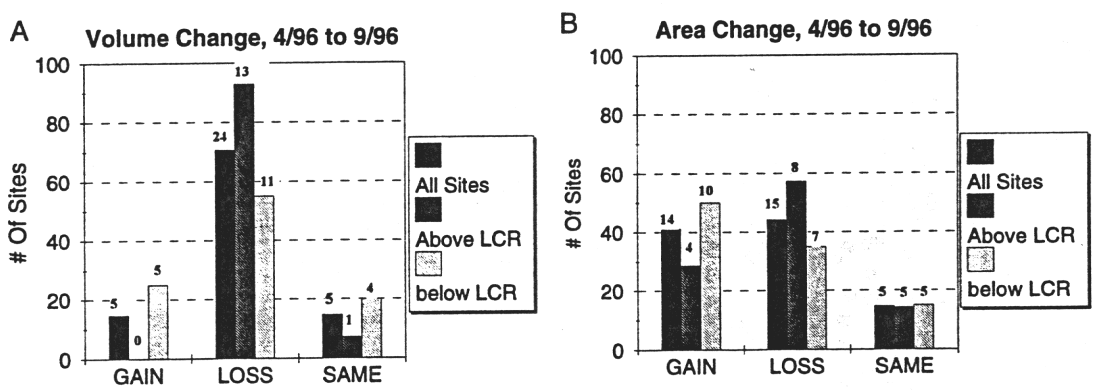


Figure 23. Histograms of site response from April-September, 1996 for A) volume change, and B) Area change.

Eddies. Six months following the test flow, subaqueous deposits in eddies recovered approximately 54,600 m^3 of sediment, close to two-thirds of the volume that was scoured from recirculation zones during the test flow (Table 2). Because there had been no significant tributary input following the test flow (Fig. 5), most of this aggradation must be from upstream eroding bars and channel margin deposits. The NVC indices for this comparison are normally distributed around a system-wide mean of -0.01 (Fig. 24a). A negative mean NVC value indicates that, as eddy systems adjusted to post-test flow dam operations, the average response of eddy systems was to lose sediment. The NVC index distribution indicates that the magnitude of volume change during this period of time was not as large as that measured directly after the test flow (Figs 14b and 24b). Individual site response was the opposite of that attributed to the test flow. Eddies that gained during the test flow lost sediment and showed a negative NVC index. Conversely, eddy

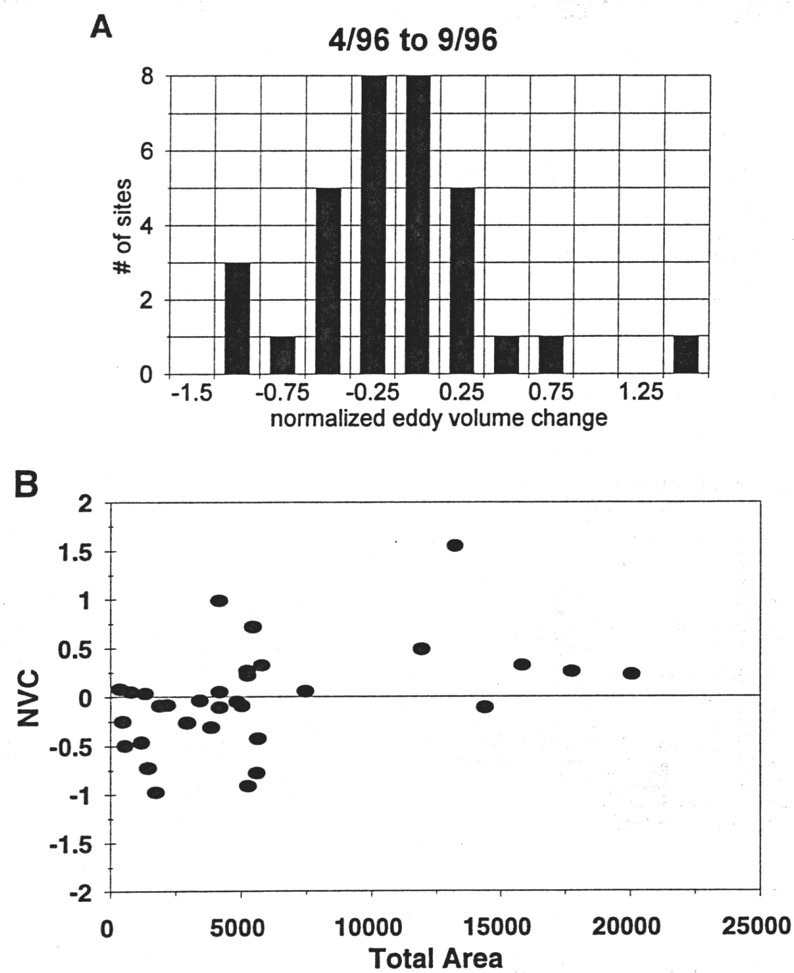


Figure 23. Normalized recirculation zone index (NVC) comparison between 4/96- 9/96. A) Histogram of NVC distribution. B) NVC index versus eddy size.

systems that lost sediment, mainly large eddy systems, generally showed a positive index that reflects the efficiency of the larger eddy systems in trapping and storing sediment (Fig. 24b). The contrast between these NVC distributions suggests that the antecedent condition of the eddy system plays an important role in determining where scour, or fill will occur following high flow events.

An isopach map from the RM 51 fan-eddy complex shows the typical pattern of sediment redistribution at complexes in wide reaches of the river after six months of dam operations (Fig. 24). Deposition was focused on the submerged, upstream portion of the reattachment bar platform and along the floor of the main channel, both of which were scoured during the test flow. As much as 7 m of sand was deposited in the center of a smaller recirculation zone, a total of 21,400 m^3 of new sediment (Table 2). A space existed in this eddy because -14,400 m^3 of sediment was scoured from the upstream area during the test flow (Table 2). A 4 m thick portion of the bar was eroded at the downstream end, the area of reattaching flow of the larger eddy that existed during the test flow and the site of most greatest sediment accumulation during the release. At this site and others, new return-current channels formed along the shore-side bank of the eddy system in front of the eroding bar platform (Figs. 10 and 16).

Main Channel Bed. Volume measurements of channel bed topography indicate that the total mass of sand stored in pools remained nearly the same or was less than that observed directly after the test flow (Table 2). The volume of sand stored on the bed was an average of 5% lower than the 16% decrease that resulted from the test flow. However, volume measurements at individual pools and cross-channel profiles show that several fan-eddy complexes did accumulate sediment on the main-channel bed (Figs. 17 and 21). At these fan-eddy complexes the main-channel thalweg was deeply scoured during the test flow and partial recovery of these sites is possibly a result of greater capacity for sand storage. Other sites were possibly ineffective at retaining sediment in the 6 months following the test flow because bed shear stresses were sufficient to pass sediment through without deposition under normal dam operations (Wiele et al., 1996). Despite accumulation at individual study sites, the total amount of sediment in storage on the channel bed did not increase because of continued, system-wide depletion from the channel bottom. Until significant tributary additions of sediment, it is likely that the channel will remain in a scoured condition. Sediment eroding from bars and channel margin deposits was either redistributed within adjacent eddies or was in transport by the mainstem and trapped by downstream eddies. When sediment concentrations in the main-stem are low, such as after the test flow, deposition rates in eddies are higher than deposition rates in the main channel.

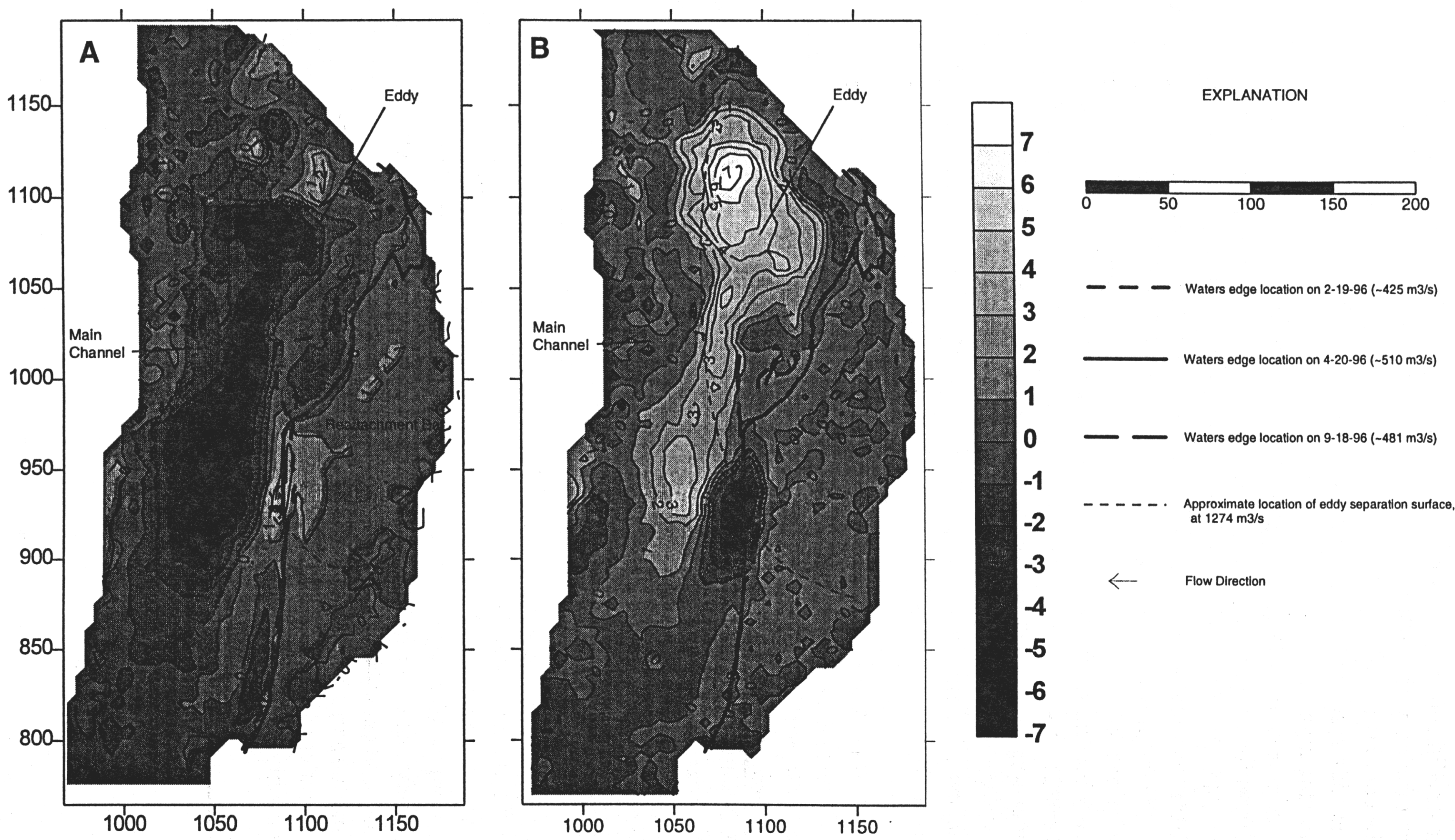


Figure 24. Isopach map of the fan-eddy complex at RM 51. Comparison of the February 19 and April 20, 1996 surveys in A, and the April 20 and September 18, 1996 surveys in B. Scale of erosion and deposition in meters.

Lateral Area Change Using Photogrammetry

Measurements of area change were acquired from two separate series of rectified images (Fig. 25). Because area measurements are sensitive to stage fluctuation, each image series was collected during a similar discharge regime. The first series was collected during constant 227 m^3/s (8,000 ft^3/s) flows on March 26, April 8, September 1, and a weekend low flow of the same discharge on October 19, 1996. The second series was collected throughout the summer months when discharges averaged 481 m^3/s (17,000 ft^3/s), but ranged from 476m^3/s to 495m^3/s (16,808 ft^3/s to 17,479 ft^3/s). Lateral change in area from the second series were determined at each site to test the hypothesis that erosion rates decline with time after a high flow event. An outline of the rectification schedule and average % change is shown in Table 4.

Test Flow Effects

Comparison of pre- and post-test flow images taken during the 227 m^3/s (8,000 ft^3/s) constant flows document the changes immediately preceding and immediately following the test flow (also see Appendix A). These measurements agree well with the changes documented by the topographic surface models. Both the rectified images and computations of area from the topographic models show that bar area increased an average of 7% because of test flow-related deposition (Figs. 6 and 25). The rectified images also show that area increases occurred throughout the system (Fig. 26), but variability increased in a downstream direction (Figure 27). Sand bars in the Marble Canyon reach, between Lee's Ferry and the LCR, increased an average of 18%, while sites below the LCR increased an average of 2% (Fig. 27). Differences in site response was also correlated with bar type (Fig. 28). Separation bars showed a small average increase in area of 3% and reattachment bars an average increase of 7%.

Table 4. Percent Area change measured from daily photography relative to first measured area

Analysis Interval	Discharge	% Change
March 26 - April 8	227 m^3/s	+7
April 10 - April 18	~481 m^3/s	-2
April 10 - May 1	~481 m^3/s	-6
April 10 - May 15	~481 m^3/s	-2
April 10 - June 18	~481 m^3/s	-2
April 10 - July 4	~481 m^3/s	-4
April 10 - July 13	~481 m^3/s	-10
March 26 - September 1	227 m^3/s	+9
March 26 - October 19	227 m^3/s	+8

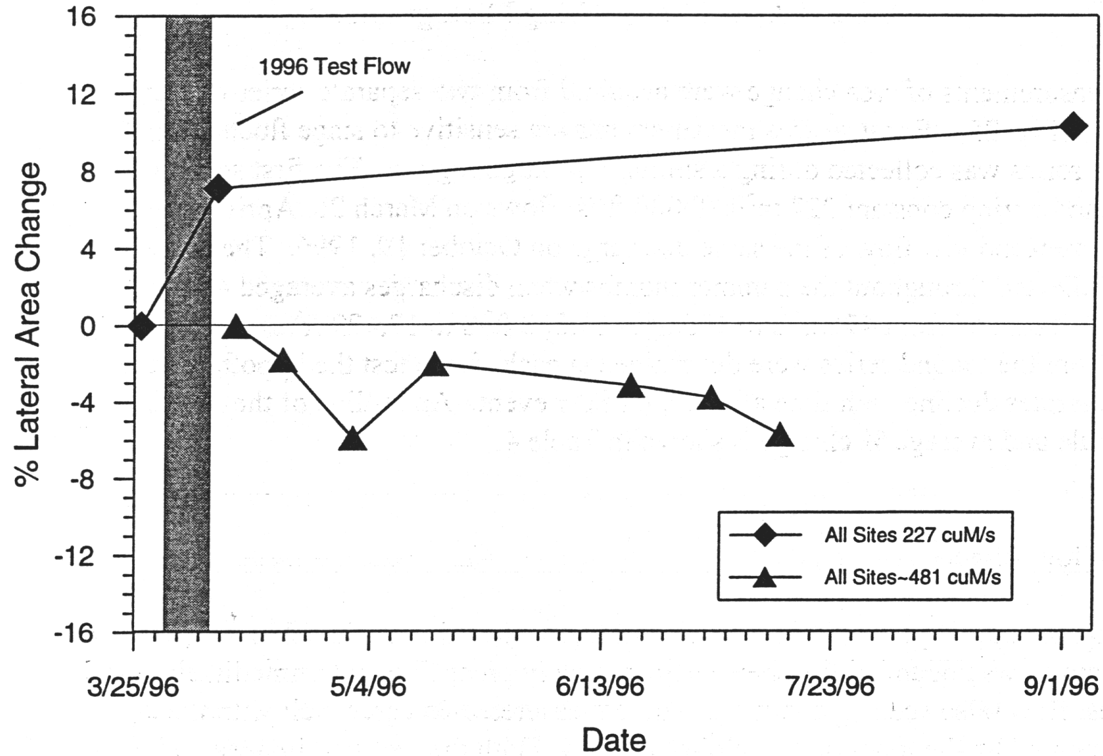


Figure 25. Normalized average % lateral area change for all sites.

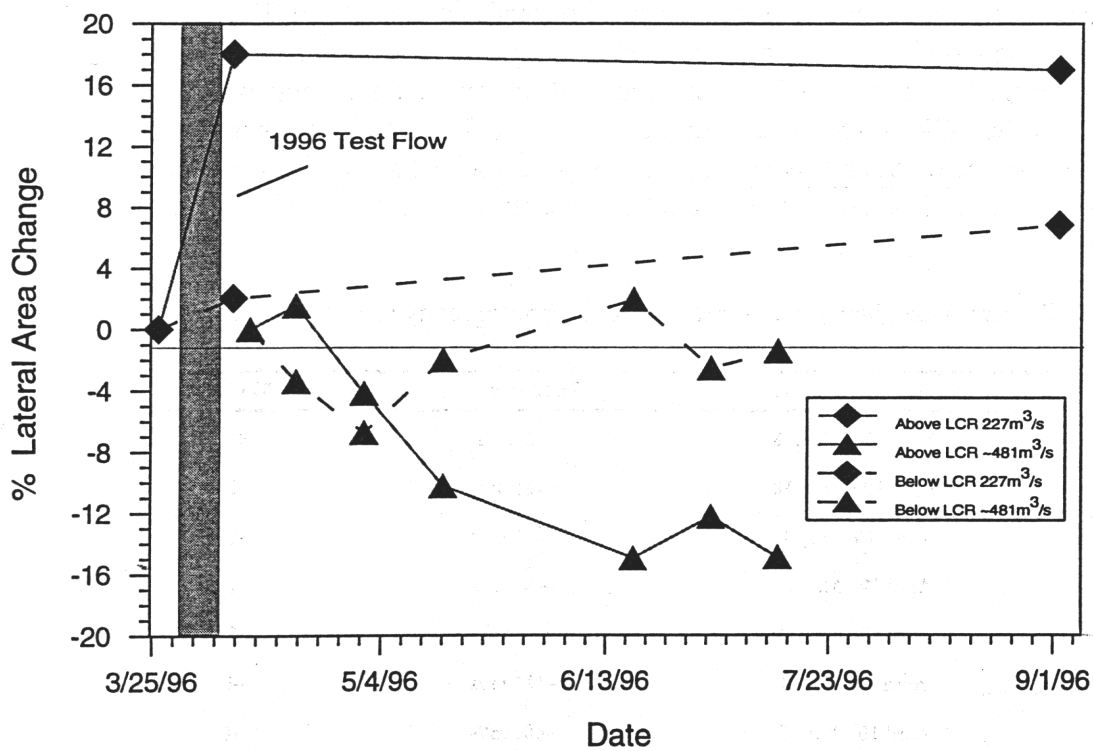


Figure 26. % area change upstream and downstream from the confluence with the Little Colorado River (RM 60).

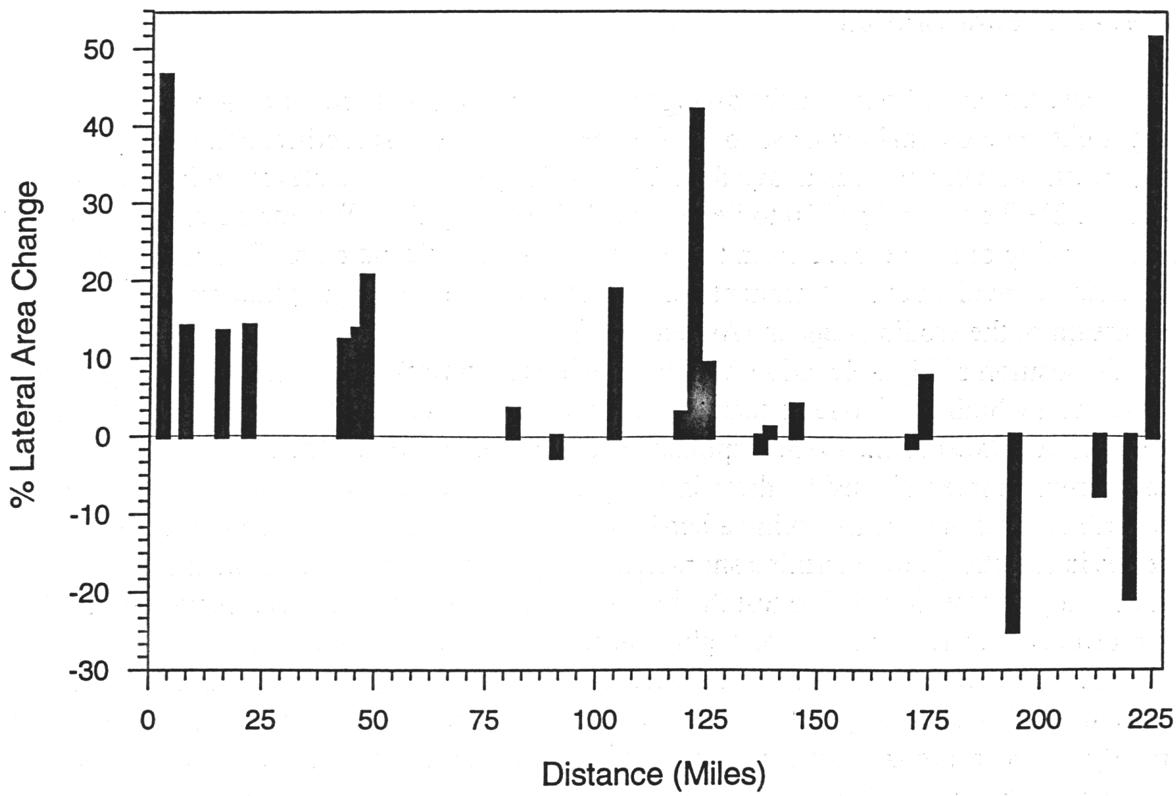


Figure 27. Pre - Post test flow % area change versus distance downstream from Lee's Ferry, Az..

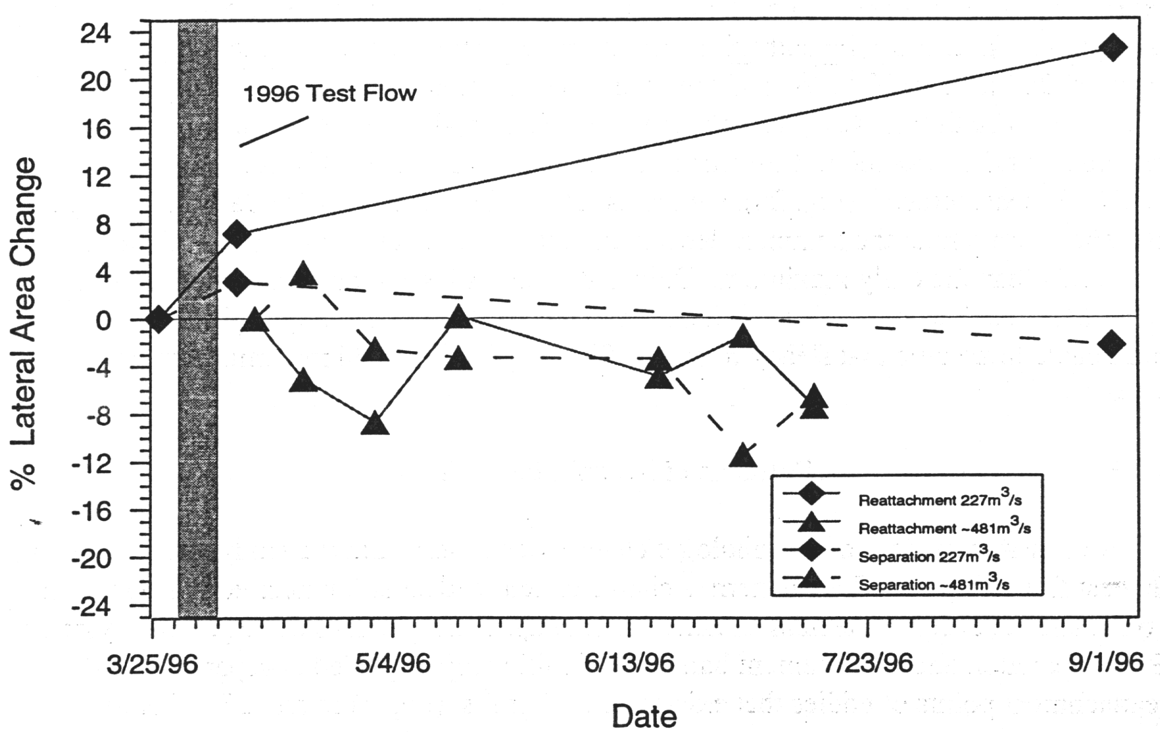


Figure 28. % area change at reattachment and separation bars following the test flow.

Post -Test Flow Erosion

Measurements of bar area following the test flow from both rectification series highlight the erosional response to GCD operations. The first rectification series shows that reattachment bar areas above the 227 m^3/s (8,000 ft^3/s) stage elevation increased from 7% to 22%, between April 10 to September 1, 1996 (Fig. 28). We attribute this area gain to reworking of sand eroded from the higher elevations of sand bars. This reworking was particularly evident at reattachment bars where lower elevation bar platforms aggraded upstream of the eroding deposit (Appendix A).

Deposition of high-elevation sand by previous high flow events in Grand Canyon was followed by high erosion rates that declined with time (Beus et al., 1995; Schmidt and Graf, 1990; Hazel et al., 1993; Kaplinski et al., 1994). However, the annual to biannual measurement interval used by these investigations did not lead to a definitive statement regarding erosion rates following a bar-building event. We used the second rectification series in an attempt to determine short-term erosion rates during the summer months following the test flow and to test the hypothesis that erosion rates decline with time. Unfortunately, site response was highly variable and determination of erosion rates between rectifications proved to be statistically insignificant (Fig. 29). Therefore, we were unable to test the hypothesis using oblique photography. The methods used to rectify and measure area could not discriminate short-term, smaller-scale change because of high uncertainty in determining the exact discharge at the time each image was taken (because of fluctuating flows) and errors in the rectification technique.

However, because the photographs provide a valuable daily visual record at each site, several trends were identified as the sand bars adjusted to the post-test flow GCD releases (Appendix A). Erosion by cutbank retreat began immediately after cessation of the constant 227 m^3/s (8,000 ft^3/s) and the return to dam releases that peaked daily to as high as 556 m^3/s (20,000 ft^3/s). Sites between Lee's Ferry and the LCR degraded rapidly in the months following the test flow and decreased an average of 14% between the April 10 - July 13 measurements (Fig. 26). Cutbanks retreated at the maximum daily flow stage elevation throughout the summer. However, cutbank retreat was not observed during flows less than the daily maximum. Daily fluctuations lessen the duration of erosion by cutbank retreat because active erosion mainly occurs during the daily high. It is reasonable to assume that steady releases of long duration would maximize erosion.

Patterns of Morphologic Change

A consistent pattern of morphologic change was observed at the study sites following the test flow (Fig. 30). This pattern is characterized by deposition near eddy stagnation points and scouring of the main channel and the upstream portions of large eddy systems. Both separation and reattachment bars were significantly aggraded at separation and reattachment points of eddies that existed at 1,274 m^3/s. (Figs. 11a and 28). Return-

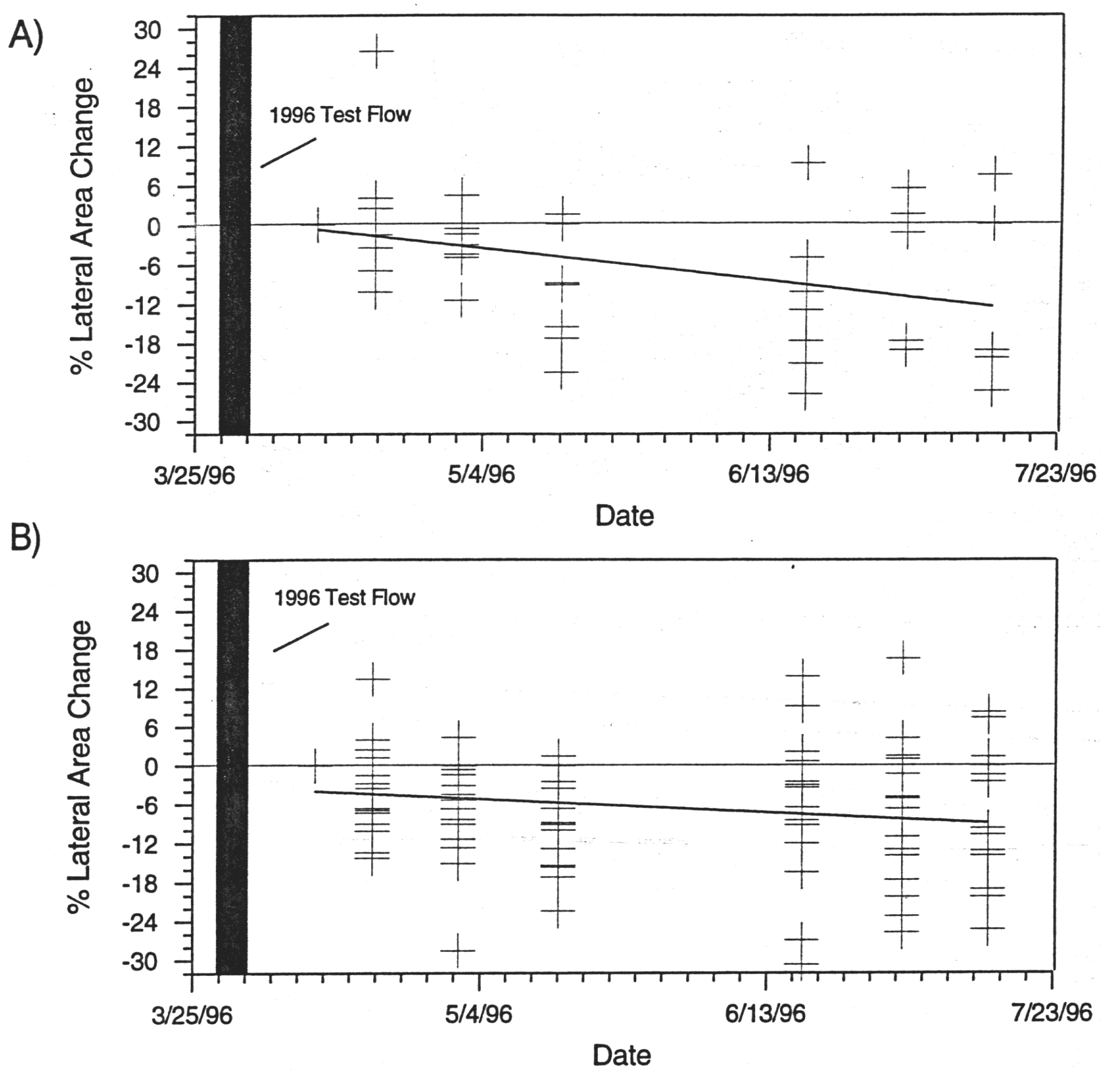


Figure 29. Photogrammetric area measurements from the second series of rectifications. A) 8 sites located in the Lees Ferry-LCR reach. B) 14 sites located in the LCR-RM 225 reach.

current channels that existed prior to the test flow were aggraded rather than scoured or remained unchanged.

This discussion focuses on reattachment bars because this bar type is an important resource in Grand Canyon, providing habitats for native and non-native, subadult fish species (Valdez and Ryel, 1995), surfaces for riparian vegetation establishment, and areas for marsh and wetlands development (Stevens et al., 1995). When bar platforms become emergent at low flows, recirculating flow in the eddy is blocked and the return-current channel forms the largest and most common type of backwater in Grand Canyon. Backwater habitats have decreased in size and number in Grand Canyon (McGuinn-Robbins, 1995) because of bar erosion and return channel in-filling during Interim Operating Criteria (Kaplinski et al., 1995).

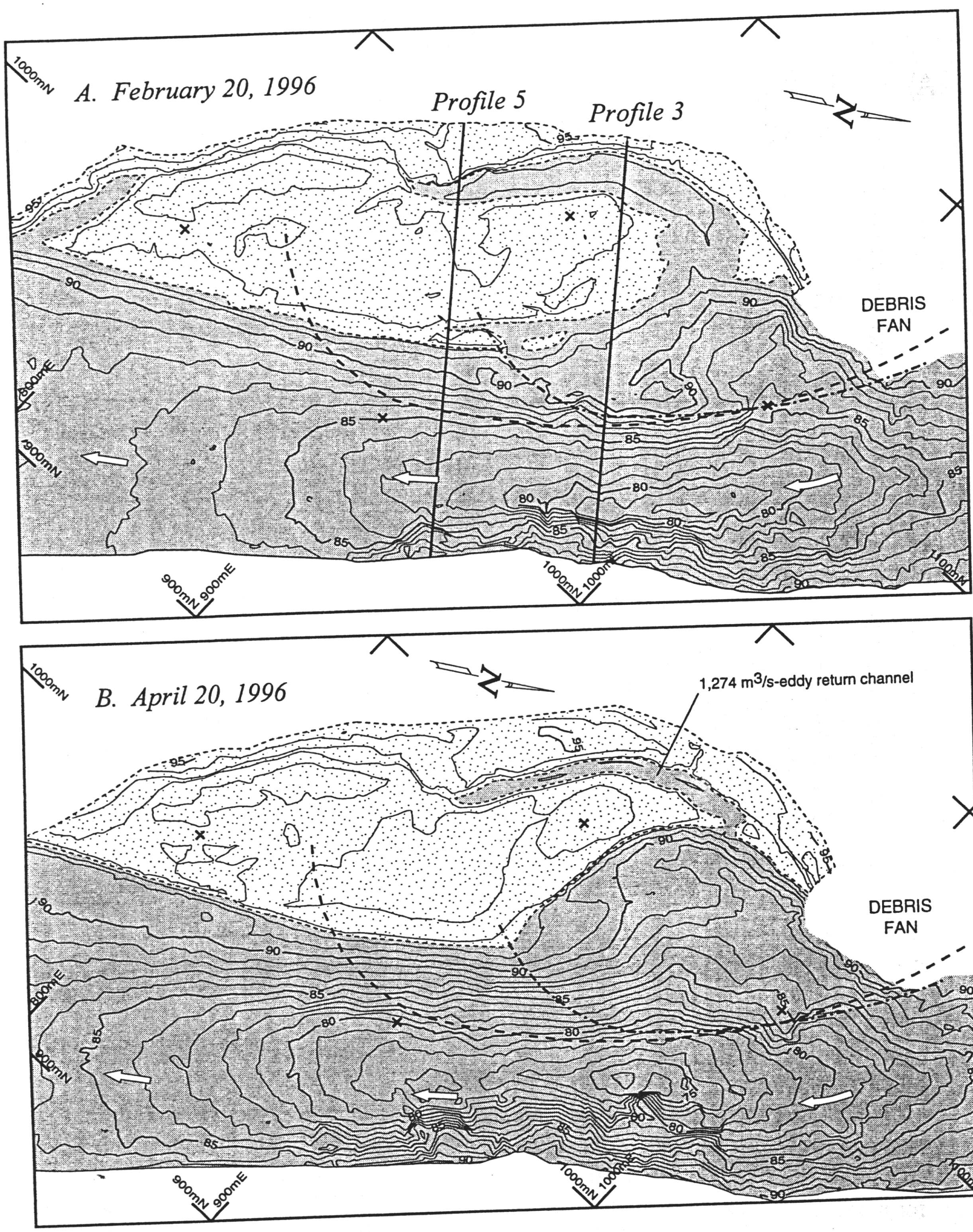
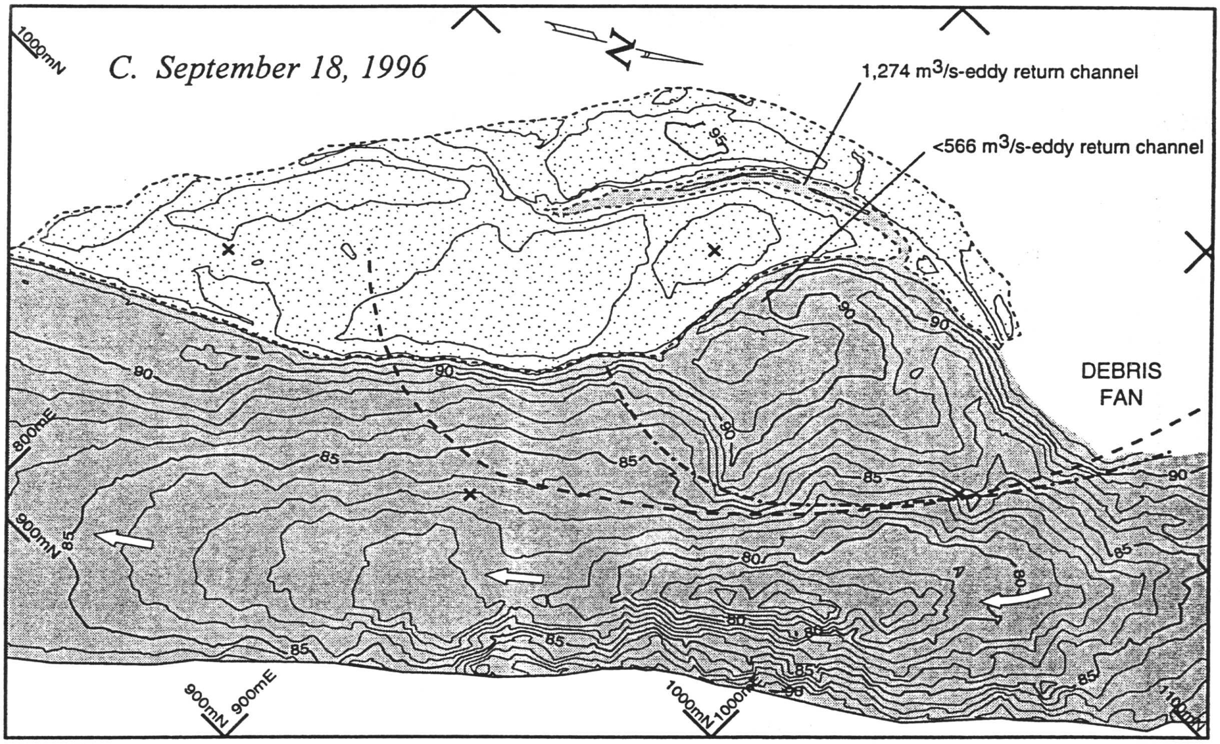


Figure 30. Topographic maps from the RM55 Kwagunt Marsh fan-eddy complex. A, February 20, 1996. B, April 20, 1996. C, September 18, 1996. Note the water surface elevation is 283 m^3/s (10,000 ft^3/s) on each map. Grid interval is 100 m. Locations of profiles in Figs. 10 and 16 are shown in A.



EXPLANATION

(dotted pattern)	Reattachment bar	——85——	Topographic contour. Elevations based on an arbitrary local datum. 1 meter interval
(shaded pattern)	Water Surface at 283 m^3/s (10,000 ft^3/s	-·-·-·-·-·-	Approximate location of separation surface, 566 m^3/s (20,000 ft^3/s)
⇦	Direction of main current	- - - - - - -	Approximate location of separation surface, 1,274 m^3/s (45,000 ft^3/s)

Figure 30.--Continued.

The Kwagunt Marsh (RM 55) fan-eddy complex is used here as a site-specific example of the typical pattern of change observed at large reattachment bars. Topographic maps are shown in Fig. 30 and an isopach map of the change between the pre- and post-test flow surveys is shown in Fig. 31. As much as 10 m of sediment was scoured from a main channel depression just downstream from the channel constricting debris fan (Figs. 16, 30 and 31). The volume of sediment scoured from the main channel was approximately 54,900 m^3 (Table 2). Deposition of 4,684 m^3 of sediment on the bar platform resulted in a 39% increase in bar volume above the 142 m^3/s stage elevation. However, the plan area of subaerially exposed bar decreased by 15%. Decrease in bar area resulted from scour of approximately 18,800 m^3 of sediment from the bar platform in the upstream part of the eddy. The NVC index at this site was -0.80 and indicates a net loss of sand from this recirculation zone (Fig. 14), similiar to the response of other fan-eddy complexes from the Lower Marble Canyon geomorphic reach (Table 2).

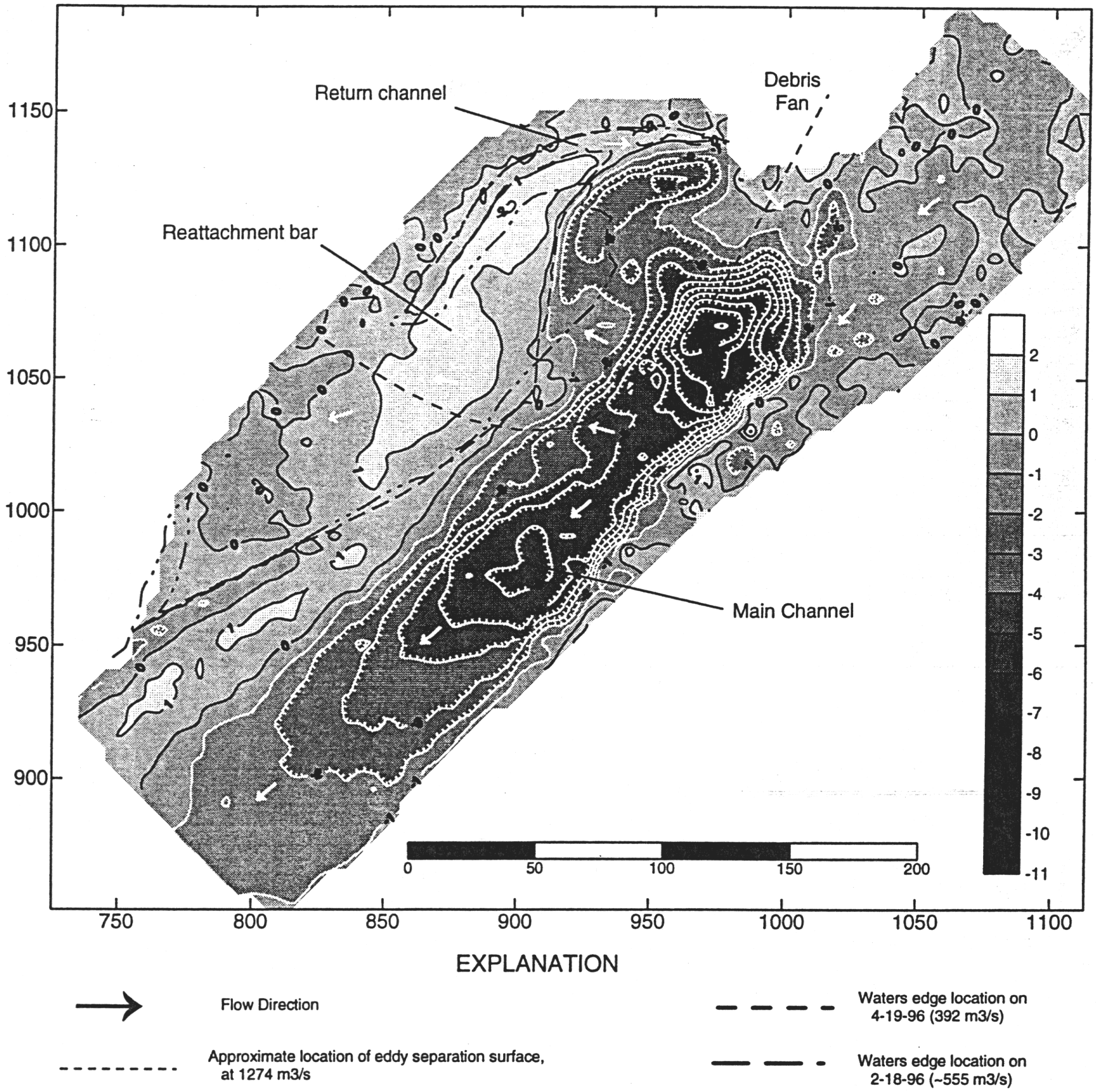


Figure 31. Isopach map of the Kwagunt Marsh (55R) fan-eddy complex constructed from the 2-18-96 and 4-19-96 surveys. Note the bed scour in the upstream portion of the eddy. Distance bar scale and scale of erosion and deposition in m.

Topographic maps and cross-channel profiles indicate that as the bar platform was aggraded with 1 to 2 m of sediment, in the vicinity of the reattachment point of the primary eddy, the bar migrated bankward and partially filled the existing return-current channel (Figs. 11, 16, and 30). Thus, the width of the return channel was decreased by progradation of the bar into the deeper parts of the channel and depth was shallowed by deposition on the bottom. The stage-discharge relation at this site indicates that flows will need to be in excess of 1,132 m^3/s (40,000ft^3/s) in order to inundate the bar. The return channel is effectively cutoff from the primary eddy when flows are lower than 283 m^3/s (10,000 ft^3/s) because of sediment deposited in the bottom and at the mouth (Fig. 31c). Between these two discharge levels water enters into the channel from the mouth and the return channel is potentially a useable backwater for native fish (Bureau of Reclamation, 1995).

A test flow hypothesis was that high flow events could rejuvenate backwater habitats (Bureau of Reclamation, 1996). Rejuvenation of backwater habitat is a function of scouring and reshaping return-current channels combined with dam releases that partially inundate reattachment bar platforms. These results show that return current channels were reshaped by deposition, not scouring (Figs. 10 and 17). Scouring was only evident in the deeper, upstream portions of eddies (Figs. 10, 15, 16, 24, and 31). The creation of new bars with return current channels may have temporarily increased the number of backwaters in the system (Ralston, 1996), but the examples in this report demonstrate that the size of backwaters that existed at the onset of Interim Operating Criteria was not increased.

History of Sediment Storage Changes from 1991 to 1996

Sandbar Deposition and Erosion

Comparing the results of the 1996 test flow with measurements made during the 5 years of Interim Operating Criteria highlights the importance flood flows in the long-term maintenance of sand bars (Fig. 32). Kaplinski et al. (1995) and Hazel et al. (1996) demonstrated that the reduced flow fluctuation and limited peak daily flow of Interim Operating Criteria decreased both sand bar area and volume. After implementation of Interim Operating Criteria and prior to the test flow only one tributary event resupplied sediment to eddies. This occurred during three closely-spaced tributary floods from the Little Colorado River in January and February, 1993 (Fig. 3). Sand bars downstream from the LCR aggraded 1-2 m above the maximum stage elevation reached by Interim Operating Criteria. Erosion rates were initially high but declined with time (Hazel et al., 1993; Kaplinksi et al., 1994). A temporary gain in storage lasted for about a year (Fig. 32). Sand bars located upstream from the LCR in Marble Canyon were not influenced by these flow events. However, the annual sand contribution from the Paria River in 1993 was the highest in over a decade and erosion rates demonstrated a short-term decrease (Fig. 5). Despite tributary contributions of sand and the limitations imposed by Interim Operating Criteria, the volume of high elevation sand stored in bars (above the 410 m^3/s stage elevation) decreased at a system-wide rate of 5 to 7% per year during five years of Interim Criteria monitoring (Fig. 32). However, the 1996 test flow resulted in system-wide deposition of high elevation sand. The volume of sand stored in bars above the 410 m^3/s stage elevation increased an average of 165% (Figs. 12b and 32).

To test the null hypothesis that there would be no net change in the size of eddy sand bars following the test flow, we tested the volume and area dataset using the nonparametric, Friedman test with multiple comparisons (Gibbons, 1985). The Friedman

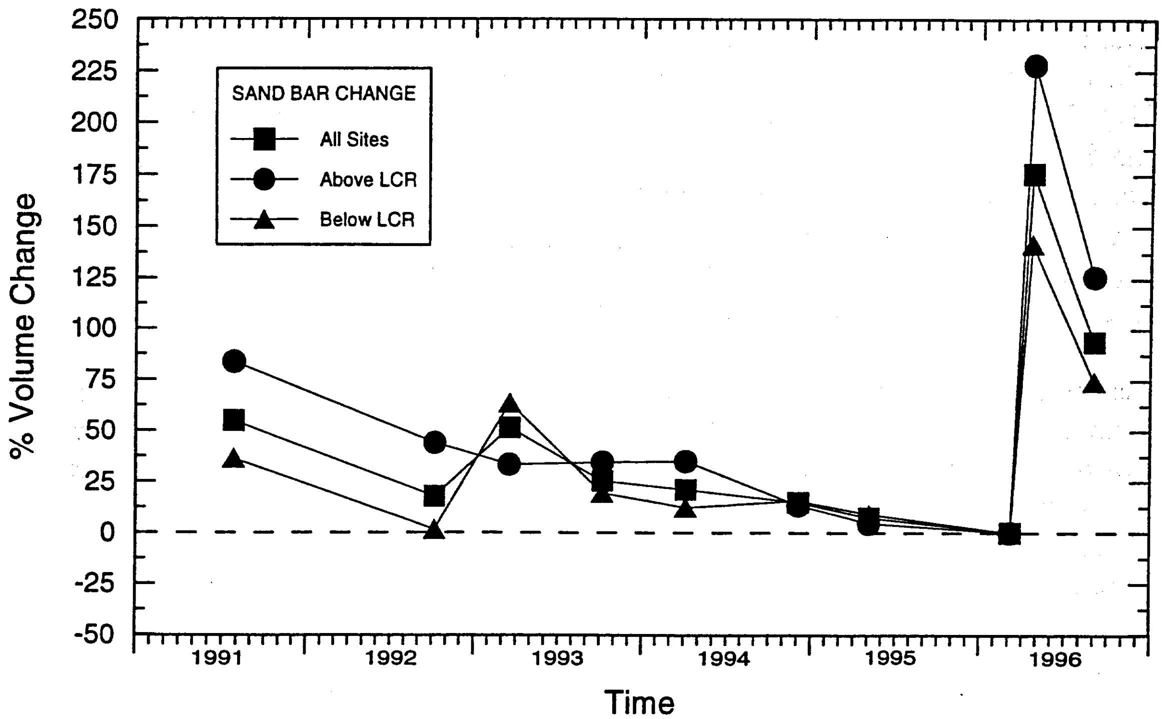


Figure 32. Averaged percent change in the upper sand bar volume zone (above the 410 m^3/s (14,500 ft^3/s) stage elevation) relative to values measured in February/March, 1996.

test does not accept null values. Therefore, sites with missing values were dropped and we tested all survey runs between 1991-1996 (9 treatments) with a total of twenty-three sites. Volume and areas were tested separately. For the volume comparison, the test statistic was S=36.31, which equates to a p value of 0.0001; therefore, we rejected the null hypothesis and concluded that there was a net change in sand bar volume between the survey runs. Next, the multiple comparison procedure was used to determine which survey runs were significantly different (Gibbons, 1985). For an overall level of 0.05 and a critical value Z=3.21, the differences between rank sums greater than or equal to 60.9 are considered significant. We found that the only significant difference between volume rank sums occurred between surveys conducted before (2/96) and after the test flow (4/96). Therefore, we conclude that the test flow significantly increased the sand volume of Colorado River sand bars. Repeating this test using measured and bar area, the test statistic S=12.53, equates to a high p value of 0.130. Therefore, we must accept the null hypothesis that there was no significant change in the area of Colorado River sand bars due to the 1996 test flow. Significant volume gains without a corresponding area increase shows that sand bars following the test flow were higher, not wider.

Sand bars were still higher six months after the test flow. Sand bar volumes measured in September, 1996, show that the upper sand bar volumes were still approximately 97% larger than before the test flow and 42% larger than volumes measured in 1991 (Fig. 32). Erosion rates of the upper bar volume zone averaged approximately 13% during the six months following the test flow. Under normal GCD operating criteria, these erosion rates would be expected to decrease with time (Beus et al., 1985; Schmidt and Graf, 1990;

Hazel et al., 1993; Kaplinski et al., 1994). However, we predict that erosion rates will not decrease in Water Year 1997 (Oct. 1, 1996- Sept. 30, 1997) due to the combination of several weeks of emergency high flows (680-765 m^3/s (24,000-27,000 ft^3/s)) in February and March and probable high steady releases at or near 566 m^3/s (20,000 ft^3/s) the remainder of the water year due to reservoir filling.

Main Channel Sand Accumulation and Transport

The cumulative storage of sand for two reaches of the Colorado River between 1990-1997 is shown in Figs. 33a and 34a. These budgets are calculated under the assumption that sand transport is only dependent on river discharge and does not change with tributary supply or the amount of sand stored within the channel (T. Randle, USBOR, written communication, 1997). While this assumption is known to be false, the sand-transport equations are still useful to compute a relative sand budget for which field values of sand stored within pools and eddies can be compared.

The total range in the volume of sand stored in the river between 1990-1997 was about 1.6 x 10^6 Mg and 9 x 10^6 Mg for the Marble Canyon (Lees Ferry-LCR) and Lees Ferry-Phantom Ranch reaches, respectively (Fig. 1). There was little accumulation during the GCES Phase II experimental discharge test flow program conducted between June, 1990-July, 1991. In an effort to retain tributary-derived sediment, flows were modified to Interim Operating Criteria (low, monthly-adjusted discharges of 142 to 566 m^3/s; Fig. 3) on August 1, 1991 (Bureau of Reclamation, 1995). Following this change in flow regime the daily mean discharge at the USGS streamflow-gaging station, Colorado River near Grand Canyon (09402500), excluding the 1996 test flow, was 356 m^3/s. The daily range in discharge was typically between about 100 and 200 m^3/s. As a result, cumulative sediment storage gradually increased in 1992. In 1993 there was large tributary inflow (Fig. 5). An estimated 4.7 x 10^6 Mg of sand-sized sediment was delivered to the mainstem Colorado River by the LCR from January 1-April 1, 1993. The Paria River supplied an estimated 1 x 10^6 Mg during this same period.

Between April, 1993-1995, a period of low tributary inflow, there was little accumulation because the reduced sand-transport capacity of Interim Operating Criteria resulted in a balance between transport and sand supply (Figs. 33a and 34a). Storage increased during the winter of 1995 because of flooding from both the Paria River and the LCR (Fig. 5). However, a substantial decline in sand storage occurred between June-October, 1995 due to unusually high reservoir releases (nearly steady 566 m^3/s), the 1996 test flow, and because of high releases following the 1996 test flow (mean daily flow of 17,000 m^3/s from April-July, 1996). In the Marble Canyon reach this sequence of discharges removed two-thirds of the mass of sediment that had previously accumulated as a result of Interim Operating Criteria. The Lees Ferry-Phantom Ranch reach was not impacted as greatly and one-fourth of the accumulated sediment was transported out of the reach. However, the calculated amounts transported in the sand mass-balance model (Figs. 33a and 34b) may vastly underestimate actual transport and most of the sediment

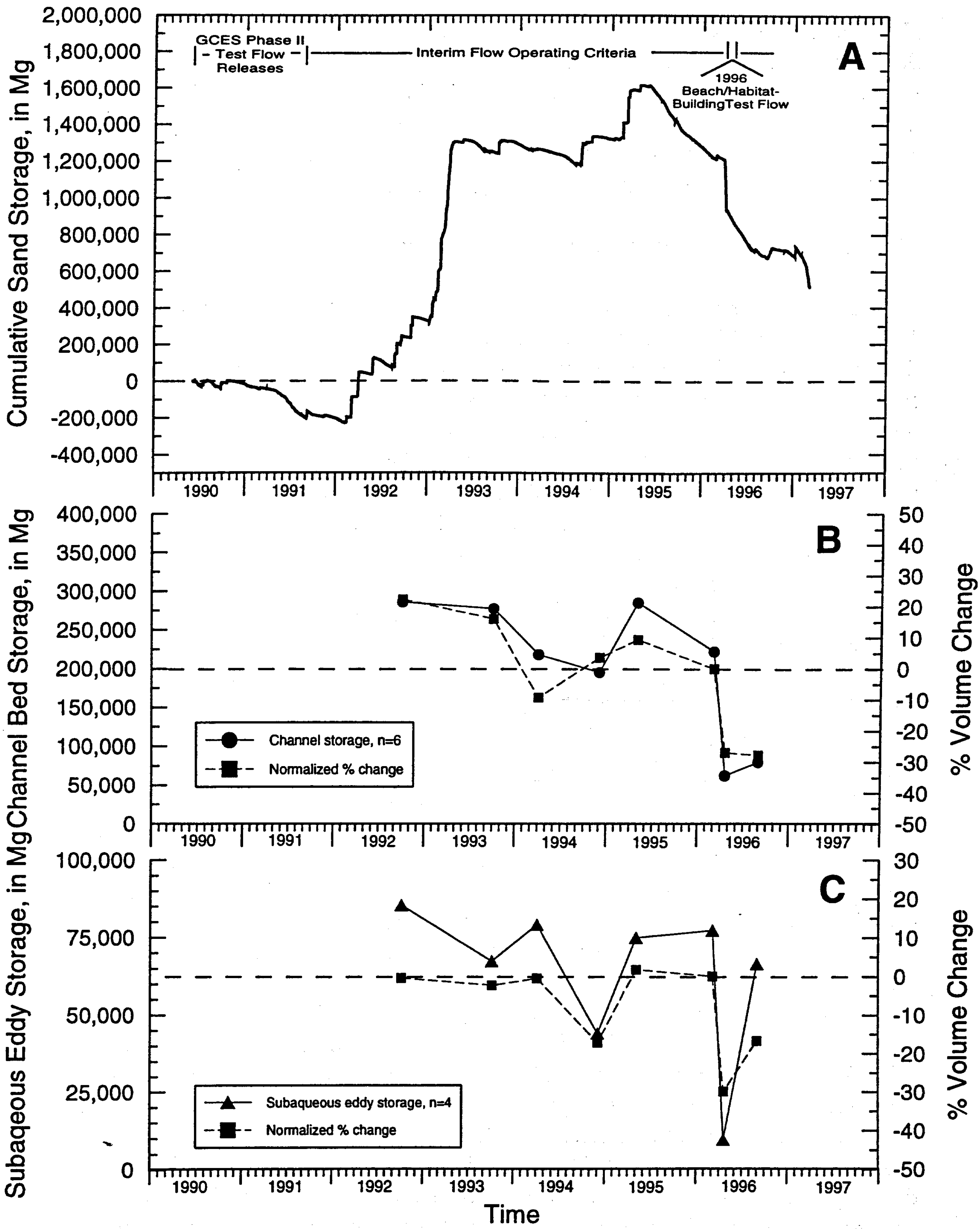


Figure 33. Cumulative sediment storage between the USGS streamflow-gaging stations at Lees Ferry (RM 0) and above the LCR (RM 60) between 1990-1997. A) sand mass-balance model, and measured sediment storage below the 142 m^3/s (5,000 ft^3/s) stage elevation from the B) main channel, and C) eddy systems.

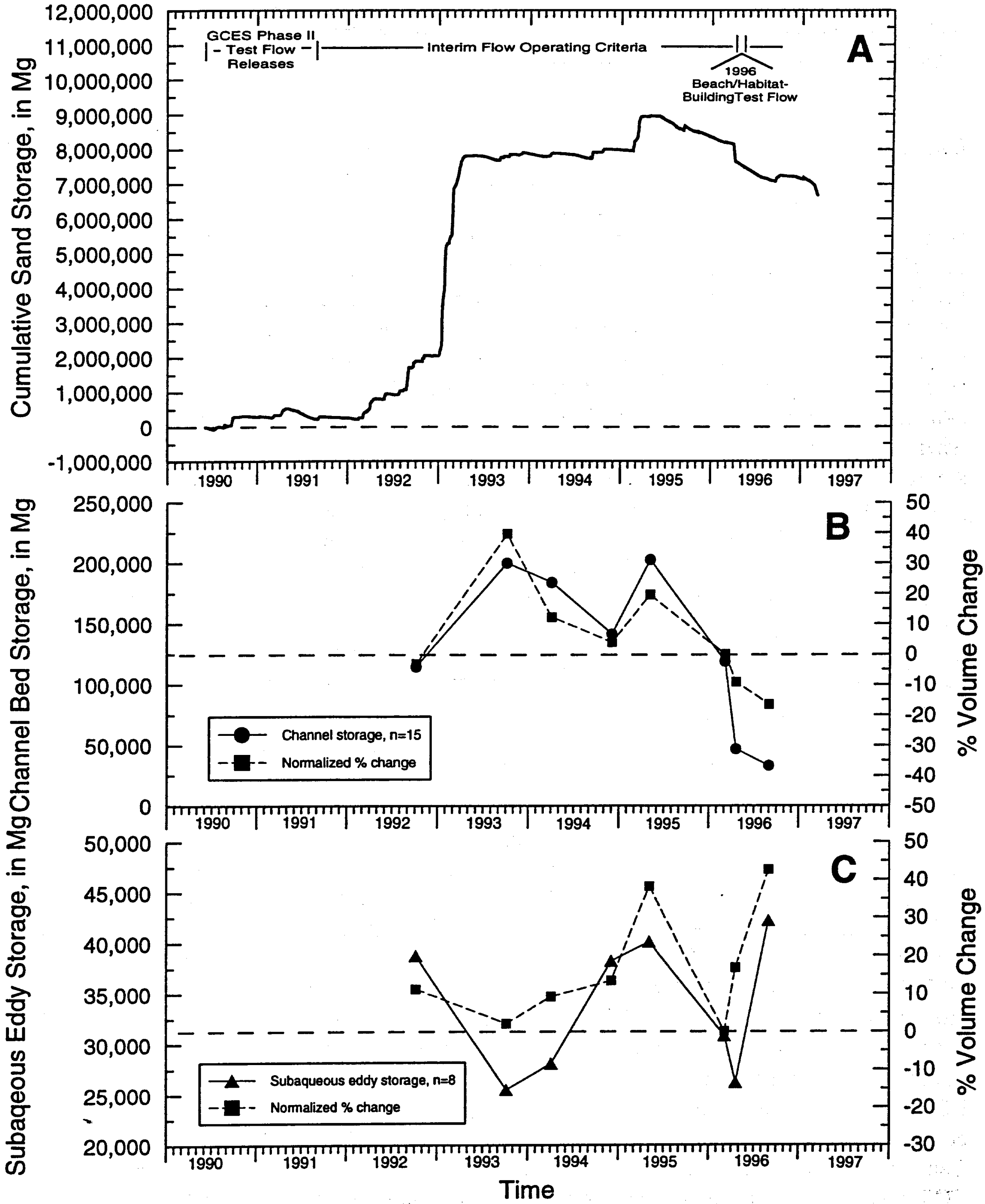


Figure 34. Cumulative sediment storage between USGS streamflow-gaging stations at Lees Ferry (RM 0) and near Grand Canyon (RM 87). A) sand mass-balance model, and measured sediment storage below the 142 m^3/s (5,000 ft^3/s) stage elevation from the B) main channel, and C) eddy systems.

that had accumulated following the high flows between 1983-1986 was removed (D. Topping, USGS, personal communication).

Channel and Eddy Bed Response

The measured pattern of main channel and eddy sediment storage at selected study sites, between 1992 and 1997, is shown in Figs. 33b,c and 34b,c. Survey coverage was sufficient during this time interval to examine sediment volume on the channel and eddy bed below the 141 m^3/s (5,000 ft^3/s) stage elevation at 21 and 12 sites, respectively. A similar pattern of sand volume increase and decrease in the average channel and eddy storage is evident in both Marble Canyon (Fig. 33b) and between the LCR and RM 225 (Fig. 34b). Comparison with the sand mass-balance model for each reach (Figs. 33a and 34a) suggests that when annual sand inputs from the Paria River and LCR are low or even when the sand load appears to be in balance with tributary supply, main channel bed storage declined during Interim Operating Criteria. For example, despite an apparent 2 year balance (1993-1995) between transport capacity and annual tributary sand input in the model, main-channel stored sand declined by 13% in Marble Canyon (Fig. 33b) and 36% between the LCR and RM 225 (Fig. 34b). The higher rate of decline downstream from the LCR confluence is attributed to removal of the 1993 LCR sand from channel storage. The LCR sand delivery was detected as far downstream as 49 km (30 mi) from the LCR confluence in April 1993 (Hazel et al., 1993; Kaplinski et al., 1995). Subaqueous eddy storage declined by 15% in Marble Canyon (Fig. 33c) but increased 11.3% between the LCR and RM 225 (Fig. 34c). The disparity in eddy storage between the two reaches is attributed to transport of the 1993 LCR sand and trapping in downstream eddies.

Cumulative storage in the sand budget increased in 1995 due to Paria River and LCR sand inputs the preceding winter (Figs. 33a and 34a). There was a corresponding main channel storage increase of 6% in Marble Canyon and 16% between the LCR-225. An increase in subaqueous eddy storage also corresponded to the tributary sand input (19% in Marble Canyon and 24.8% between the LCR and RM 225). However, the nearly constant 566 m^3/s (20,000 ft^3/s) flows from June-October, 1995 resulted in a 9.4% and 19.7% decrease in main channel sand storage for the two respective reaches. High releases in 1995 also decreased eddy sand volume downstream from the LCR by 38%, but Marble Canyon changed little. Prior to the 1996 test flow, main channel sand surplus in Marble Canyon had decreased by 22.4 % from 1992-1996 (Fig. 33b). Between the LCR-RM 225, however, main channel sand storage was about the same as the 1992 condition (Fig. 34b). Subaqueous eddy storage prior to the 1996 test flow in Marble Canyon was about the same as the 1992 condition but had declined by 11% between the LCR-RM 225. In comparison, subaerially exposed sand bars continued to erode regardless of reach between 1992-1996 (Fig. 32).

The 1996 test flow decreased the remaining channel sand storage in Marble Canyon by 27% and between the LCR-RM 225 by 9%. Eddy sand storage was reduced by 30% but increased by 17% in the same respective reaches. At the close of Water Year 1996, 6 months after the test flow, eddies that were scoured during the test flow had recovered over half of the sand lost during the test flow. There had been no significiant tributary input up to this time and most of this aggradation was from upstream eroding bars and channel margin deposits. There was little accumulation (<1%) in main channel storage at this time. Until tributary sand input occurs, sand storage recovery following the test flow was limited to eddies and the main channel remained depleted compared to the pre-test flow condition.

SUMMARY AND CONCLUSIONS

1996 Beach/Habitat-Building Test Flow Objectives

An important objective in the GCD-EIS for conducting beach/habitat building flows was redeposition of high elevation sand (Bureau of Reclamation, 1995). Analyses of topographic survey data, daily photographs, and bar sedimentology show that the 1996 test flow increased the volume of sediment stored in fan-eddy complexes by redistributing stored sediment from the river bed. Deposition occurred system-wide, regardless of geomorphic reach or bar type (Fig. 11a). Sand bar volumes increased by an average of 48% (Fig. 12a). In contrast, sand bar plan area increased only slightly by 7% (Fig. 12a). Volumes from the upper elevations (above the 410 m^3/s elevation contour) of the sand bars increased by 176%. A Friedmann Test of bar volume and area shows that the volume change was significant, while area change was not. The difference between changes in sand bar volume and area indicates that, in general, the test flow resulted in sand bars that were higher, not wider.

The main channel bed at most fan-eddy complexes was scoured (Fig. 11c). We estimate a total loss of approximately 222,000 m^3 of sediment from the main channel at our study sites (Table 2). In comparison, the the cumulative amount deposited on sand bars was approximately 47,000 m^3, about 20% of the amount scoured from the main channel bed (Table 2). The amount and distribution of sand and finer material on the channel bed was a major factor in the success of the test flow in building high elevation sand bars and highlights the importance of antecedent conditions for future high flow events.

The upstream, low elevation areas of large reattachment bars were scoured and supplied a large amount, approximately 82,700 m^3, of sediment during the test flow (Fig. 11b). This source was available because of accumulation at lower bed elevations in eddies during Interim Operating Criteria by deposition on reattachment bars (Kaplinski et al., 1995; Schmidt and Leschin, 1995). There was a strong correlation between eddy size and degree of filling or removal. Despite extensive scour at large eddies, NVC indices at the study sites were normally distributed with a mean of 0.23. The positive mean value indicates that the net system-wide response of fan-eddy complexes was to gain sediment (Fig. 14a). These results agree with a similiar, normally distributed eddy deposition index calculated from reach-scale mapping of bar area using aerial photographs (Schmidt and Leschin, 1996).

erosion of the upstream portions of reattachment bars, decreased the overall area of return-current channels. We conclude that geomorphic rejuvenation of backwaters did not occur at our study sites. Nonetheless, the test flow achieved many of the management objectives outlined in Patten et al. (1994) and in the GCD-EIS (Bureau of Reclamation, 1995). The test flow rebuilt sand bars at higher elevations and restored some of the dynamics of a natural system (Fig. 35).

High elevation sand deposited by the test flow still remained after 6 months of GCD operations. Measured volumes from the upper bar zone were about 97% larger than before the test flow and 42% larger than volumes measured in 1991 (Fig. 32). The upper bar zone area decreased an average of 18 % as cutbanks retreated at the maximum daily flow stage elevation. Erosion rates of the upper bar volume zone averaged approximately 13% during the six months following the test flow but we were not able to determine a monthly or daily rate. It has been suggested that availability of erodible sediment largely determines erosion rates (Schmidt, 1992), however, rates also depend on flow fluctuation, especially the duration of the daily high. Observations of cutbank retreat indicate that steady releases of long duration will maximize erosion.

The total plan area of sand bars above the 141 m^3/s (5,000 ft^3/s) stage elevation did not decrease because sediment eroded from high elevation locations was transferred to lower elevations. Sediment eroding from bars was either redistributed within adjacent eddies or was in transport by the mainstem and trapped by downstream eddies. The main channel volume calculations indicate that the bed remained scoured (Figs. 33b and 34b; Table 2). When sediment concentrations in the main-stem are low, such as after the test flow, deposition rates in eddies are higher than deposition rates in the main channel. The substantial recovery of subaqueous deposits within eddies scoured by the test flow, close to two-thirds of the volume (Figs. 33c and 34c; Table 2), shows that the capacity of eddies to trap sediment during normal flows is much greater than the channel.

Management Implications

The timing of future beach/habitat-building flows will require careful monitoring and management of sand supply and discharge. Occasional discharges exceeding powerplant capacity will be needed because erosion is a pervasive process that has been documented at all discharge regimes, including Interim Operating Criteria (Fig. 32). Erosion of bars will occur even when mass accumulation is occurring in the system (Schmidt 1992). A sufficient sediment supply must be available for future flow releases in order to build bars (Rubin et al., 1994). The success of the 1996 test flow was dependent on the antecedent condition of sediment storage in the system at the time of the flow. If the supply of sediment in Grand Canyon is depleted, then bar-building floods have the potential to be net erosive (Schmidt et al., 1993). In a different canyon river with abundant debris fans, the Snake River in Hells Canyon, Schmidt et al. (1995) demonstrated that a succession of high dam discharges, combined with a lack of tributary sediment supply, caused significant sediment depletion and net scour in eddies.

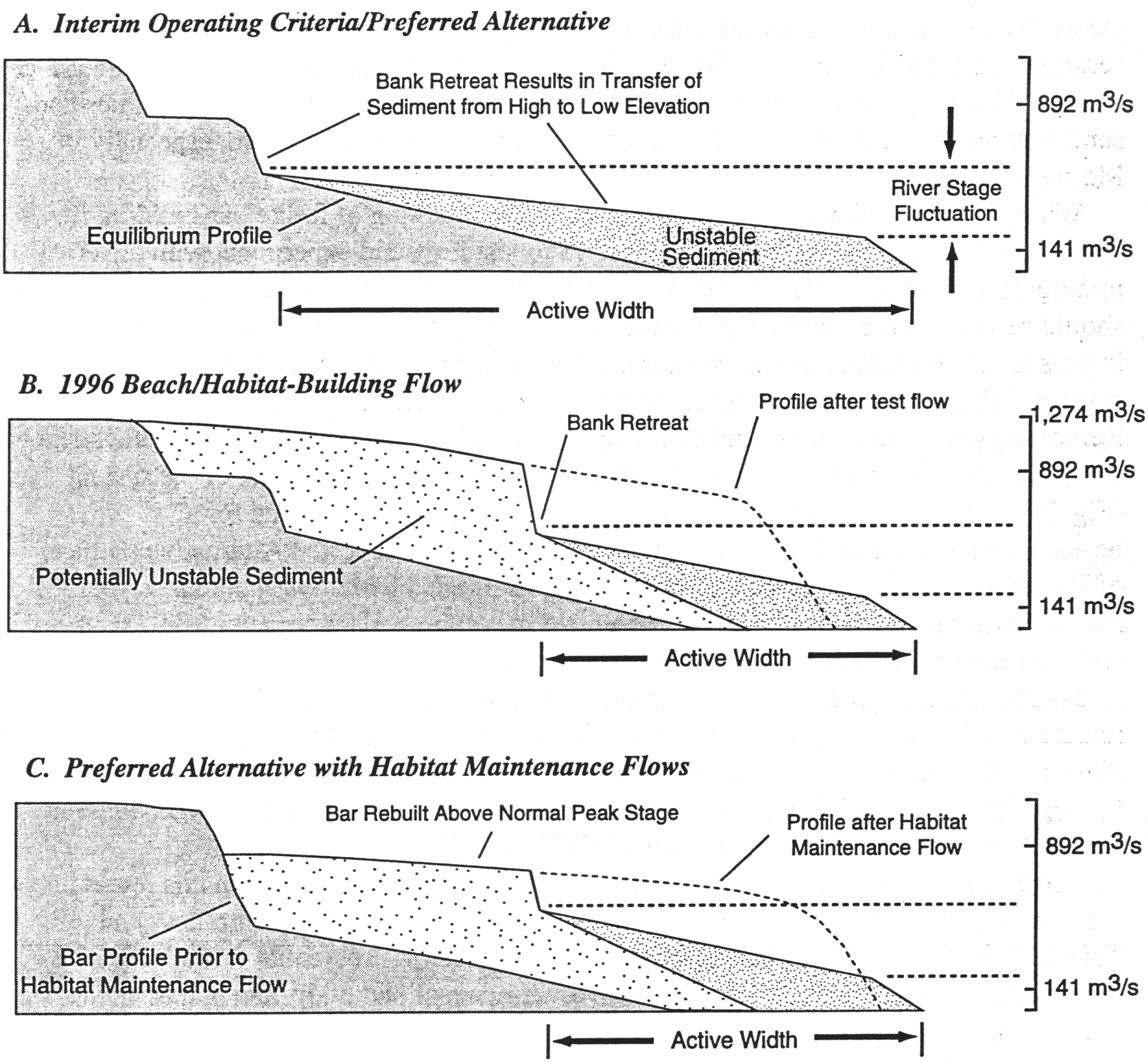


Figure 35. Schematic cross sections of the active width and height of a hypothetical sand bar. In A) Preferred Alternative, B) after the 1996 Beach/Habitat-Building Test Tlow, and C) after a Habitat Maintenance Flow. Both B and C are shown following the return to the Preferred Alternative.

The upward coarsening in grain size within the test flow deposits, described by us and other researchers (D. Rubin, USGS, personal communication, 1997) and suspended-sand measurements taken during the test flow indicate that there was a decrease in sand concentration and increase in median grain size during the course of the experiment (D. Topping, USGS. personal communication, 1997). The depletion of fines from the channel bed and topographic evidence of low bed-elevation in main-channel pools suggests that sand remaining on the bed may not be available for transport except at discharges greater than the 1996 test flow. This is similiar to the situation in the 1980's. High flows in 1983 aggraded sand bars, but because these flows had transported much of the available sediment out of the system, discharges between 1984-1986 deposited little sediment on bars (Rubin et al., 1994). We conclude that the channel at the close of Water Year 1996 is in a sediment-depleted condition. Until tributary sand delivery, eddies and sand bars are the primary storage location of sediment within the system, especially in Marble Canyon.

When it is determined that a sand surplus exists, planning of future bar-building flows should utilize information gained from the 1996 test flow and experiment with different hydrographs in order to maximize the attainment of management objectives. Sand bars should be considered the preferred location for storing sediment because sediment stored in bars is removed from downstream mainstem transport and becomes available for riparian habitat development and recreational camping area (Kaplinki et al., 1995). Removing sediment from mainstem transport maximizes the residence time of sediment at a particular site and minimizes the eventual transport of sediment out of the system (Fig. 35b). Based on existing data, we continue to emphasize the need for a beach/habitat-building flows as included in the GCD-EIS Preferred Alternative (Bureau of Reclamation, 1995). An integrated component of this alternative should be a yearly habitat maintenance flow of short duration at or near powerplant capacity (~892 m^3/s) to replace sediment eroded during the remainder of the year (Fig. 35c). Alternatively, a stair-stepped hydrograph should be considered. This might consist of a short duration release of 1,274 m^3/s or greater, followed by several days of 850 m^3/s to rework bar platforms and result in stable bar morphologies less susceptible to rapid cutbank retreat. Bar-building by a lower magnitude flow might define new return channels that are more in-phase with the Preferred Alternative and increase backwater habitat.

Monitoring the topography of sand bars with the methods described in this report provides an important assessment of the effects of flow events, both high flow and "normal" dam operations, on sand-dependent resources. It is essential that a long-term monitoring program include volumetric measurements of bar, eddy, and main-channel sand storage to assess the impacts of future flows from GCD on the sediment resources of the Colorado River.

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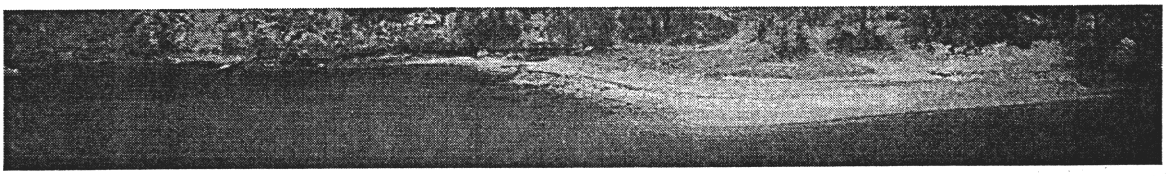
APPENDIX A

Selected Daily Photography Sites With Periodic Image Slices

3 Mile



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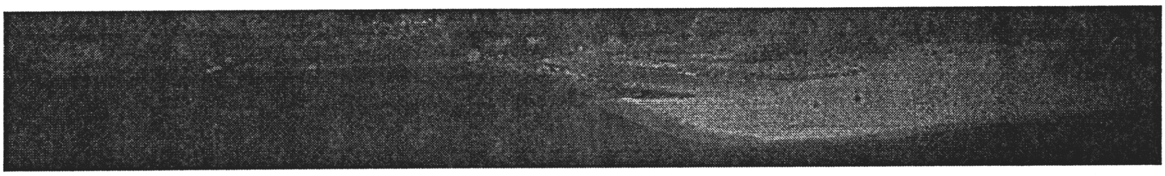

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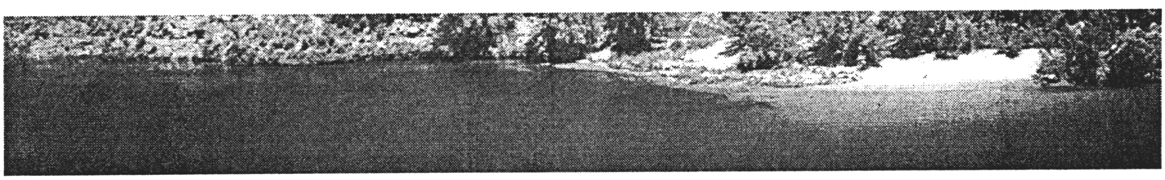

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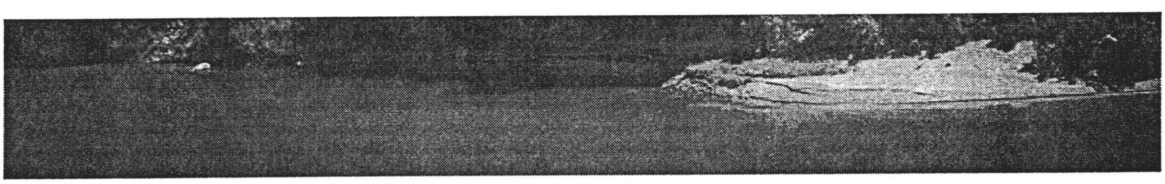

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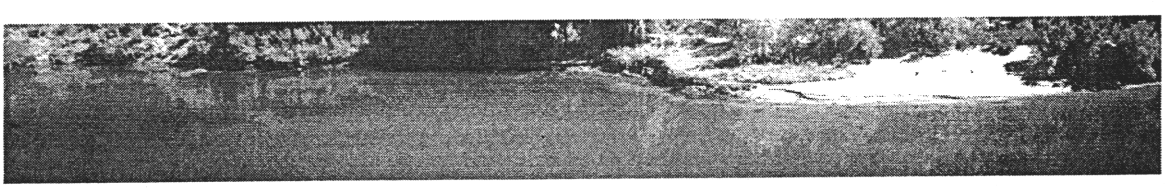
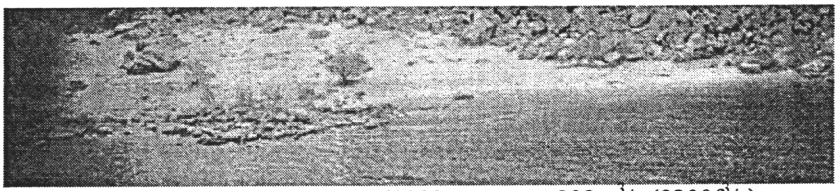


961011 $232m^3/s(8200f^3/s)$

8 Mile



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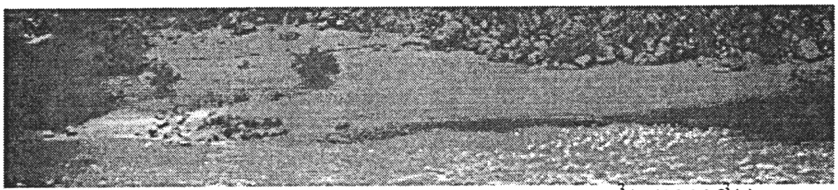

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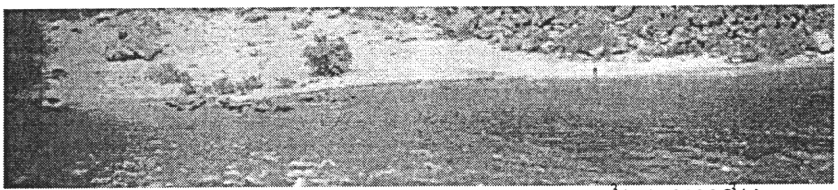

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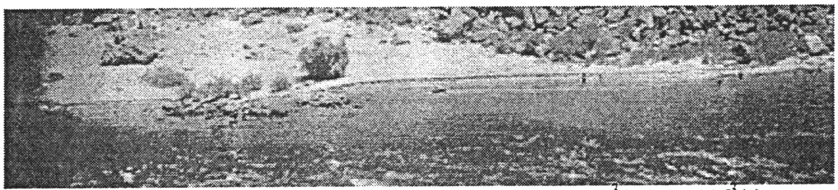

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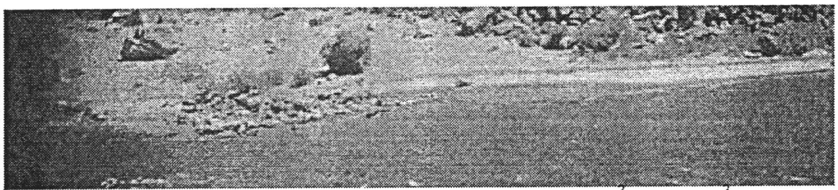

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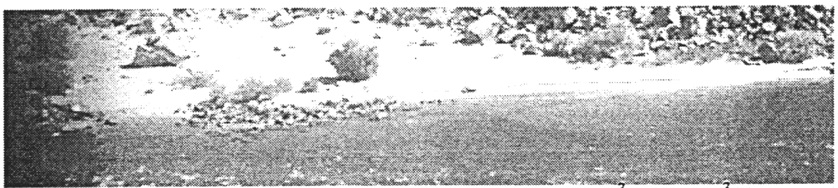

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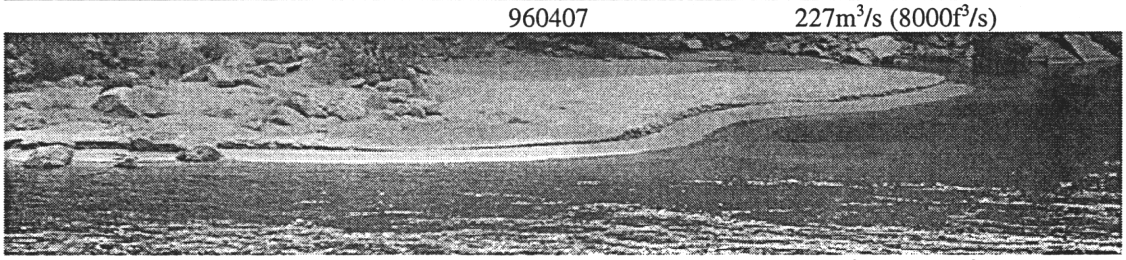
16 Mile

960323 227m³/s (8000f³/s)

960407 227m³/s (8000f³/s)



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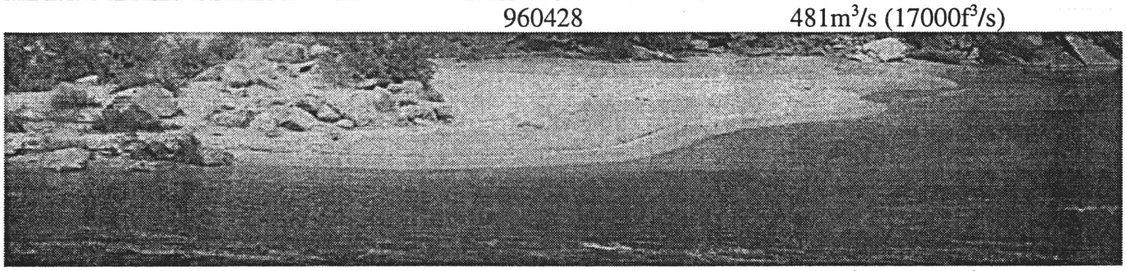

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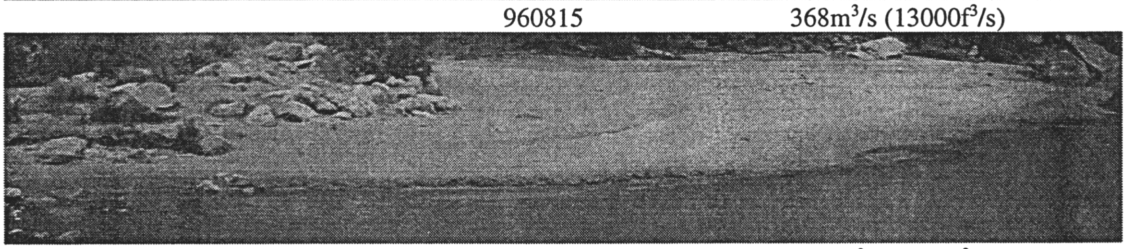

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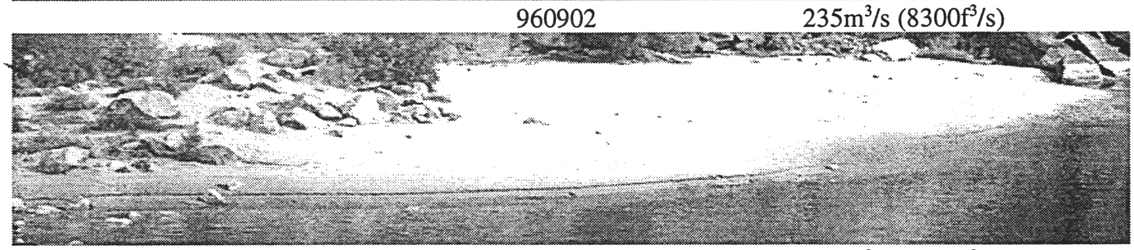

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22 Mile

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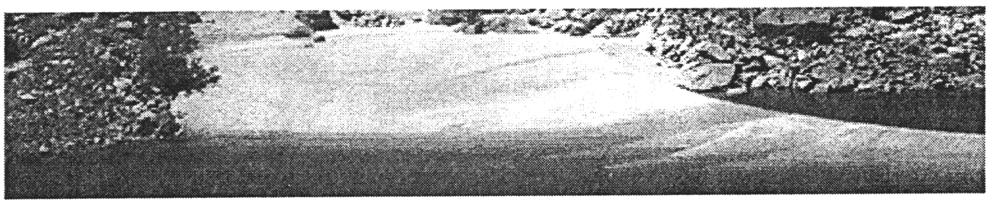

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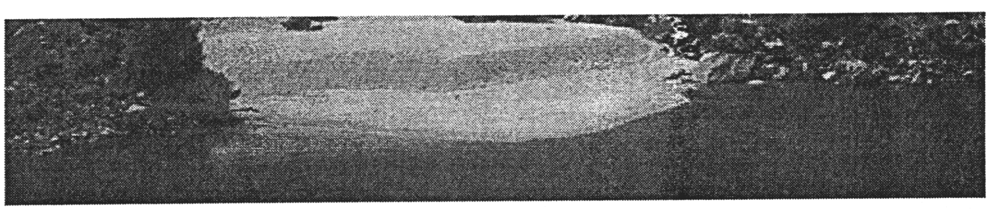

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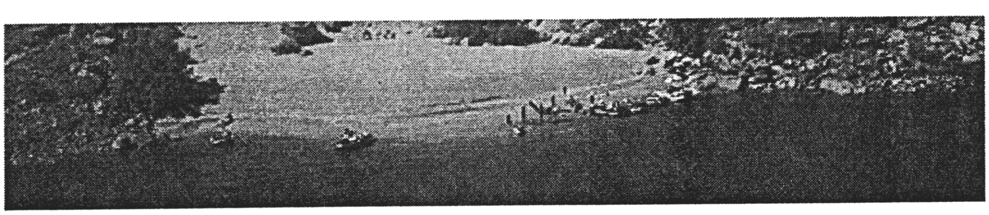
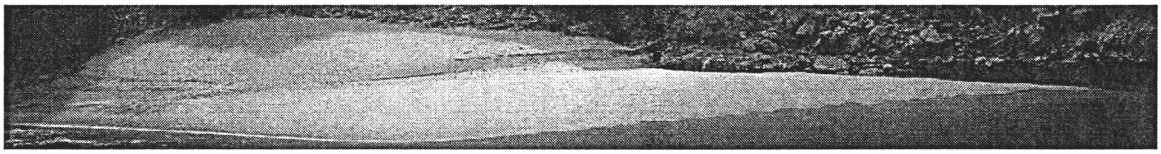


961010 227m^3/s(8000f^3/s)

30 Mile



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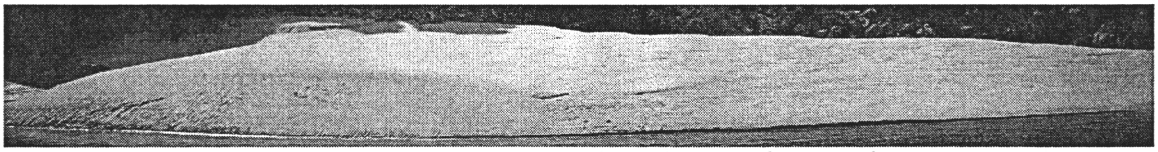

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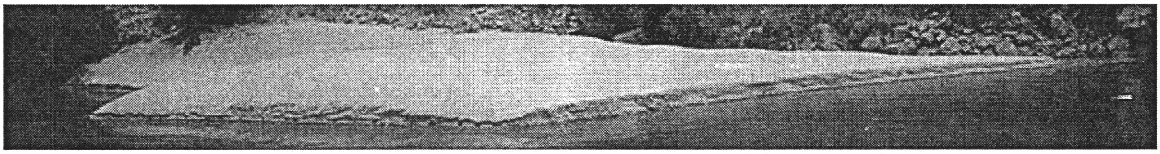

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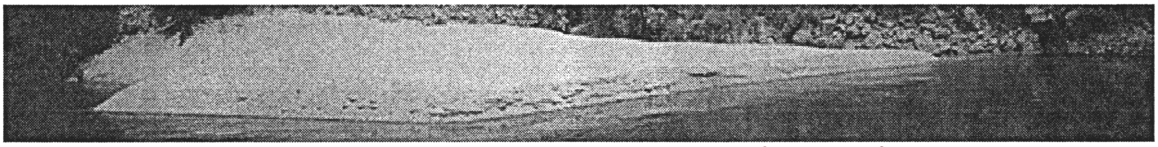

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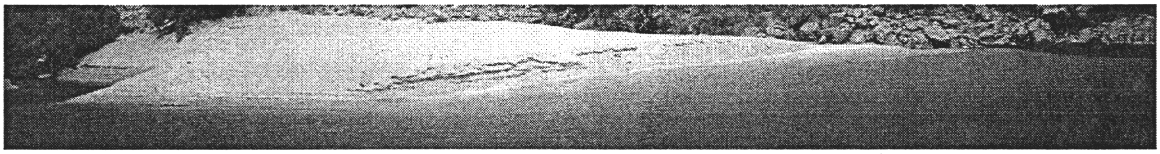

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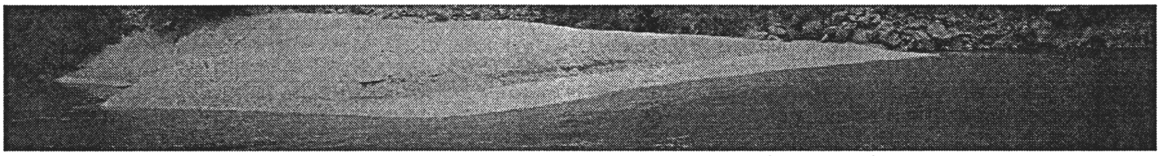

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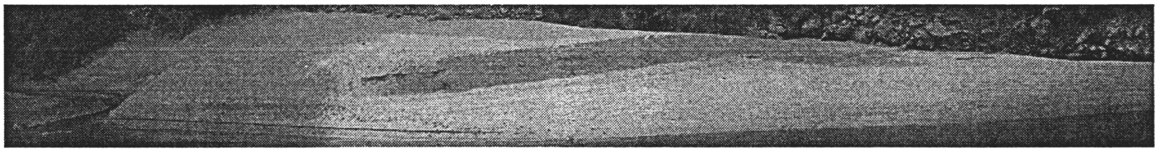

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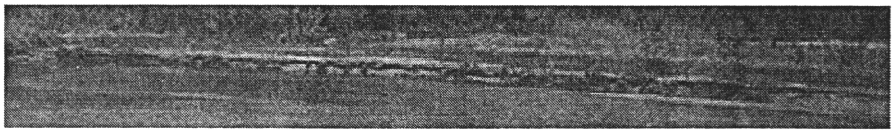
51 Mile



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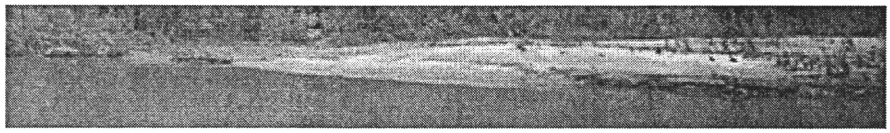

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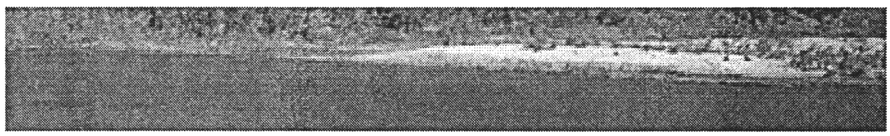

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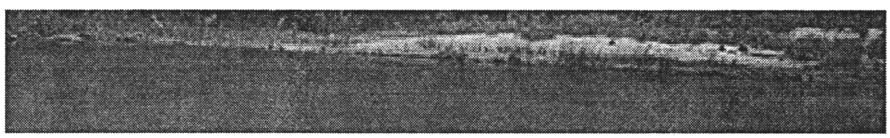

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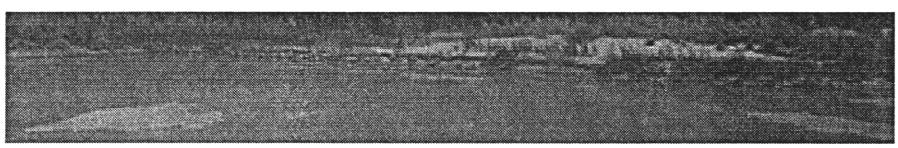

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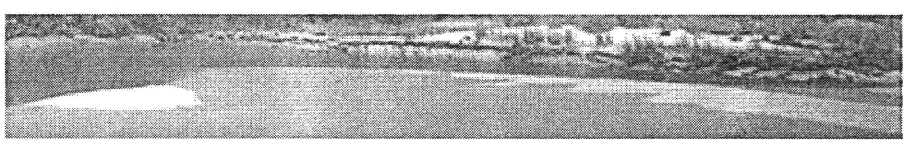
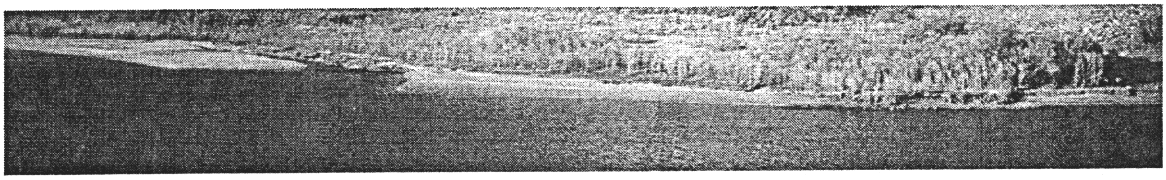
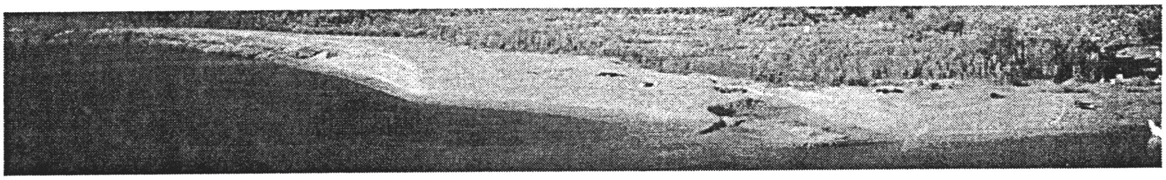


961013 227m³/s (8000f³/s)

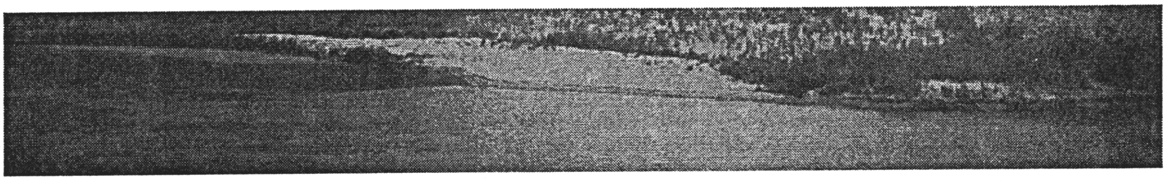
68 Mile



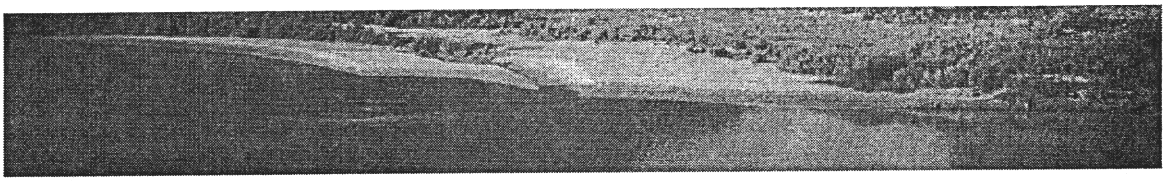
960327 $227m^3/s(8000f^3/s)$



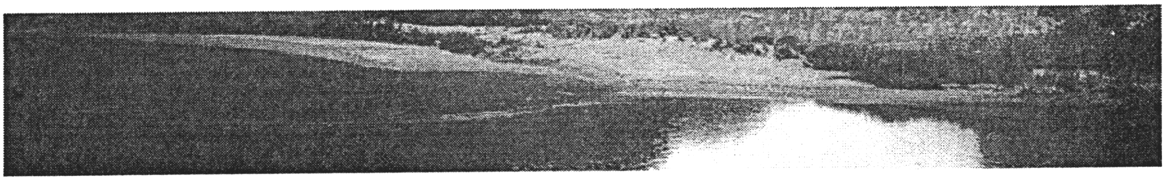
960408 $230m^3/s(8400f^3/s)$



960707 $464m^3/s(16400f^3/s)$

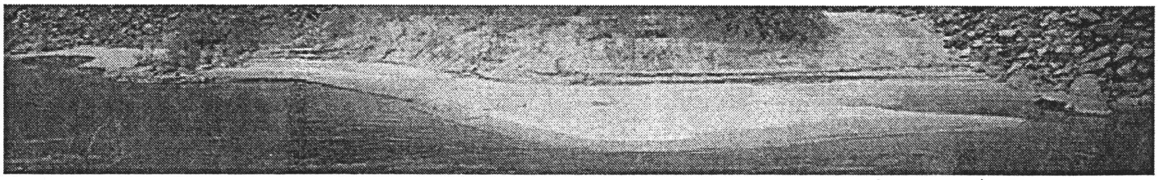


960903 $249m^3/s(8800f^3/s)$

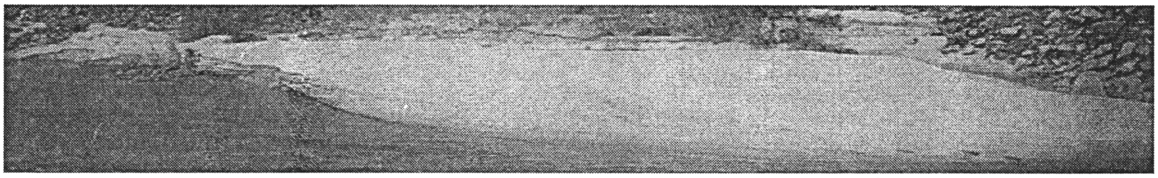


961011 $227m^3/s(8000f^3/s)$

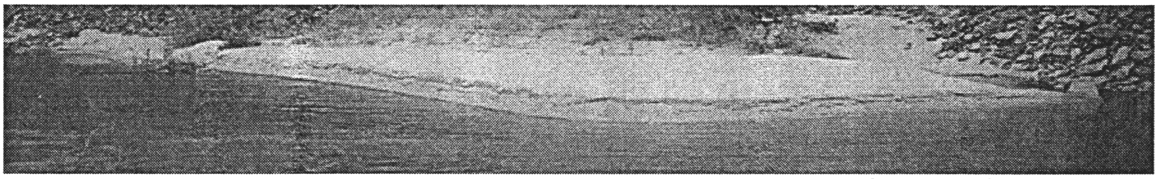
119 Mile



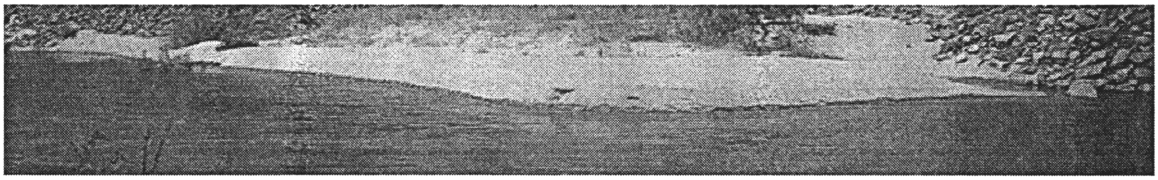
960325 232m³/s (8400f³/s)



960405 232m³/s (8400f³/s)

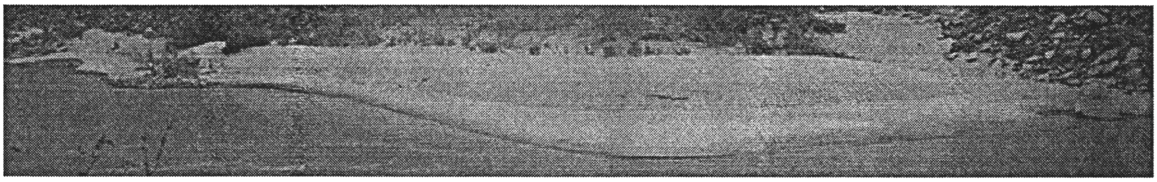


960429 464m³/s (16400f³/s)

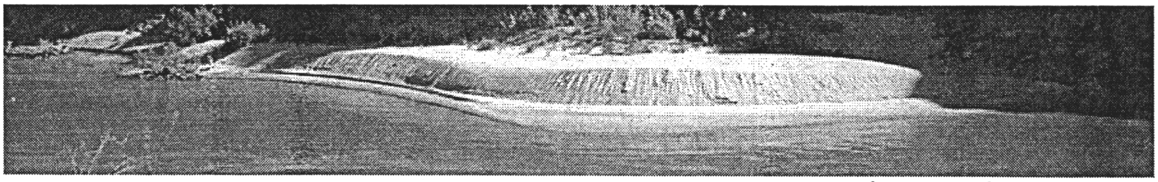


960601 481m³/s (17000f³/s)

960707 464m³/s (16400f³/s)

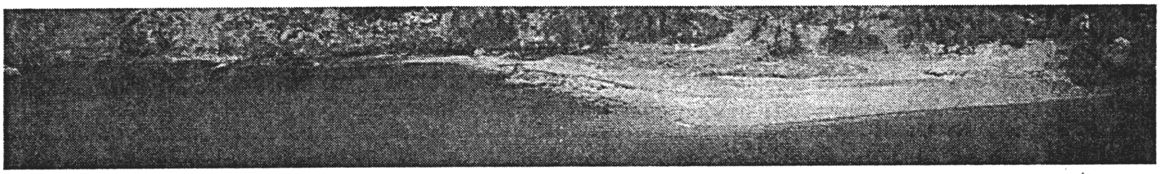


960903 249m³/s (8800f³/s)

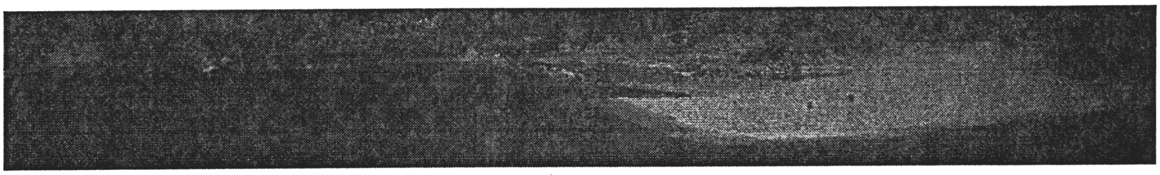


961011 283m³/s (10000f³/s)

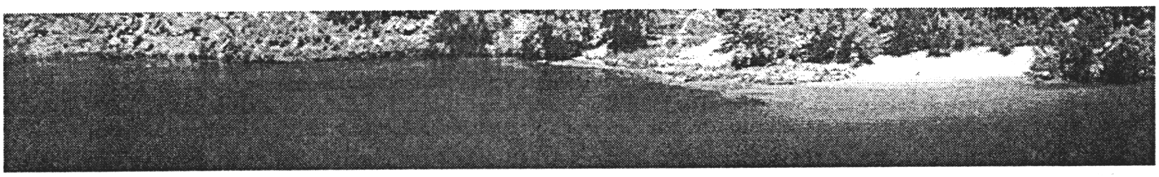
3 Mile



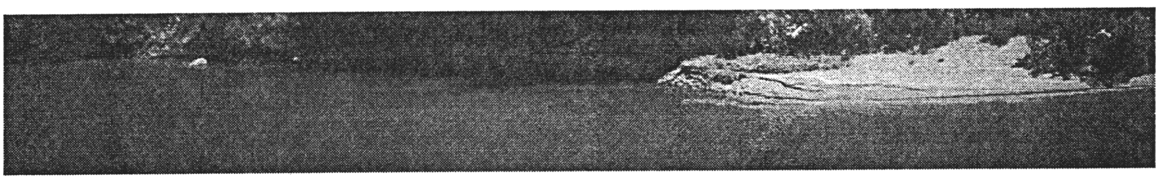
960326 227m^3/s(8000f^3/s)



960408 227m^3/s(8000f^3/s)



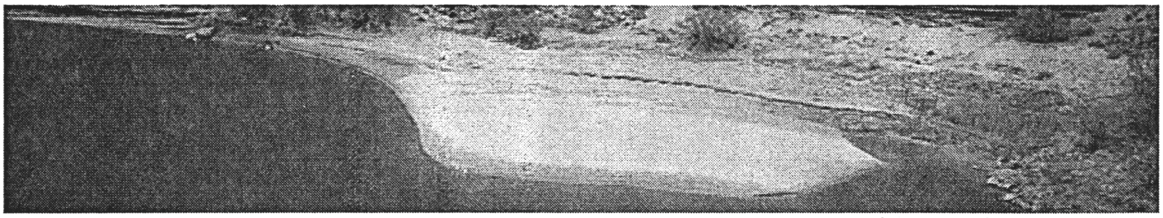
960518 454m^3/s(16000f^3/s)



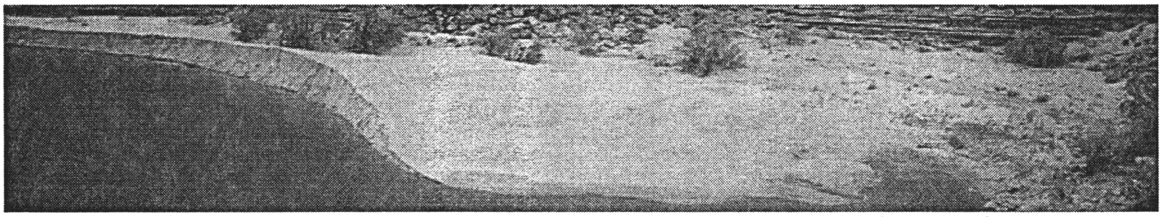
960902 232m^3/s(8200f^3/s)

961011 232m^3/s(8200f^3/s)

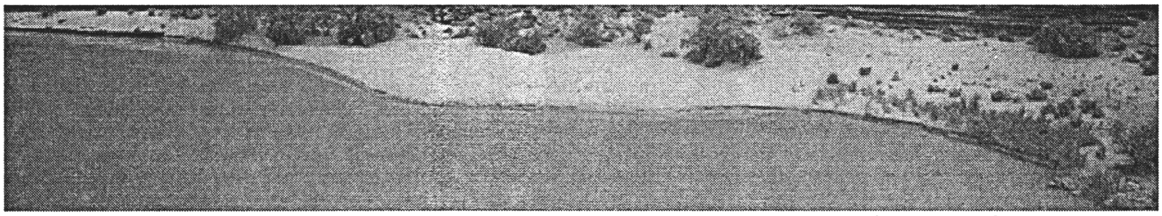
122 Mile



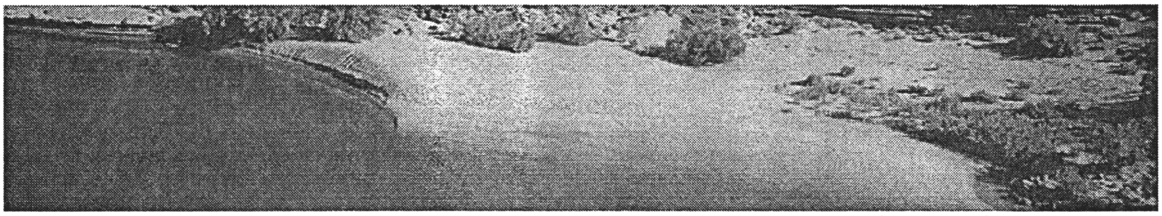
960325 $232 m^3/s$ ($8400 f^3/s$)



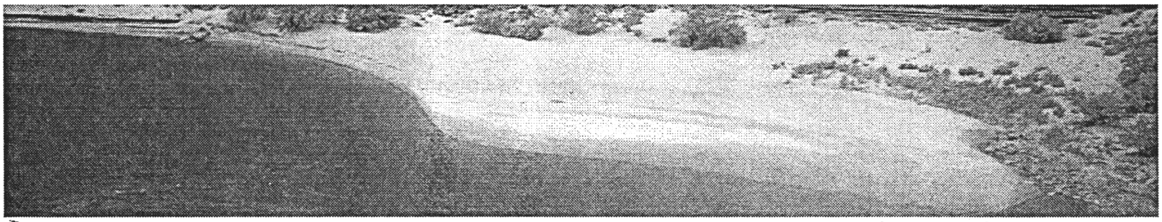
960407 $232 m^3/s$ ($8400 f^3/s$)



960708 $439 m^3/s$ ($15500 f^3/s$)

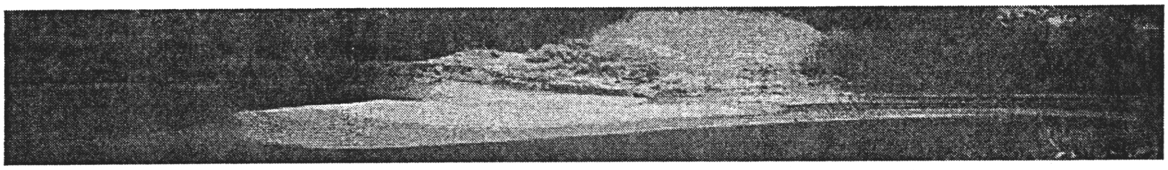


960903 $230 m^3/s$ ($8300 f^3/s$)

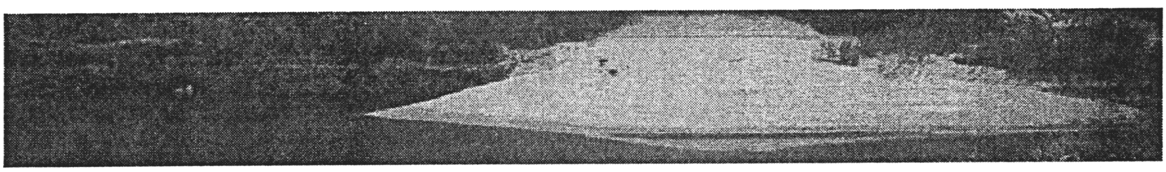


961014 $227 m^3/s$ ($8000 f^3/s$)

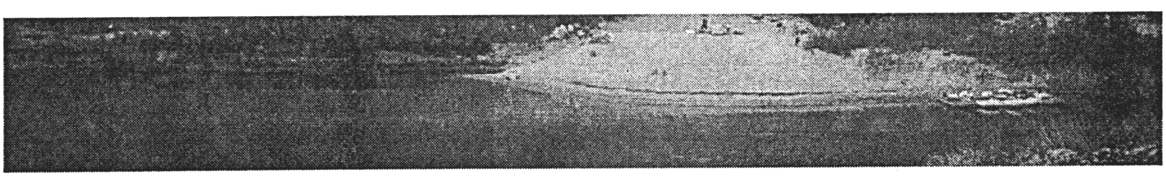
123 Mile



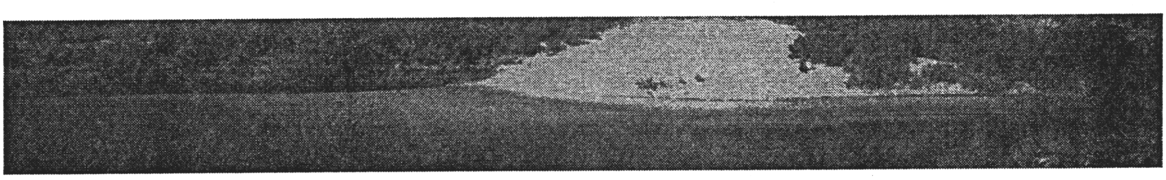
960326 230m^3/s(8200f^3/s)



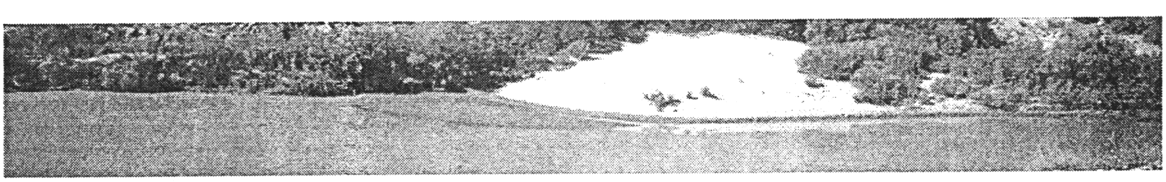
960408 230m^3/s(8200f^3/s)



960521 368m^3/s(13000f^3/s)

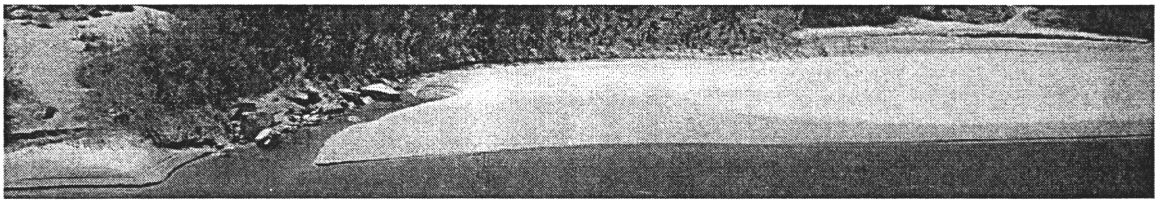


960818 359m^3/s(12700f^3/s)

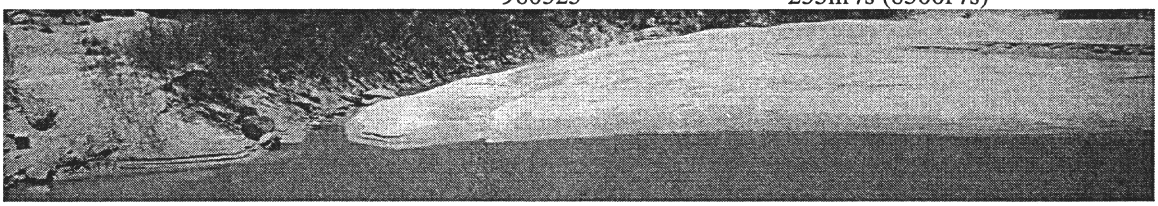


960923 335m^3/s(11811f^3/s)

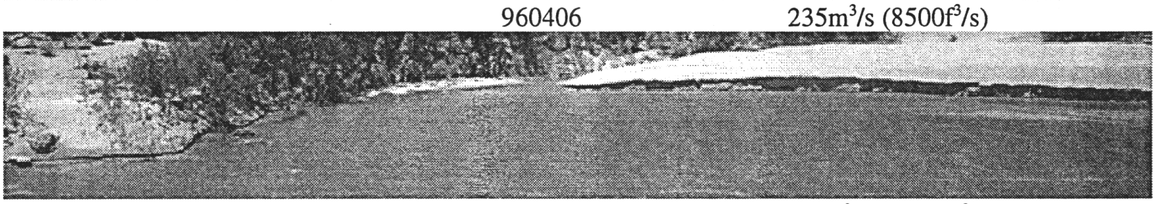
137 Mile



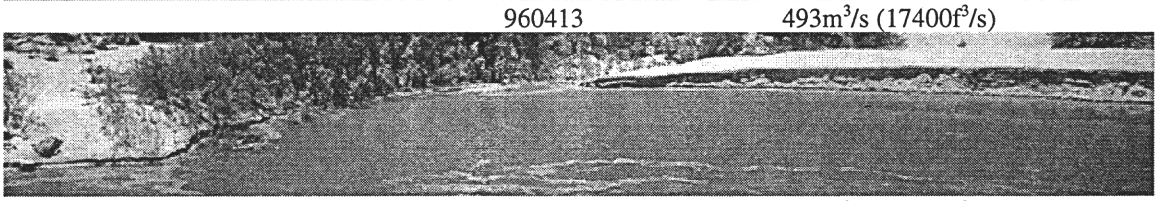
960325 235m^3/s (8500f^3/s)



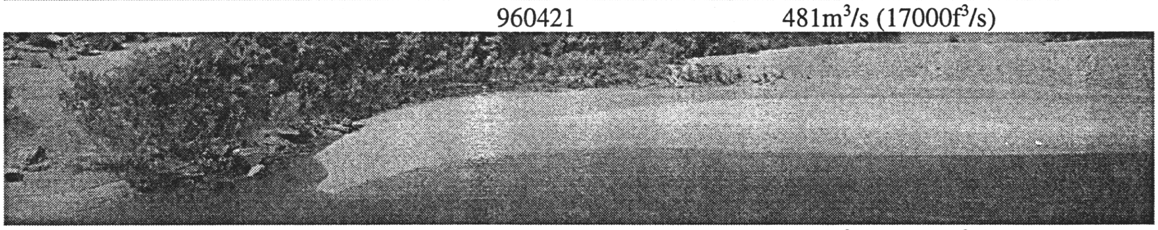
960406 235m^3/s (8500f^3/s)



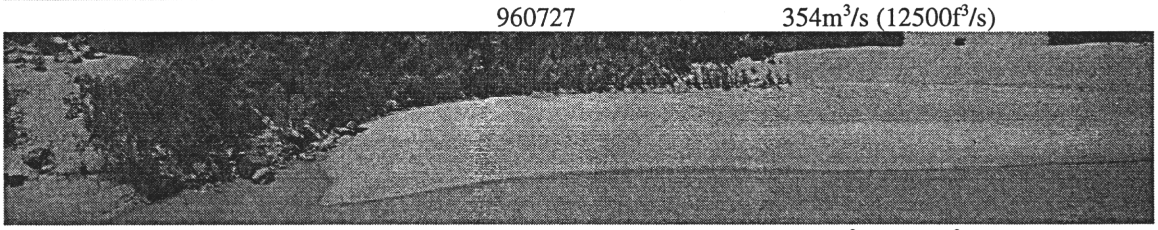
960413 493m^3/s (17400f^3/s)



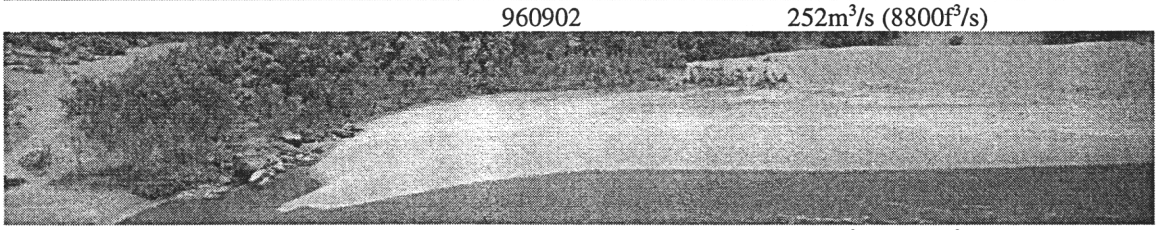
960421 481m^3/s (17000f^3/s)



960727 354m^3/s (12500f^3/s)

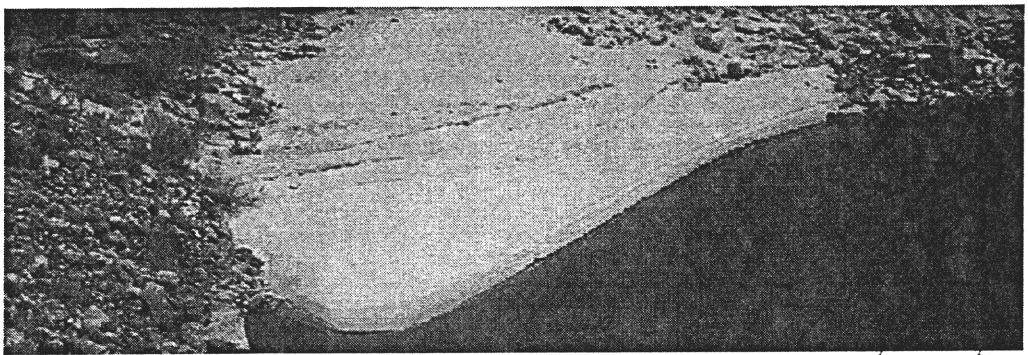


960902 252m^3/s (8800f^3/s)

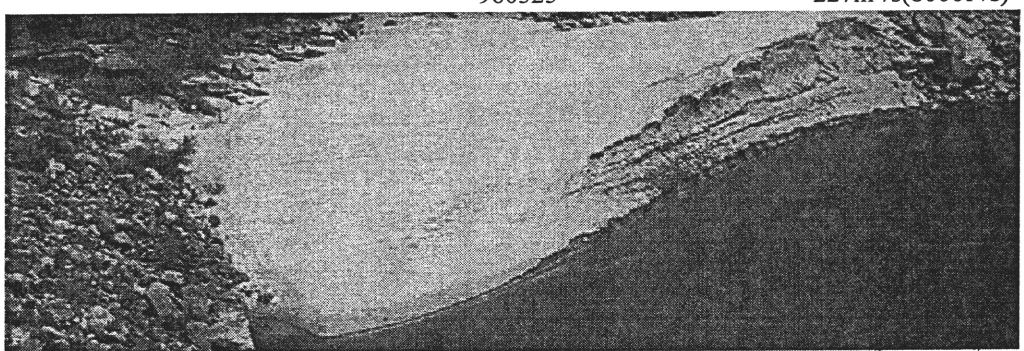


961013 246m^3/s (8700f^3/s)

145 Mile

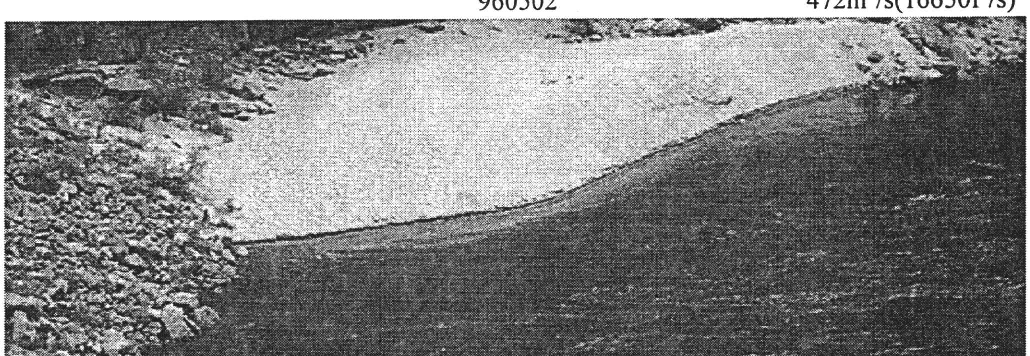


960325 227m³/s(8000f³/s)

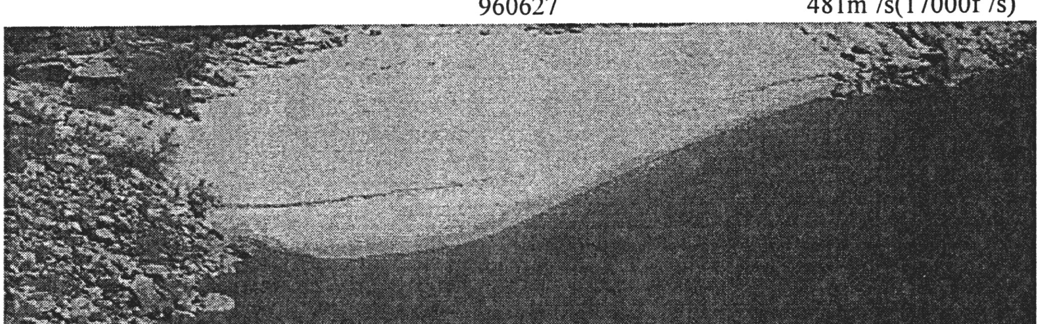


960406 230m³/s(8200f³/s)

960502 472m³/s(16650f³/s)

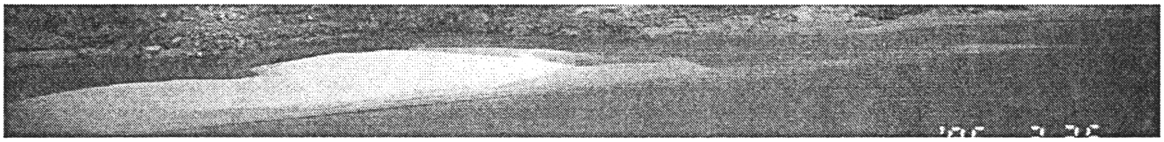


960627 481m³/s(17000f³/s)



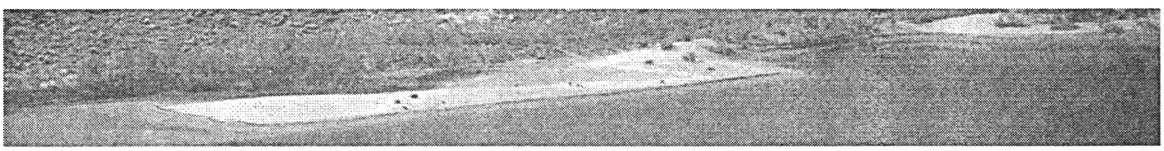
960817 359m³/s(12700f³/s)

172 Mile

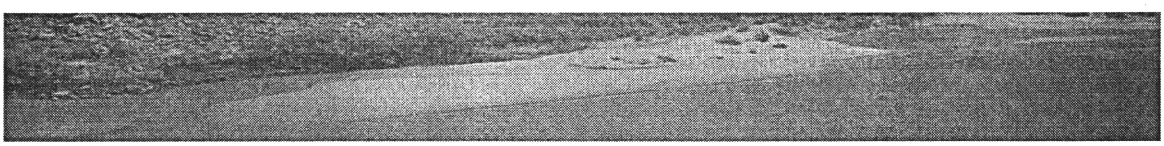


960325 235m^3/s (8500f^3/s)

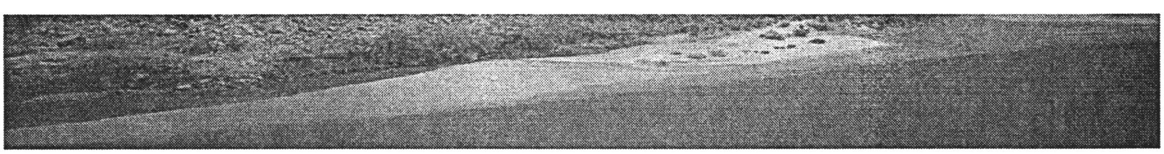
960407 235m^3/s (8500f^3/s)



960707 464m^3/s (16400f^3/s)

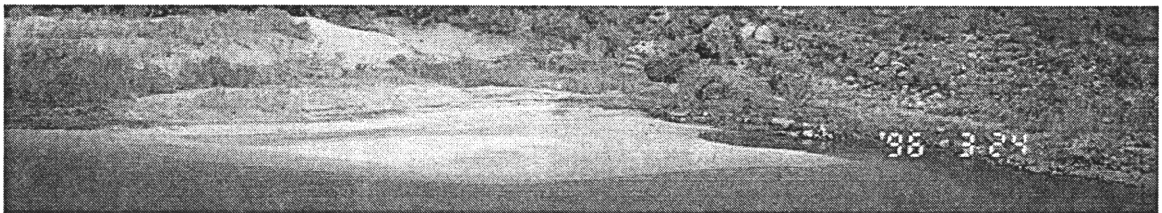


960903 246m^3/s (8700f^3/s)



961013 246m^3/s (8700f^3/s)

183 Mile

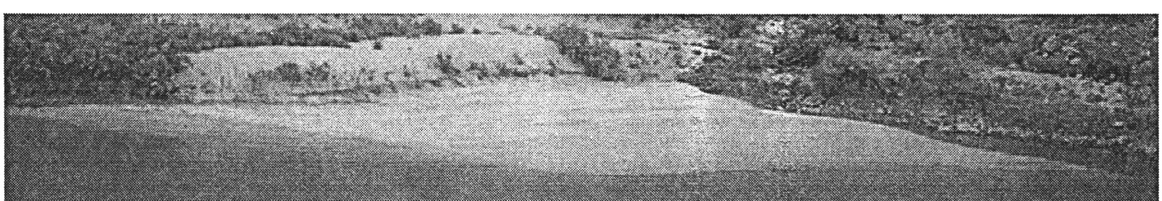


960324 232m^3/s (8400f^3/s)

960407 232m^3/s (8400f^3/s)

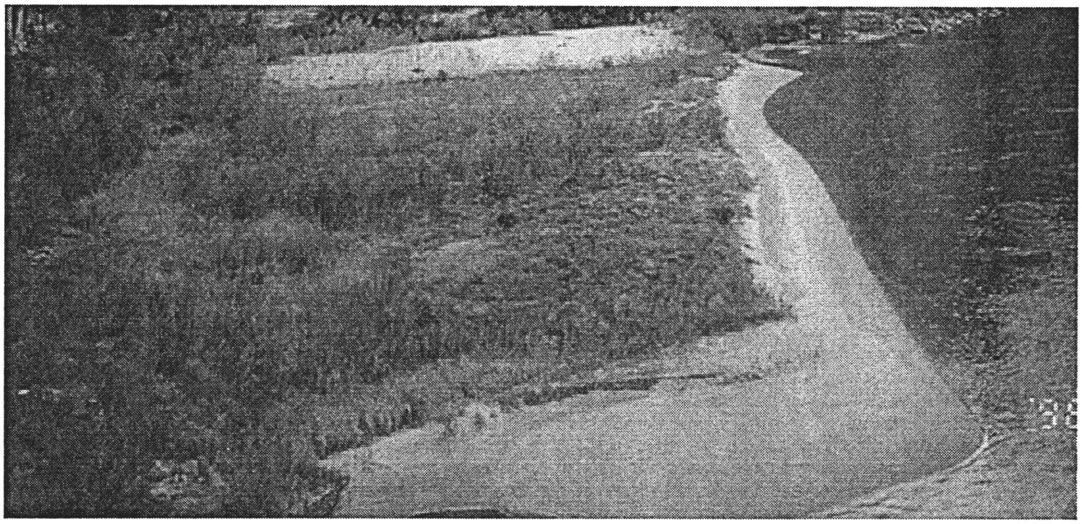
960707 464m^3/s (16400f^3/s)

960903 249m^3/s (8800f^3/s)

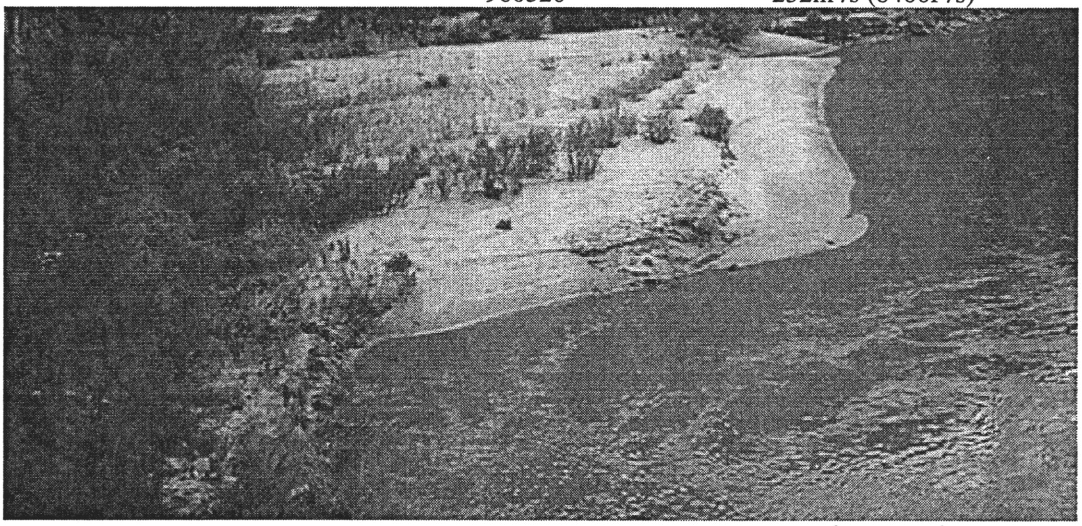


961014 227m^3/s (8000f^3/s)

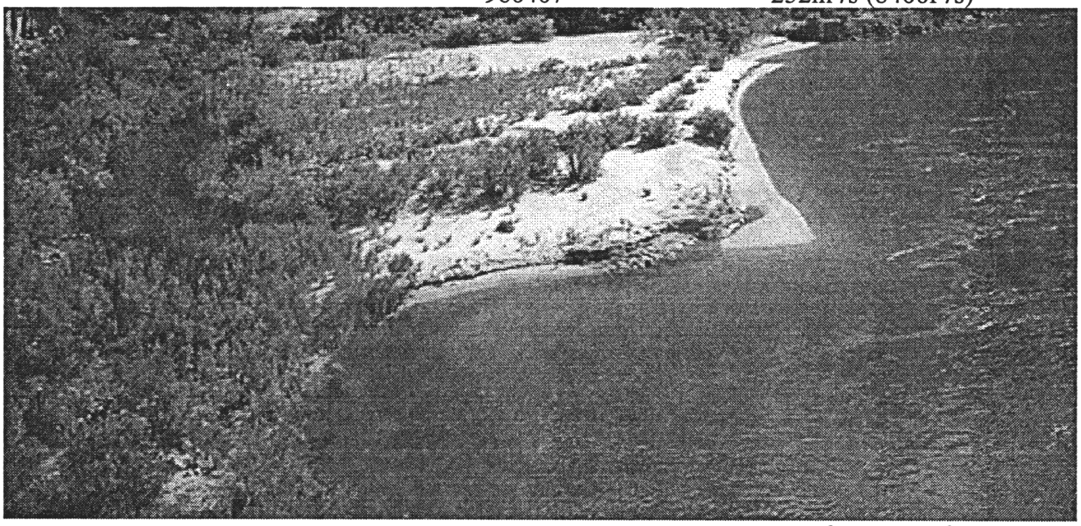
194 Mile



960326 232m^3/s (8400f^3/s)

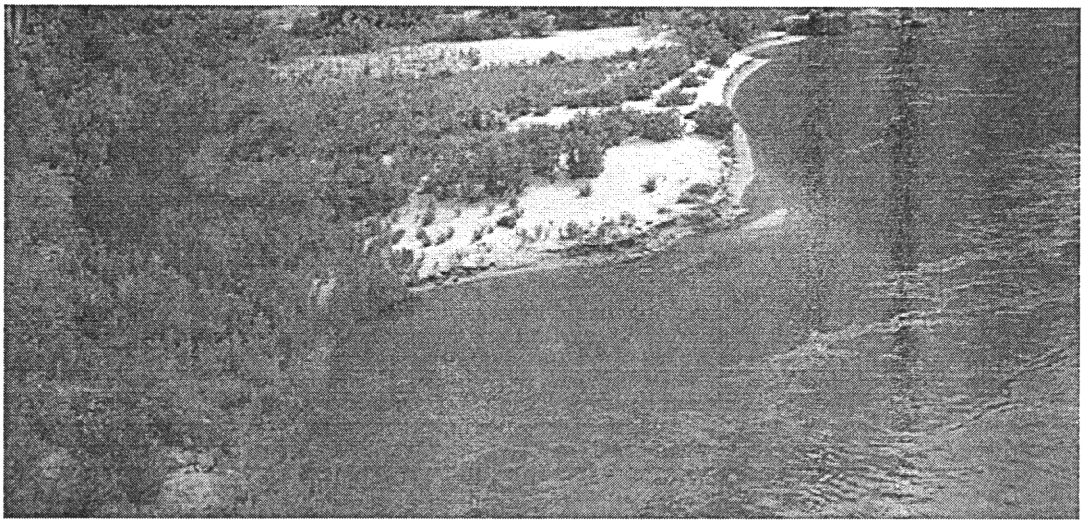


960407 232m^3/s (8400f^3/s)

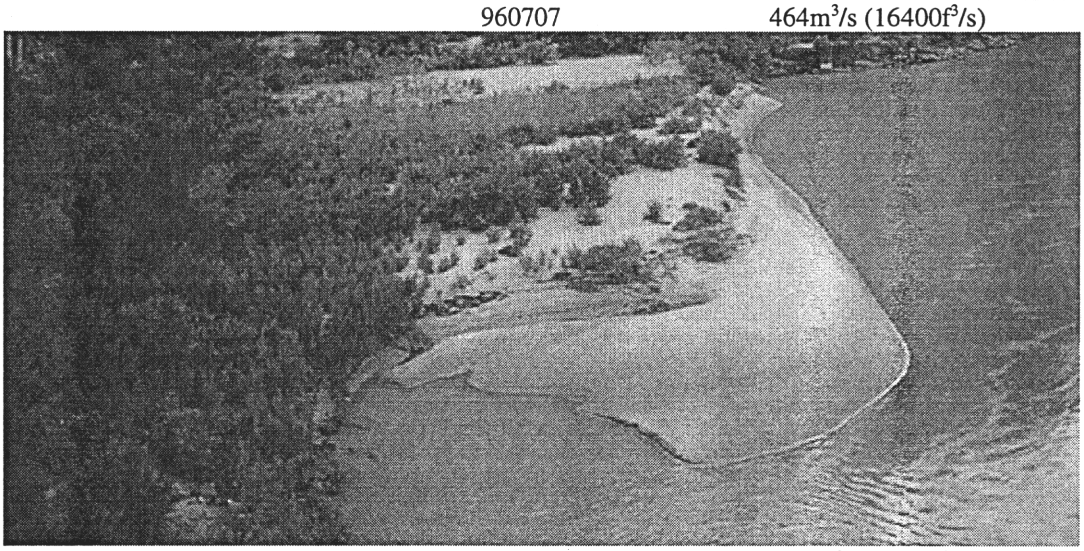


969603 481m^3/s (17000f^3/s)

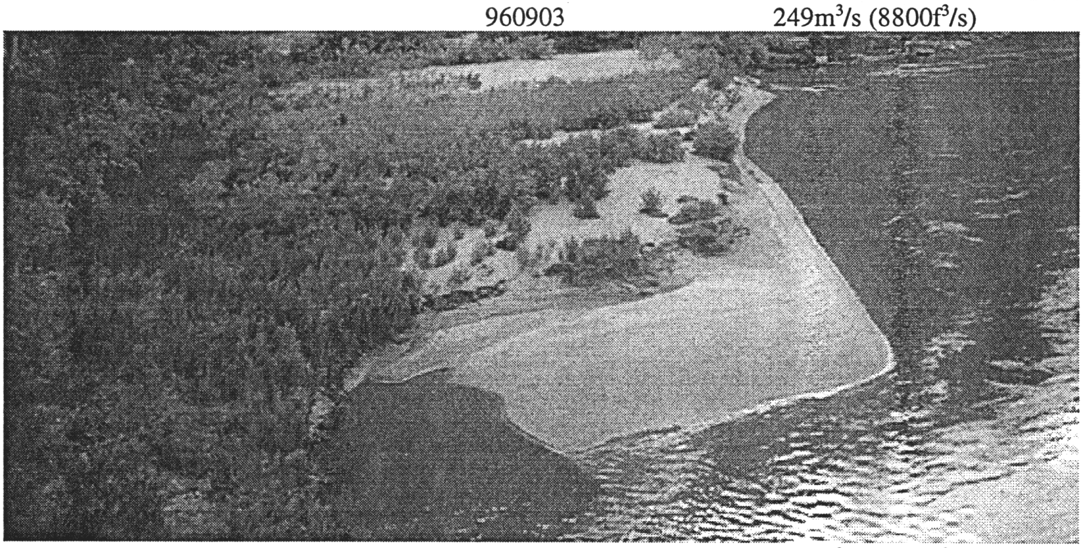
194 Mile (con't)



960707 464m^3/s (16400f^3/s)



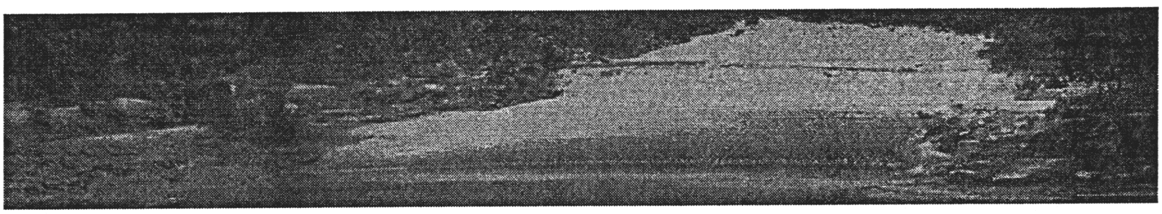
960903 249m^3/s (8800f^3/s)



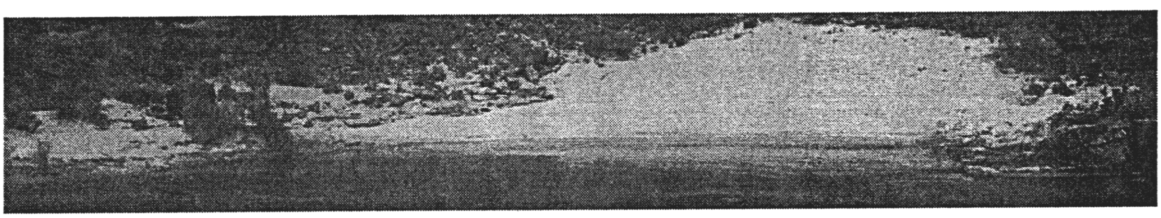
961014 227m^3/s (8000f^3/s)

213 Mile

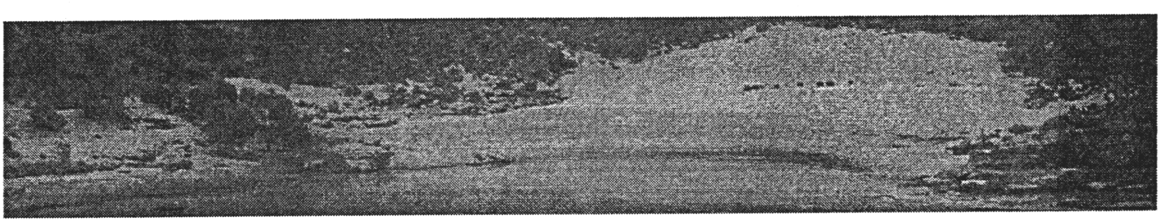
960326 $230 m^3/s (8200 f^3/s)$



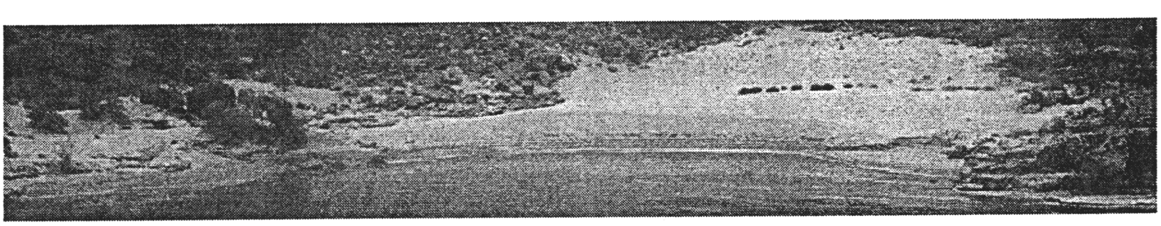
960407 $230 m^3/s (8200 f^3/s)$



960604 $481 m^3/s (17000 f^3/s)$

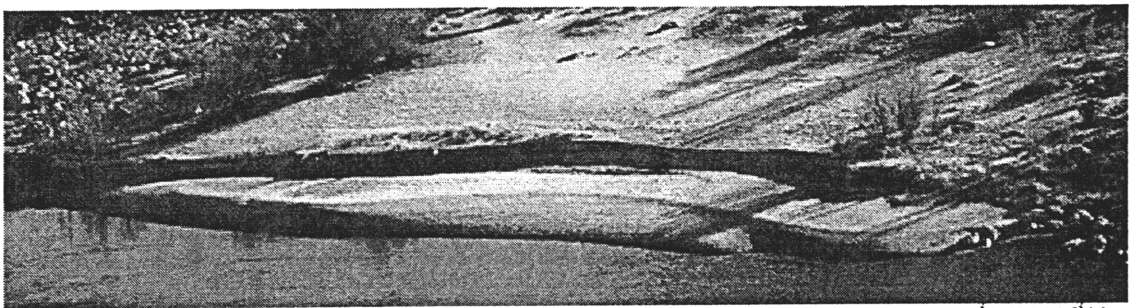


960902 $235 m^3/s (8300 f^3/s)$

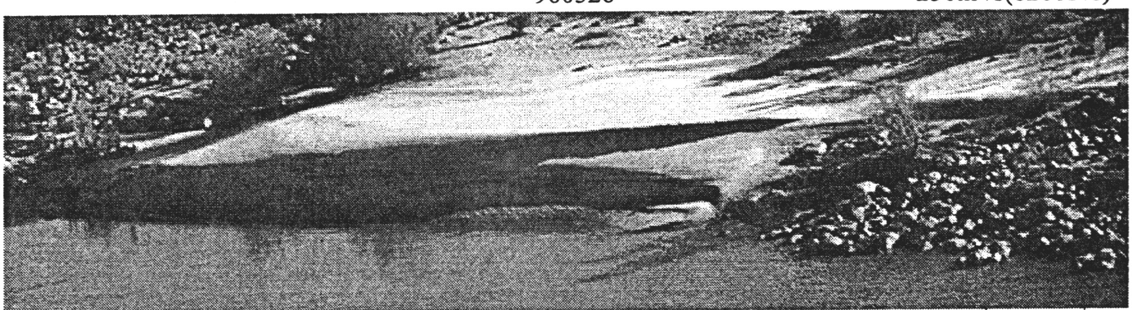


961013 $230 m^3/s (8200 f^3/s)$

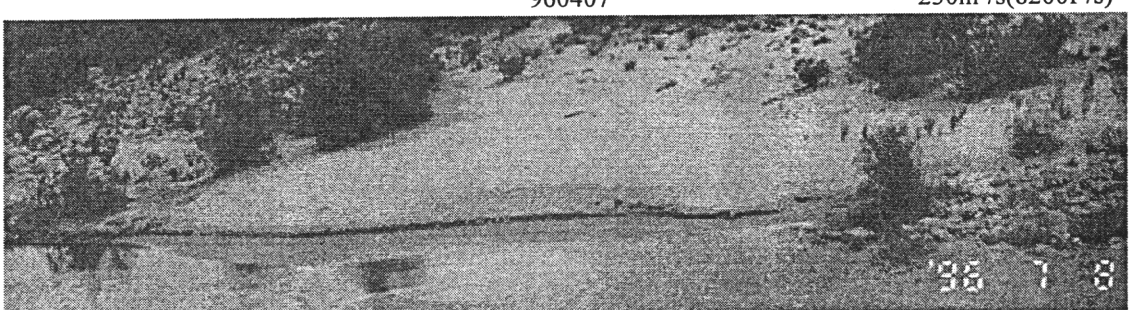
220 Mile



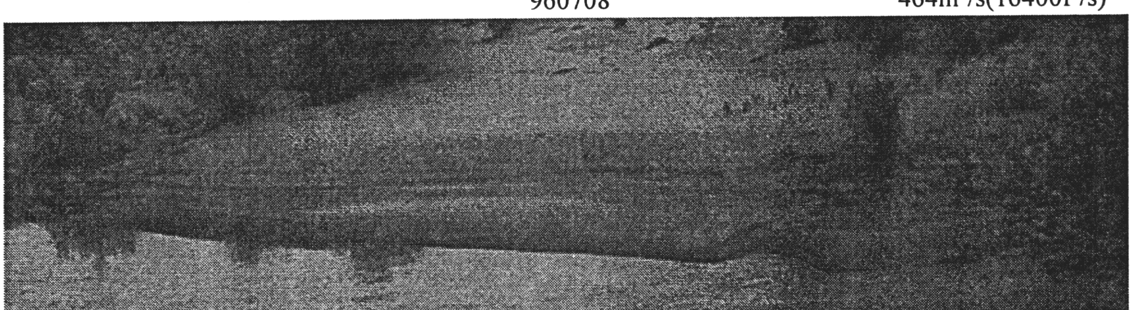
960326 230m³/s(8200f³/s)



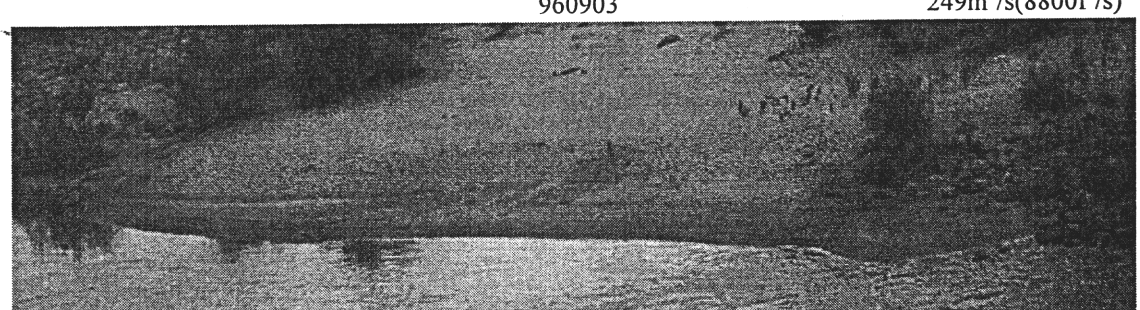
960407 230m³/s(8200f³/s)



960708 464m³/s(16400f³/s)



960903 249m³/s(8800f³/s)



961014 230m³/s(8200f³/s)