INTEGRATION OF PHOTOGRAPHIC AND TOPOGRAPHIC DATA TO DEVELOP TEMPORALLY AND SPATIALLY RICH RECORDS OF SAND BAR CHANGE IN THE POINT HANSBROUGH AND LITTLE COLORADO RIVER CONFLUENCE STUDY REACHES

Final Report

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ABSTRACT

Large and abundant sand bars, emergent at low discharge, were a distinctive attribute of the landscape of the Colorado River corridor prior to completion of Glen Canyon Dam. Development of a goal towards which river restoration in Grand Canyon might proceed must partly be based on understanding the variability in size, number, and attributes of these bars prior to river regulation. We developed 60-100 year time series of sand bar change at seven sites located between Lees Ferry and Phantom Ranch. Three of the sites (Anasazi Bridge, Eminence Break, and Saddle Canyon) are located in Marble Canyon and six sites (62-Mile, Crash Canyon, Salt Mine, Carbon Canyon, Palisades Creek, and Tanner Canyon) are located in the reach downstream from the Little Colorado River confluence.

We integrated data from air and ground photography and from ground surveys; some sites had been measured between 50-70 times, yet these data had never before been analyzed as an integrated time series. We also measured the characteristics of sand bar change in every sand bar along 31 km of the river for periods between aerial photos by mapping the distribution of sand and analyzing change within a GIS framework. The topographic data are used to ground truth and calibrate the measurements made by aerial photographs.

Each measurement method contributed to our understanding of sand bar change and to the development of the long-term time series of change at each site. Topographic/bathymetric surveys provide detailed areal and volumetric information about a limited number of sites since 1990. Surficial geologic mapping from aerial photographs provides less detailed information about every site in a given reach but provides data about topography prior to 1990. The photographic and topographic measurement methods are generally consistent when the spatial and temporal extent of the measurements are similar.

No long-term trends of sand bar degradation were identified at these sites, which are located more than 95 km downstream from Glen Canyon Dam. The area of low-elevation sand in eddies in these reaches has varied widely in both the pre- and post-dam era. We found at least one time between 1984 and 1996 at each of the nine sites when bar area was as great as in 1935. There is large variation in bar change among eddies in the

same reach. Although a dominant style of bar change can be identified in a specific reach, there are always extremes whose magnitude of erosion or deposition exceeds the reach average.

Reach-average time series for the 3 study reaches show decline in the area of exposed sand at 226 m^3/s between 1935 and 1965-1973 and between 1984 and 1996 prior to the controlled flood. Consistent depositional trends occurred between 1973 and 1984, between 1990 and 1993 in reaches downstream from the Little Colorado River, and during the 1996 controlled flood.

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INTRODUCTION

Large dams can have profound effects on downstream river environments including drastic alterations to hydrologic and sediment regimes (Williams and Wolman, 1984). Many studies have attempted to measure and quantify these effects on various portions of the 400-km reach of the Colorado River downstream from Glen Canyon Dam, which began storing water in March 1963.

Studies of the effects of Glen Canyon Dam on channel-side fine-grained alluvial deposits began in 1974, prompted by concern that sand bars, which are valued as campsites for recreationists and habitat for endangered fish, were eroding (Howard, 1975). Many studies have concluded that the average size of eddy bars throughout Grand Canyon has decreased since dam completion, based on rephotography, analysis of aerial photographs, and inventories of campsites (Schmidt and Graf, 1990; Kearsley and others, 1994; Webb, 1996). Other studies have employed different measurement methods to evaluate sand bar erosion and deposition at shorter spatial and temporal scales (e.g. Beus and others, 1985; Beus and others, 1992; Cluer, 1992; Cluer and Dexter, 1994; Graf and others, 1997; Kaplinski and others, 1995; Schmidt and Leschin, 1995). Neither the temporal sequence of bar change for the entire period since dam completion nor how this temporal sequence differs at various distances downstream from the dam have been determined. Moreover, the abundant ground-based data that have been collected since 1990 have never been integrated with the findings from previous studies. Thus, no study has yet attempted to comprehensively integrate the findings of the multitude of studies that have monitored sand bar change.

The temporal sequence of sediment storage change in eddy bars, utilizing all available monitoring and historical data, is crucial to evaluating the role of various flow regimes in causing erosion or deposition on bars. Without historical data analysis we lack the context that is needed to understand results from current monitoring efforts. Because sediment supply to Grand Canyon is limited, an understanding of the degree to which sand bars have irreversibly scoured and the length of the reach where those changes have occurred is essential. Sediment resupply to Grand Canyon is most limited upstream from the Little Colorado River, and there is a greater potential that erosion problems are greatest in that reach.

Purpose and Objectives

This study describes some of the different measurement methods that have been used to monitor sand bar change, their advantages and disadvantages, and proposes new techniques for integrating and analyzing these data. This type of information is vital to resource managers in their efforts to manage the limited resource of sand bars in Grand Canyon. Thorough analysis and integration of existing data is a critical step in formulating future research and monitoring objectives.

There are several difficulties in determining the long-term temporal sequence of sediment storage change in eddies. The monitoring of sand-bar topography has been inconsistent and has included tape-and-level transects (e.g. Howard, 1975), topographic measurements using geodetic total stations (e.g. Kaplinski and others, 1995), bathymetric measurements, photogrammetric measurements (e.g. Cluer, 1992; Cluer and Dexter,1994), and analysis of aerial photography using geographic information systems (e.g. Schmidt and Leschin, 1995). Study sites have been measured for different lengths of time. Thus, a comprehensive, integrated analysis of sand storage change in the eddies of Grand Canyon has yet to be completed.

Development of a comprehensive large-scale analysis depends on several preliminary steps, including:

1. Development of methodologies by which aerial photograph and surficial geologic map data can be compared with field survey data and determination of the accuracy of those methods;
2. Synthesis of data obtained by different methods at specific study sites, and development of detailed histories of sand bar change at specific sites;
3. Analyses of sand bar change at large spatial scales determined from aerial photograph and surficial geologic mapping; and

4. Integration of the results from each of the types of studies listed above with data concerning flow and sediment transport into a comprehensive history of sand bar change.

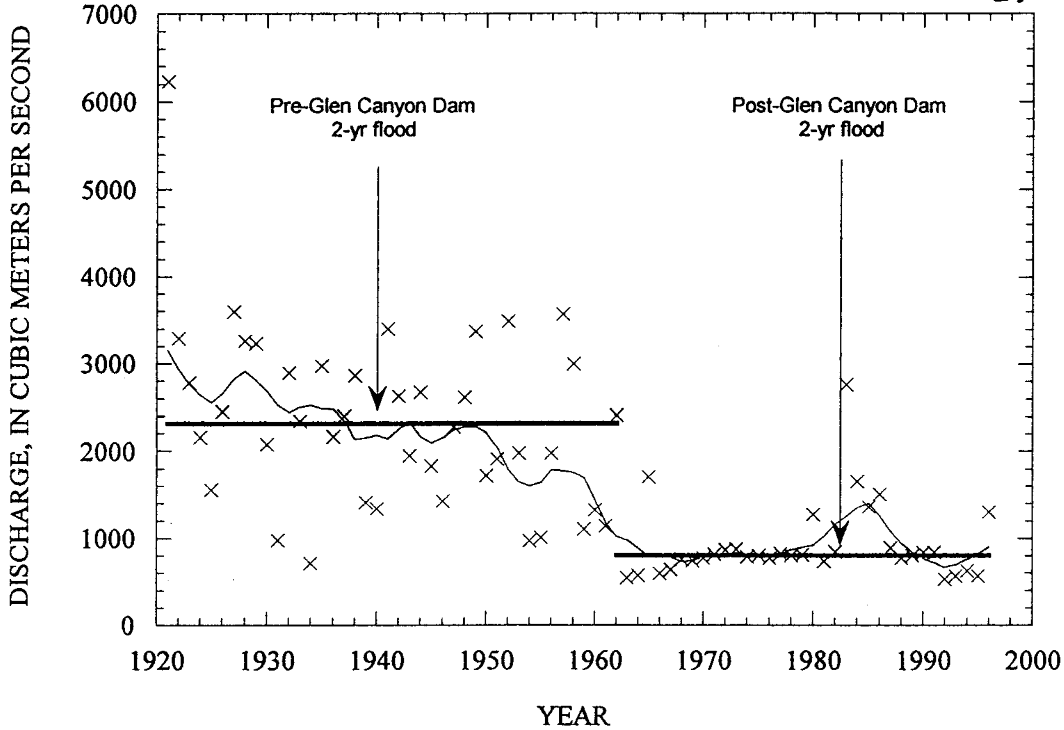
The purposes of this report are to (1) outline the methods we have developed to make comparisons between the several existing data sources, (2) discuss the comparisons between monitoring methods with respect to compatibility and utility, and (3) summarize the history of sediment storage change at 9 study sites in 2 reaches of the Colorado River, based on integration of data collected from all available sources. These results can be compared with the large spatial scale analyses conducted by Schmidt and Leschin (1995). We also integrate data collected from these data sources and evaluate the effectiveness of the 1996 controlled flood. Comprehensive analysis of the entire history of eddy sand bar change awaits completion of similar syntheses in other reaches and analyses of the history of flow and sediment transport.

This report responds to comments on the draft report of April 1998 and represents a substantial revision of the reach-scale analysis and integration.

HISTORY OF STREAMFLOW AND THE SEDIMENT BUDGET

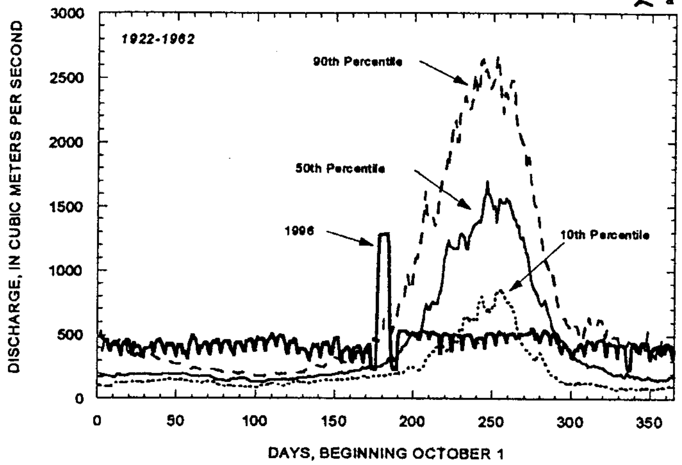
The history of streamflow in Grand Canyon can be divided into pre- and post-dam periods. Although diversion of water around the construction site began in 1959, the last year of unregulated streamflow was 1962. Flow regulation greatly reduced the magnitude of annual peak flows and changed the shape of the annual hydrograph. The 2-yr recurrence annual peak discharge of the Colorado River at Lees Ferry, Arizona was 2,309 m^3/s for the period 1921 to 1962 and was 804 m^3/s for the period between 1963 and 1996 (Figure 1). Spring floods that occurred in the pre-dam period occur only rarely in the post-dam period. Instead, seasonal variations in the post-dam period are very small and have been replaced by daily and weekly fluctuations driven by hydroelectric power considerations (Figure 2). Normal dam operations between 1963 and 1990 consisted of wide-ranging fluctuating flows. Although discharge through the powerplant could range from 28 to 892 m^3/s, daily discharge fluctuations of between 280 and 570 m^3/s were typical.

1.

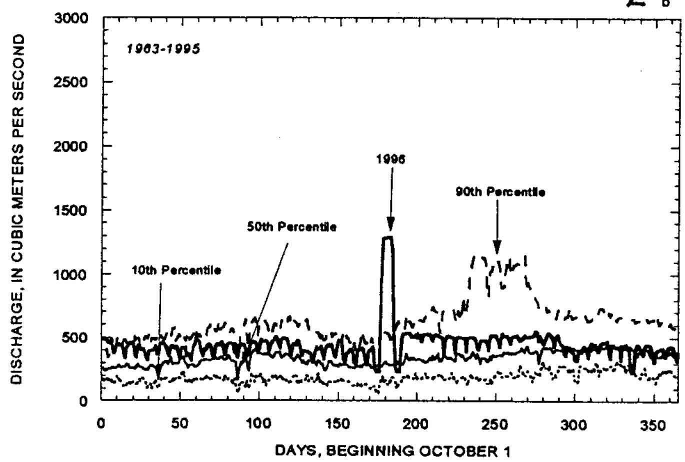


Pre-Glen Canyon Dam
2-yr flood
Post-Glen Canyon Dam
2-yr flood
DISCHARGE, IN CUBIC METERS PER SECOND
0
1000
2000
3000
4000
5000
6000
7000
1920
1930
1940
1950
1960
1970
1980
1990
2000
YEAR

2 a


1922-1962
90th Percentile
50th Percentile
1996
10th Percentile
DISCHARGE, IN CUBIC METERS PER SECOND
DAYS, BEGINNING OCTOBER 1

2 b


1963-1995
1996
90th Percentile
50th Percentile
10th Percentile
DISCHARGE, IN CUBIC METERS PER SECOND
DAYS, BEGINNING OCTOBER 1

Streamflow has rarely exceeded the 892 m^3/s capacity of the powerplant at Glen Canyon Dam. Between late April and late June 1965, releases up to 1,705 m^3/s occurred when the Bureau of Reclamation tested the dam's outlet works and spillway. In 1980, the outlet works were again tested briefly when a peak of 1,269 m^3/s was sustained for a few hours. The highest post-dam flow, which was 2,755 m^3/s, occurred in June 1983 following an exceptionally wet winter in the western United States. High flows of 1,648 m^3/s, 1,356 m^3/s, and 1,506 m^3/s occurred again in 1984, 1985, and 1986, respectively. Releases did not exceed maximum powerplant capacity again until the March 1996 controlled flood, which had a peak discharge of 1,300 m^3/s.

Releases from Glen Canyon Dam below powerplant capacity were manipulated for research purposes but did not exceed powerplant capacity between May 1990 and August 1991. The release pattern that occurred during this time was designed to study the effects of different dam operating regimes on downstream resources, including sandbars. Hereafter referred to as the "test flows," these releases included high-volume fluctuating flows (large daily range), low-volume fluctuating flows (low daily range), and steady flows (Beus and others, 1992). Discharges typically fluctuated between about 142 and 850 m^3/s during high-volume fluctuating flows and between about 142 and 566 m^3/s during low-volume fluctuating flows. Steady flows during this period were 142 m^3/s. Following the test flows, the "interim flow criteria" were adopted, which limited releases from Glen Canyon Dam to low-volume fluctuating flows with daily minimums of about 170 m^3/s and daily maximums of between 450 and 510 m^3/s.

Extreme floods on major tributaries to the Colorado River in Grand Canyon can significantly affect mainstem hydrology and sediment conditions. The most significant of these events that was bracketed by measurements of bar topography occurred when series of floods on the Little Colorado River (LCR) in January and February 1993 resulted in a peak discharge of 878 m^3/s on the Colorado River at the Grand Canyon gage.

Howard and Dolan (1981) analyzed the sediment budget of the reach between the Lees Ferry and Grand Canyon gages and showed net sediment accumulation in this reach between dam closure and 1970, which they attributed to the combination of reduced peak flow magnitude and continued input of sediment from tributaries. This sediment-storage change corresponded with net increases in bed elevation at the Grand Canyon gage, indicating that average bed-elevation changes in this reach were approximated by the bed-elevation changes at the Grand Canyon gage (Howard and Dolan, 1981). Randle and others (1993) conducted a similar analysis of the sediment budget and also showed net accumulation of sediment in years of low dam releases. Using the daily measurements of sediment concentration, rather than the published sediment rating relation, Topping (in preparation) recalculated the sediment budget for those periods when sediment transport data were collected. This analysis (Figure 3) demonstrates that periods of sediment accumulation and sediment depletion occurred annually in both the pre- and post-dam periods. Prior to the closure of Glen Canyon Dam, sediment typically accumulated between mid-July and the following April. Depletion of fine sediment typically occurred during the annual snowmelt flood in the months of May and June. The period of sediment accumulation is much shorter in the post-dam period and erosion occurs over a larger portion of the year because the source area of fine sediment is limited by the presence of the dam

GEOMORPHOLOGY OF FINE-GRAINED ALLUVIAL DEPOSITS

Studies of fine-grained alluvial deposition and erosion initially focused on sand bars that are used as campsites (Howard and Dolan, 1975; Beus and others, 1985; Schmidt and Graf, 1990). More recent studies have evaluated erosion and deposition at all bars in a given reach (Schmidt and Leschin, 1995; Schmidt and others, 1999). Schmidt and Graf (1990) described the detailed characteristics of these bars and distinguished several bar types. According to their classification, separation bars and reattachment bars occur in eddies and channel-margin deposits are linear flood-plain like deposits that form in downstream flow conditions (Figure 4). Eddies, which are zones of recirculating flow, occur in channel expansions downstream from constrictions that are typically created by debris fans but may be caused by bedrock or talus obstructions. Separation bars typically mantle the downstream side of debris fans at the upstream end of the eddy. This name is derived from the position of the bar near the point where downstream flow separates from

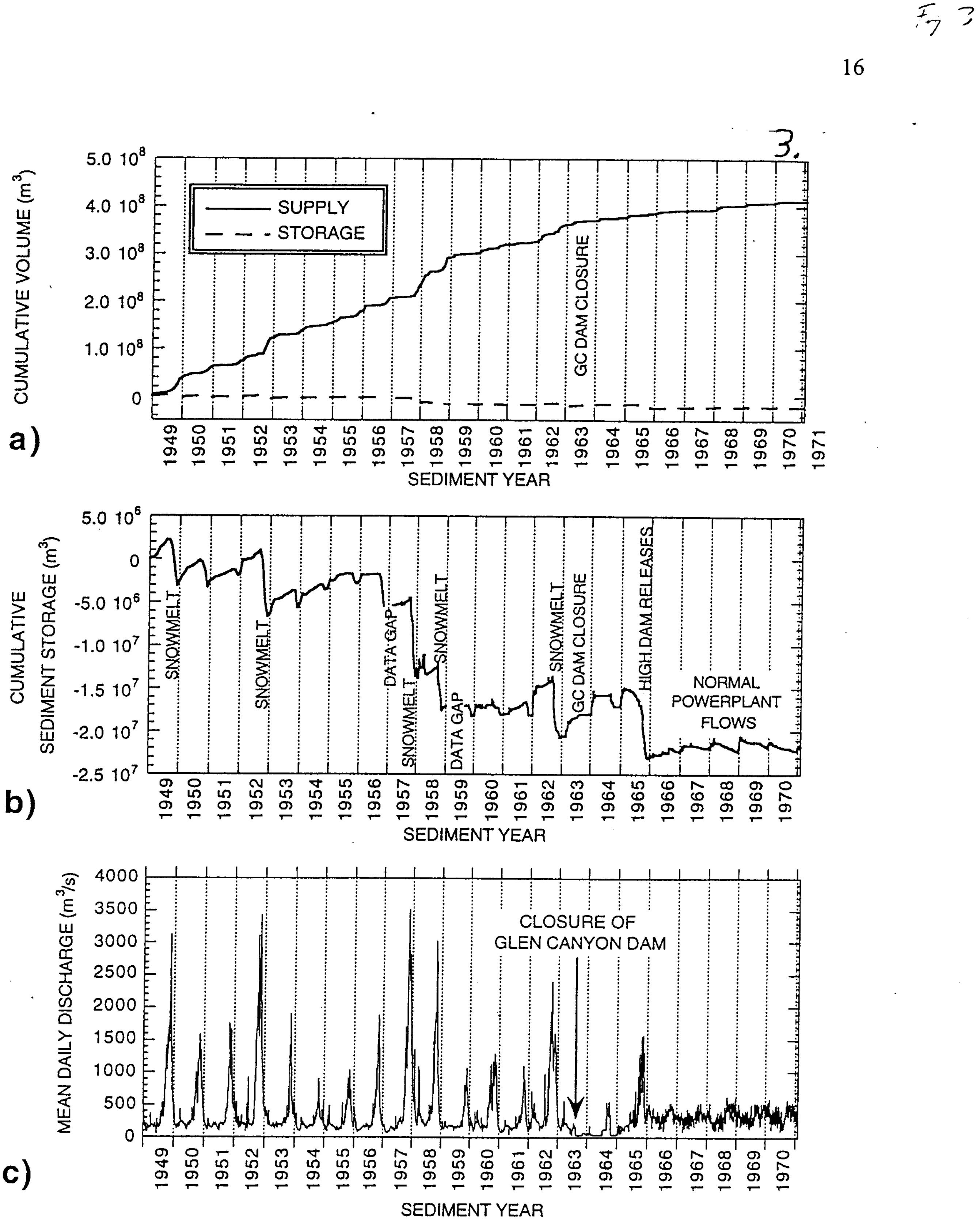


Fig 3
3.
5.0 10^8
4.0 10^8
3.0 10^8
2.0 10^8
1.0 10^8
0
CUMULATIVE VOLUME (m^3)
SUPPLY
STORAGE
GC DAM CLOSURE
a)
1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971
SEDIMENT YEAR
5.0 10^6
0
-5.0 10^6
-1.0 10^7
-1.5 10^7
-2.0 10^7
-2.5 10^7
CUMULATIVE SEDIMENT STORAGE (m^3)
SNOWMELT
SNOWMELT
DATA GAP
SNOWMELT
SNOWMELT
DATA GAP
SNOWMELT
GC DAM CLOSURE
HIGH DAM RELEASES
NORMAL POWERPLANT FLOWS
b)
1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970
SEDIMENT YEAR
4000
3500
3000
2500
2000
1500
1000
500
0
MEAN DAILY DISCHARGE (m^3/s)
CLOSURE OF GLEN CANYON DAM
c)
1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970
SEDIMENT YEAR

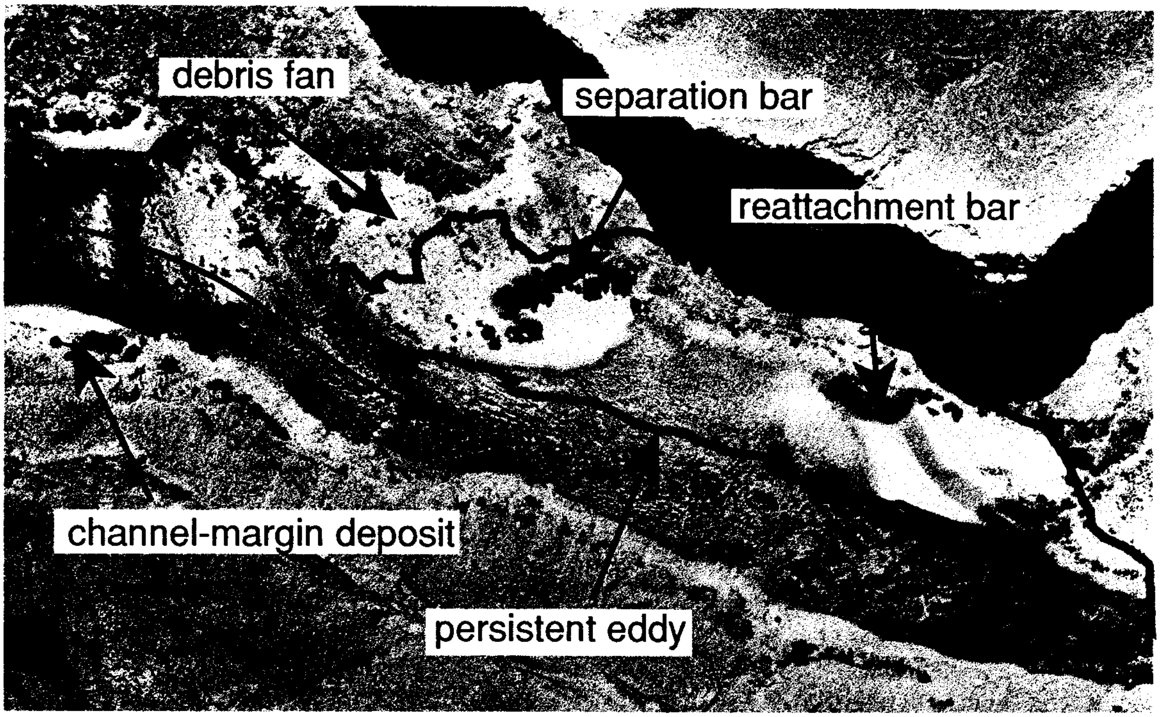


Figure 4. Typical fan-eddy complex in Grand Canyon showing separation and reattachment bars and channel-margin deposits. The region defined as the persistent eddy from aerial photograph analysis is also shown. Streamflow is from left to right. The eddy shown is the Eminence Break site in the Point Hansbrough reach (RM 45).

the bank. Reattachment bars form in the center and downstream end of the eddy and project upstream from the point where downstream flow reattaches to the bank. Leschin and Schmidt (1995) described deposits that form in recirculating flow but lack the morphology typical of separation or reattachment bars and termed these undifferentiated eddy deposits. Rubin and others (1990) described the detailed stratigraphy and depositional forms of eddy bars, and Schmidt and others (1993) described direct observations of eddy deposition in flume experiments.

Schmidt and Rubin (1995) argued that fan-eddy complexes are the fundamental geomorphic unit in canyons with abundant debris fans. The extent of these complexes is determined by the control that debris fans exert on river hydraulics. Persistent eddies occur along the channel margin downstream from virtually every debris fan; deep pools occur in the channel immediately downstream from debris fans. Gravel bars typically occur downstream from the persistent eddies and deep pools, and these bars occur at the downstream end of most fan-eddy complexes.

Because the locations of debris fans that form constrictions are stable (Webb, 1996), downstream eddies are persistent features of the Colorado River ecosystem. Eddy bars do not migrate as do bars in meandering alluvial channels, but do change in size. While the bars within eddies may deposit and erode, exhibiting dynamic form and size, the boundaries of potential deposition are the relatively stable confines of the area of recirculating flow. The persistence of these depositional locations makes it possible to monitor sand storage by tracking the amount of sand contained in individual eddies through time.

The size of individual eddies in specific reaches was determined by Schmidt and Leschin (1995) and Schmidt and others (1999). A persistent eddy was defined as the largest area of contiguous fine-grained eddy-formed deposits visible in all years of available aerial photography. The area of each persistent eddy is a representation, based on all available historical air photography, of the total possible area of sand that would be emergent at baseflow within that eddy (Figure 4).

PREVIOUS STUDIES OF THE HISTORY OF EDDY SAND BAR SIZE

Overview

An extremely diverse range of approaches, methods, and technologies has been applied towards understanding sand bar erosion and deposition. Monitoring of channel-side deposits has been underway for more than 20 years, and historical studies have extended our database as far back as 1872, the year photographs were taken during the second Powell expedition (Stephens and Shoemaker, 1987). As technology advanced, measurements by engineers' level and tape were replaced by integrated topographic and bathymetric surveys of the channel and banks. Similarly, analysis of aerial photographs progressed from inventory-style methods to spatial analysis of digitized maps.

All studies of sand bar change have addressed three fundamental factors of scale: (1) measurement detail, (2) spatial extent of measurements, and (3) temporal frequency of measurements. Feasibility necessitates emphasizing one of these components at the expense of the remaining two. Typically, studies that utilize detailed measurement methods only obtain data at a few locations while studies that measure or inventory sand bars over a large area must make comparatively gross measurements. Studies that collect a rich temporal record are typically conducted at only a few sites using less detailed methods. The discussion of sand bar monitoring studies below is, therefore, structured according to these broad categories of monitoring styles.

Studies Emphasizing Measurement Detail

The first detailed measurements were initiated when the Bureau of Reclamation established channel cross sections in 1956 between the dam and the mouth of the Paria River, located 24 km downstream (Pemberton, 1976). Laursen and Silverston (1976) suggested that sand bar deposition and erosion were directly related to local bed sediment conditions. Thus they predicted that bar erosion would proceed in a downstream direction as bed degradation extended downstream. By resurveying the original Bureau of Reclamation cross sections, Pemberton (1976) demonstrated that by 1965 the bed scoured in the entire 24 km reach between the dam and Lees Ferry. Continued scour, at a significantly decreased rate, occurred between 1965 and 1975 (Pemberton, 1976). The actual downstream extent of bed scour can not be determined because the next location for which pre-dam bed-elevation data are available is 165 km downstream from the dam at the Grand Canyon gage, where bed degradation has not occurred. Thus the hypothesis of Laursen and Silverston (1976) has never been tested downstream from Lees Ferry because bed scour has not been compared with sand bar erosion.

Howard (1975) initiated monitoring of channel-side sediment storage with the establishment of repeatable topographic profiles at selected sites. This program was continued and expanded by Beus and others (1985; 1992), Schmidt and Graf (1990), and Kaplinski and others (1995). The results of these repeat surveys have been summarized by Beus and others (1985) and Kyle (1992). Between 1974 and 1980, erosion approximately equaled deposition and the average net change at these monitoring sites was small (Beus and others, 1985). The flood of 1983 caused significant deposition at most sites and erosion at a few sites. Most of these sites and a few additional sites continued to erode during the 1984 high flows. Deposition between 1983 and 1984 occurred at only a very few of these monitoring sites. The net change between 1974 and 1984 was significant deposition at 8 sites, significant erosion at 8 sites, and no significant change at 2 sites. The magnitude of deposition was generally greater than the magnitude of erosion, and the net change for the 10-yr period was slightly depositional.

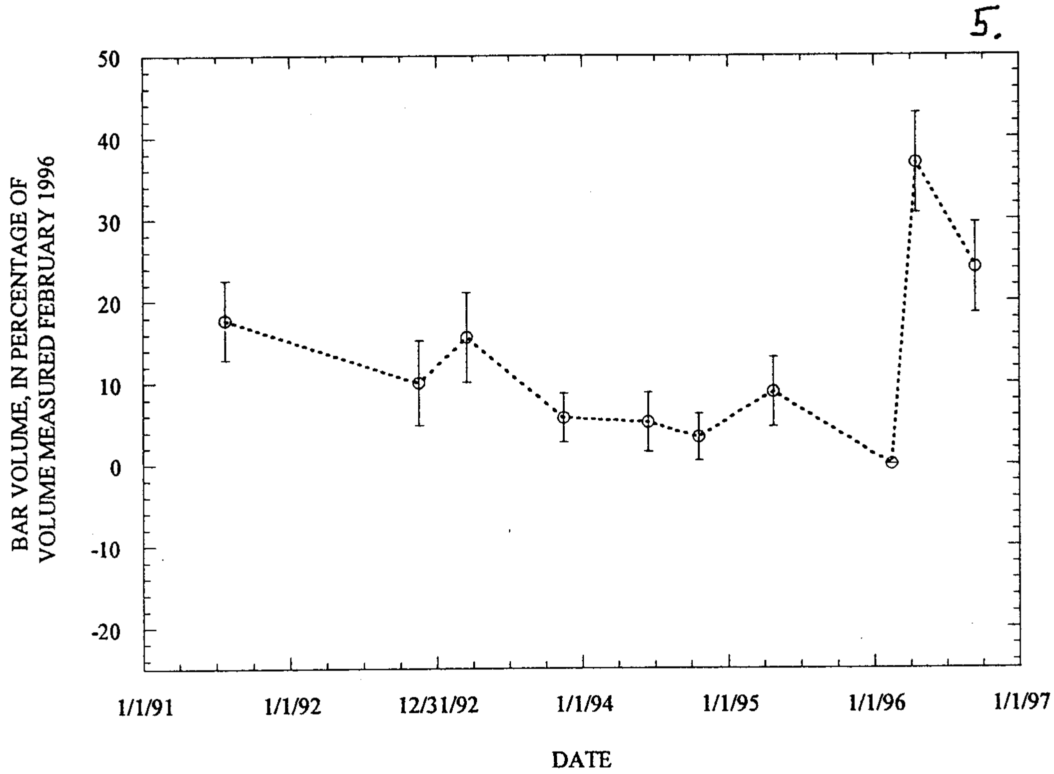
The present monitoring network, maintained by Northern Arizona University (NAU), involves repeat topographic and bathymetric surveys of parts of 34 persistent eddies. These surveys were made twice monthly during the 1990-1991 test flows, twice yearly between 1992 and 1996, and annually beginning in 1997. The frequent surveys during the test flows could not document consistent erosional or depositional patterns associated with specific flow regimes (Beus and others, 1992). This study did, however, demonstrate that antecedent conditions do affect bar erosion or deposition; aggradation tended to occur at sites that had recently degraded. Beus and others (1992) also documented aggradation during fluctuating flows during or following tributary sediment inputs. While a correlation between dam operations and sand bar response could not be determined during the 1990-1991 test flows, twice-yearly surveys between 1991 and 1996 of the same bars documented progressive depletion in the volume of sand stored in the eddies and low-elevation parts of sand bars (Figure 5) (Hazel and others, 1999). Hazel and others (1999) also showed large increases in low- and high-elevation parts of bars following the 1996 controlled flood. These increases corresponded to decreases in the volume of sand contained in the adjacent eddy and channel settings.

Studies of Large Spatial Extent

Schmidt and Graf (1990) inventoried 399 eddies between Lees Ferry (River Mile 0) and River Mile (RM) 118 for the presence or absence of sand in 1973 and 1984 aerial photographs. Net erosion was indicated by a decrease in the number of deposits from RM 0 to 36 and from RM 77 to 118. Aggradation was indicated by an increase in the number of eddy deposits from RM 36 to 77. Schmidt and Graf (1990) also measured the change in area of sand bars between 1973 and 1984 for two reaches (RM 0 to 36 and RM 122 to 150) in which the discharge at the time of those aerial photographs was approximately equal. This analysis indicated no change in the total area of exposed sand in those reaches but did show net erosion of reattachment bars between RM 11.4 and 22.5, net erosion of separation bars between RM 140 and 150, and net deposition of channel-margin bars between RM 140 and 150. Schmidt and Graf (1990) concluded that there was no significant net change in the reaches studied but that there was significant change at 70% of the measured sand bars, indicating that reach-average changes may not reflect changes at specific sites. In other words, individual sites may have eroded or deposited while the reach-average bar size did not change significantly.

Zink (1989) determined sand bar change in ten 5-mi reaches between Lees Ferry and RM 214 by examining 1973 and 1984 aerial photographs for erosion indicated by cutbank retreat and the presence of newly-exposed boulders. Zink (1989) concluded that significant degradation had occurred between Lees Ferry and RM 36 and no significant changes occurred further downstream.

Kearsley and others (1994) documented a decrease in the size of campsites between 1965 and 1990, based on analysis of aerial photographs using methods similar to those of Zink (1989). Kearsley and others (1994) also compared field inventories of campsite carrying capacity conducted in 1973, 1983, and 1991. Between 1973 and 1983,


5.
50
40
30
20
10
0
-10
-20
BAR VOLUME, IN PERCENTAGE OF
VOLUME MEASURED FEBRUARY 1996
1/1/91
1/1/92
12/31/92
1/1/94
1/1/95
1/1/96
1/1/97
DATE

deposition resulting from the 1983 flood increased the size of many campsites. The 1991 inventory indicated some erosion since 1983. Between 1973 and 1991, 18% of the bars increased in size, 46% decreased in size, and 36% did not change significantly. This campsite inventory was not entirely consistent with aerial photograph analysis because it did not detect increased campsite sizes in 1984. Kearsley and others (1994) attributed this to erosion of the 1983 deposits that may have occurred between the time of the campsite inventory in 1983 and the time of the aerial photographs in 1984. More recent studies, however, have demonstrated deposition between 1973 and 1984 using the same 1984 aerial photographs (Schmidt and Leschin, 1995). The method of aerial photograph analysis used by Kearsley and others (1994) and Zink (1989) may have been biased to miss deposition because these methods explicitly looked for evidence of erosion and did not explicitly look for deposition, as more recent studies have (i.e. Schmidt and Leschin, 1995).

Methods of aerial photograph analysis were expanded by Schmidt and Leschin (1995) and Schmidt and others (1999), who mapped the distribution of all sand bars along 30 km of the river as they existed in 1935, 1965, 1973, 1984, 1990, 1992, 1993, 1996 pre-controlled flood, and 1996 post-controlled flood (Table 1). Analysis of these photographs showed that sand bars progressively eroded between 1984 and 1993; the area of high-elevation sand decreased and the area of low-elevation sand increased. These data also demonstrated that sand bar change during a given time period can be highly variable even within a single geomorphically similar reach. Additional results from this mapping are discussed in the body of this report.

Sand bar erosion and deposition during the 1990-1991 test flows was also measured by a study utilizing low-altitude aerial photographs taken during steady discharge (Cluer, 1992). No correlation between bar change and dam operations could be demonstrated, consistent with the results of repeat ground-based surveys during the same period. Also consistent with other studies, Cluer (1992) reported that bar change (erosion or deposition) was greatest when sediment concentrations were greater than average.

Table 1. Aerial photographs used to make surficial geologic maps and discharge at time of photography.

Date	(nominal scale)	Agency and Photos	Discharge (m^3/s)	Discharge (ft^3/s)
Point Hansbrough study reach				
31-Dec-35	(1:30,000*)	SCS 8433 - 8436	108	3814
14-May-65	(1:12,000)	USGS 80 - 99	708	25003
16-Jun-73	(1:14,400)	USGS 114 - 135	142	5015
21-Oct-84	(1:3000)	GCES 2-176 to 2-221	141	4979
30-Jun-90	(1:4800)	GCES 29-2 to 32-10	141	4979
11-Oct-92	(1:4800)	GCES 34-4 to 37-9	226	7981
30-May-93	(1:4800)	GCES 33-1 to 37-6	226	7981
24-Mar-96	(1:4800)	GCES 33-1 to 37-7	226	7981
4-Apr-96	(1:4800)	GCES 33-1 to 37-8	385	13596
LCR confluence study reach				
31-Dec-35	(1:30,000*)	SCS 100-107, 152-153	113	3991
14-May-65	(1:12,000)	USGS 113 - 136	708	25003
16-Jun-73	(1:14,400)	USGS 114 - 135	297	10488
21-Oct-84	(1:3000)	GCES 2-176 to 2-221	141	4979
30-Jun-90	(1:4800)	GCES 37-10 to 50-5	141	4979
11-Oct-92	(1:4800)	GCES 42-11 to 48-7	226	7981
30-May-93	(1:4800)	GCES 42-11 to 48-7	226	7981
24-Mar-96	(1:4800)	GCES 42-11 to 48-8	226	7981
4-Apr-96	(1:4800)	GCES 42-11 to 48-9	385**	13596**

* Scale varies from 1:30,000 to 1:35,000

* Discharge dropped from 385 to 226 m^3/s during period of photography.

Studies of Rich Temporal Record

Temporally-rich records of sand bar condition have been constructed by interpreting topography from historical photographs. At Badger Creek Rapids, located at RM 8, the volume of stored sand in the separation bar decreased precipitously after dam closure and never recovered (Figure 6). Webb (1996) documented the condition of Grand Canyon sand bars in 1890 based on analysis of the photography of R.B. Stanton. These photographic comparisons indicated that a significantly greater percentage of sand bars in the upstream half of Grand Canyon (upstream from about RM 110) were smaller in the 1990's than in 1890 and relatively few bars increased in size or did not change (Figure 7). Downstream from this point, erosion at some sites was balanced by deposition or no change at other sites, indicating no change in overall sediment storage.

Rich temporal records sand bar size have also been constructed using daily photographs taken by ground-based remote cameras. Cluer and Dexter (1994) documented rapid erosion events at 14 out of 20 study sites during a 2-year study conducted in 1992 and 1993. This study demonstrated that measurements made at weekly or greater time intervals will suggest misleading rates of erosion and deposition and that processes of sand bar erosion and deposition can only be fully understood by frequent and abundant temporal measurements.

Summary

These data show that both local and reach-scale processes control the size and distribution of alluvial sand bars. While daily measurements show that sand bars may scour or fill in the course of several hours or a few days, annual or less frequent measurements do indicate reach-scale and temporal trends. Schmidt and others (1999) showed that individual sites did not all receive deposition at the same rates or volumes during the 1996 controlled flood, and Wiele and others (1996) showed that this is probably caused by local adjustments between bed topography and the flow field.

STUDY AREA DESCRIPTION

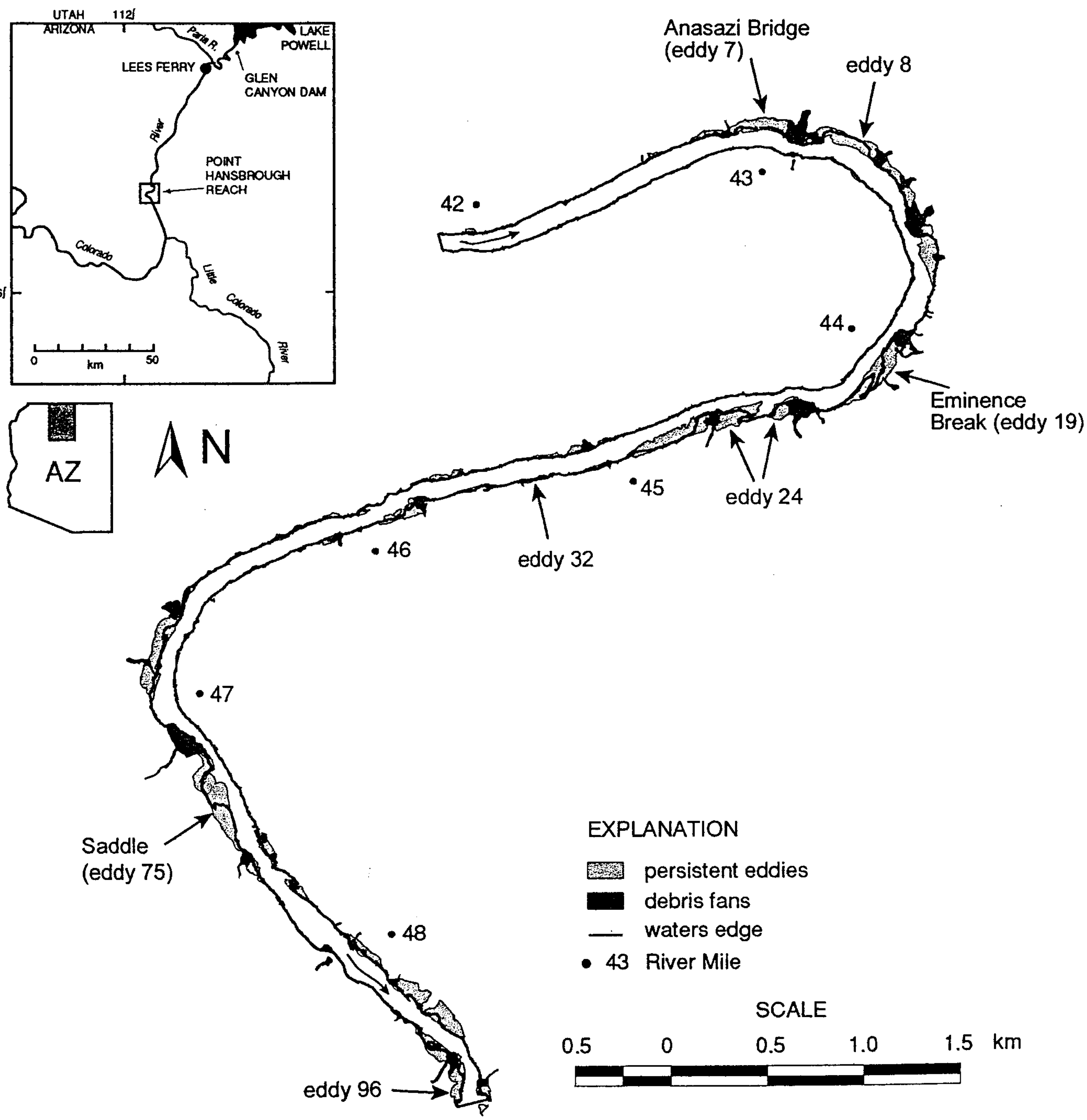
In an effort to evaluate the history of sand bar change in reaches where there is good temporal and spatial data, study sites were selected based primarily upon data availability. Therefore, sites were only chosen within reaches where Schmidt and Leschin (1995) and Schmidt and others (1999) have completed detailed mapping of surficial geology from multiple years of aerial photography. These are the Point Hansbrough Reach (also referred to as GIS Site 3) and the Little Colorado River Confluence Reach (GIS Site 5). The Little Colorado River Confluence Reach is usually subdivided into the Tapeats Gorge and Big Bend reaches. 1:2400 scale topographic (0.5-m contour interval) and orthophoto data are available for these reaches. The 10.8-km Point Hansbrough reach begins 92 km downstream from Glen Canyon Dam and 68 km downstream from Lees Ferry, Arizona (Figure 8). The Tapeats Gorge (8.0 km) reach begins 124 km downstream from Glen Canyon Dam and 100 km downstream from Lees Ferry (Figure 9). The Big Bend reach is immediately downstream from the Tapeats Gorge and is 12.1 km long (Figure 10). In some cases, we refer to these two adjacent reaches as the Little Colorado River (LCR) confluence reach.

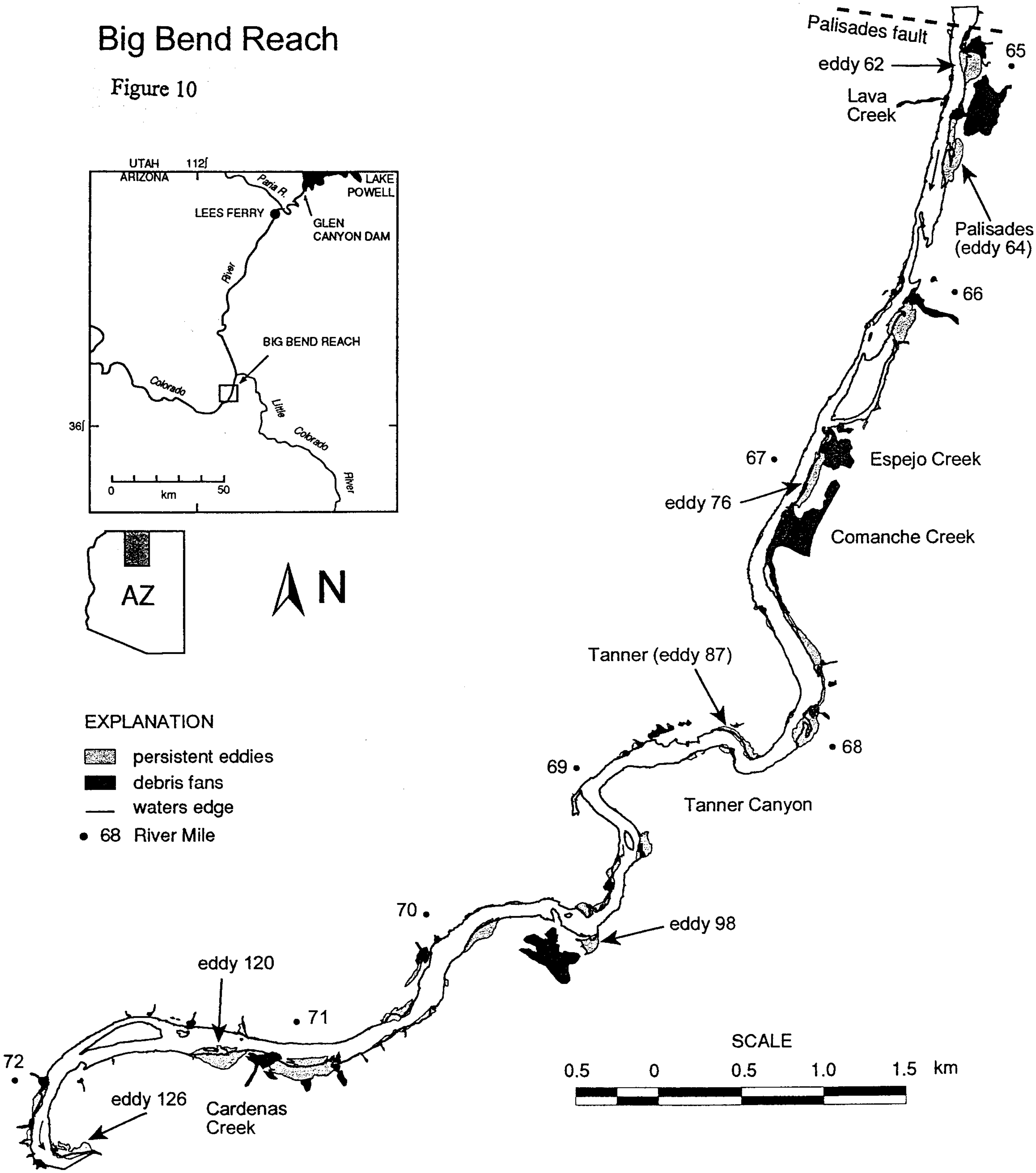
The Point Hansbrough reach is entirely within what Schmidt and Graf (1990) called lower Marble Canyon, which is one of the 11 geomorphic reaches that they identified. Lower Marble Canyon has the second-flattest reach-average channel gradient and second-largest channel width of these reaches. The width of the alluvial valley, measured as the distance between bedrock outcrops, is between 150 and 300 m, and bedrock at river level is the Cambrian Muav Limestone. The average channel width is about 100 m at a discharge of about 680 m^3/s. As measured on the large-scale topographic maps used in this study, the average gradient of the Point Hansbrough reach is 0.0008. Debris fans formed by tributaries with a drainage basin area greater than 0.01 km^2 occur at a frequency of 1.5 fans per km (Melis and others, 1995), and nearly all of the drop in channel gradient occurs near these fans.

Schmidt and Graf (1990) considered the LCR confluence to be the boundary between lower Marble Canyon and Furnace Flats. We determined, however, that significant geomorphic change of the Colorado River occurs near Palisades Creek

Point Hansbrough Reach

Figure 8





Big Bend Reach
UTAH
ARIZONA
112ʃ
Paria R.
LAKE POWELL
LEES FERRY
GLEN CANYON DAM
River
BIG BEND REACH
Colorado
Little
Colorado
River
36ʃ
0
km
50
AZ
N
EXPLANATION
persistent eddies
debris fans
waters edge
68 River Mile
Palisades fault
65
eddy 62
Lava Creek
Palisades (eddy 64)
66
67
Espejo Creek
eddy 76
Comanche Creek
Tanner (eddy 87)
68
69
Tanner Canyon
70
eddy 98
eddy 120
71
72
eddy 126
Cardenas Creek
SCALE
0.5
0
0.5
1.0
1.5
km

Figure 10

reach and the 2 km of the Tapeats Gorge that are upstream from the LCR confluence. Much higher sediment loads occur in the downstream part of the Tapeats Gorge and in the Big Bend, because more sediment is delivered to the Colorado River from the LCR than from any other tributary in Grand Canyon (Andrews, 1991)

Each of the 9 detailed study sites examined in this study contains a different suite of historical and monitoring data (Table 2). Thus, the methods of comparison and format of final results varies between these sites. Three sites are located within the Point Hansbrough Reach, four sites are located within the Tapeats Gorge, and two sites are located in the Big Bend Reach. Five of these sites are included in the long-term Northern Arizona University sand bar monitoring network (Kaplinski and others, 1995; Hazel and others, 1998) and an additional two sites have similar data for the 1996 controlled flood. Thus the integration and comparison among these data sources is common to 7 of the site reports.

METHODS

The methods used in the data analysis presented in this report are described below. Methods employed in each referenced study are not described in detail; the reader is referred to the original publications and reports for discussion of these methods. The methods of Schmidt and Leschin (1995) and Schmidt and others (1999) are summarized below because they have been slightly modified from the original reports.

Surficial Geologic Mapping

Maps of surficial geology for the study reaches have been used to determine the size of alluvial deposits and analyze areas of erosion and deposition (Schmidt, 1992; Schmidt and Leschin, 1995; and Schmidt and others, 1999). The details of this method, referred to herein as "surficial geologic mapping," are described by Schmidt and Leschin (1995) and are summarized below.

The Glen Canyon Environmental Studies program prepared detailed topographic base maps for parts of Grand Canyon, these "GIS Sites" are in Glen, Marble, and Grand Canyons. These maps were made from 1:2400 scale rectified orthophoto maps compiled

Table 2. Characteristics of detailed sites included in this study.

Site Name	River Mile	Side	Reach[1]	Eddy Number[2]	Eddy Area[3]	Current Monitoring Data[4]	Other Data[5]	Older Data[5]	Historic Photos	First Survey
Anasazi Bridge	43.1	L	PH	7	21,600	yes	RC,CI			Jul-91
Eminence Break	45.6	L	PH	19	33,200	yes	RC,LAP,CI	S		May-85
Saddle	47.1	R	PH	75	41,700	yes	RC,LAP,CI	S		Jul-91
Below LCR Confluence	61.8	R	TG	25	6,800		CI	P		Jun-74
Crash Canyon	62.4	R	TG	31	18,500	yes	RC,CI		yes	Apr-93
Salt Mine	63.1	L	TG	36	32,300					Mar-96
Carbon Creek	64.6	R	TG	54	19,900	yes				Mar-96
Palisades	65.5	L	BB	64	28,100		CI	P	yes	Jun-74
Tanner	68.2	R	BB	87	11,800	yes	RC,LAP,CI			Jul-91

[1] Study Reaches PH (Point Hansbrough), TG (Tapeats Gorge), and BB (Big Bend).

[2] The eddy numbers are those used by Schmidt and others (1999) and are for the indicated reach.

[3] Area of the persistent eddy.

[4] Sites currently included in the Northern Arizona University monitoring program. These sites are topographically and bathymetrically surveyed at least once yearly.

[5] Types of data include: remote camera (RC), campsite inventory (CI), low-altitude aerial photographs during test-flows (LAP), pre-1990 topographic surveys (S), and pre-1990 topographic profiles (P).

from 1990 aerial photographs. The printed maps have a 0.5-m contour interval and are at a scale of 1:2400.

Surficial geology was mapped directly on mylar overlays on aerial photographs for each year of aerial photography that was mapped (Table 1). Map units were established on the basis of topographic level and depositional facies (Table 3). Topographic level was inferred from stereoscopic inspection and the color of sand at different elevations that is caused by different water content. Air photos of the Colorado River in Grand Canyon show submerged deposits when water clarity is high. Sand bars are typically darker near the water's edge, because the sand is damp. High-elevation parts of bars are typically dry and appear white on photos. Additional topographic levels on dry parts of sand bars were determined stereoscopically. Schmidt and Rubin (1995) showed that some of the surfaces of these bars are longitudinally correlated and related to specific flow regimes or events.

Schmidt and Leschin (1995) also mapped the depositional form of surficial deposits according to the classification of Schmidt and Graf (1990). The bar types mapped were separation bars, reattachment bars, channel-margin deposits, and undifferentiated eddy bars. These maps were then used to calculate the size of persistent eddies as the largest area of contiguous fine-grained eddy-formed deposits in all years of available photography. Separation and reattachment bars that were not contiguous were grouped within the same persistent eddy if we observed both bars to have formed within the same recirculating eddy.

Topographic change is typically measured by field survey or by photogrammetry. These strategies are not appropriate for the comprehensive evaluation of erosion and deposition in reaches that extend 10's of km, or which involve analysis of historical aerial photography that is often of poor quality. We used a method developed by Schmidt and Leschin (1995) to compare large-scale topographic change between pre- and post-flood conditions. This method does not require photogrammetric measurements of surface elevation, and it permits comparison among historical photos for which field data are unavailable.

Areas of significant erosion or deposition, and areas of no significant change, were determined by using a geographic information system to compare the topographic level

Table 3. Description of units used in pre- and post-controlled flood geomorphic maps.

Pre-1996 deposits

submerged sand at 226 m^3s^{-1}
Coarse- to fine- grained sand, underwater, and visible on aerial photos. Extent of deposits is partially dependent on the quality of each aerial photo, the angle of the sun in the photo, the distribution of shadows in each photo, the electomagnetic wavelength used for photography, and the depth and turbidity of the river at the time of photography.

wet sand, inundated at between 226 and 550 m^3s^{-1}
Coarse- to fine-grained sand with some silt and clay. These deposits appear darker on aerial photos than adjacent or nearby subaerial deposits of similar type. This level typically occurs adjacent to the river or to submerged deposits.

fluctuating-flow sand, inundated at between 550 and 890 m^3s^{-1}
Very-fine- to fine-grained sand with widely ranging colors of light gray, brown, and reddish brown. The deposits are typically separated from the river by a single scarp and slope smoothly down into wet or submerged deposits or directly into the river. Well-defined bedforms are occasionally visible.

Little Colorado River (LCR) flood sand, inundated at less than 990 m^3s^{-1}
Mainstem alluvial deposits of the winter 1993 LCR flood occurs only downstream from the LCR confluence. Deposits are higher in elevation than fluctuating-flow sand. In the 1993 photos, these deposits have no new vegetation growing on them but may extend into previously vegetated areas.

high flow sand, inundated at between 890 and 1400 m^3s^{-1}
Medium- to very-fine grained sand, with some silty layers. Deposited by 1984-1986 Glen Canyon Dam bypass releases. High-flow deposits are typically separated from adjacent fluctuating-flow deposits by a cutbank. Dune bedforms are sometimes present and are distinct from the smaller and sharper bedforms that occur on fluctuating-flow deposits.

flood sand of 1983, inundated at between 1400 and 2700 m^3s^{-1}
Medium- to very-fine-grained sand, very well-sorted to well-sorted, distinctive very light gray with some salt- and-pepper coloring. Deposited by the 1983 spillway flood. Internal structures include ripples, climbing ripples, cross-laminations, and planar bedding. Smooth, planar sand deposits present in the 1984 aerial photos and higher in elevation than high-flow deposits were mapped as flood sand. The 1983 peak stage is often indicated by a driftwood line.

<u>**1996 Controlled-flood deposits**</u> (interpreted from aerial photos taken immediately after flood recession)

submerged sand at between 226 and 385 m^3s^{-1}
Coarse- to fine-grained sand, underwater, and visible on aerial photos. Extent of deposits is partially dependent on the quality of each aerial photo, the angle of the sun in the photo, the distribution of shadows in each photo, and the turbidity of the river at the time of photography.

wet sand, inundated at between 226 and 550 m^3s^{-1}
Coarse- to fine-grained sand with some silt and clay. These deposits appear darker on aerial photos than adjacent or nearby subaerial deposits of similar type. This level typically occurs adjacent to the river or to submerged deposits.

perched wet sand, inundated at greater than 550 m^3s^{-1}
Fine-grained sand that appears wet in photos but is located far from the river. In some cases, occurs at locations known to be more than a vertical meter from the water surface at the time of photography.

controlled-flood sand, inundated at between 550 and 1274 m^3s^{-1}
Coarse- to fine-grained sand appearing clean and fresh in photos. Deposit forms are generally sharp and well-defined. Deposits are typically lighter colored than the nearby older fine-grained deposits. In some vegetated areas and in some low-velocity areas deposits may appear wet or darker due to higher silt content.

and area of every map unit before and after the 1996 controlled flood. We used different algorithms to make this comparison, depending on how similar river discharge was in the pre- and post-flood photos (Figure 11). One algorithm was developed assuming that discharge was the same in both photo series; the other algorithm assumed that discharge in the post-flood photos was greater than in the pre-flood photos, as was the case in the Point Hansbrough reach and the upstream 4 km of the Tapeats Gorge.

We developed and calculated 2 metrics for each eddy. One metric was the ratio of actual deposition to potential deposition, termed the eddy-filling ratio. We estimated the area of potential controlled flood deposition as the area of each persistent eddy lower in elevation than the upper margin of all 1984 high-flow deposits and 1996 controlled-flood deposits. The flood of 1984 was similar in magnitude to the controlled flood of 1996. The second metric was net-normalized aggradation (NNA), which was defined as:

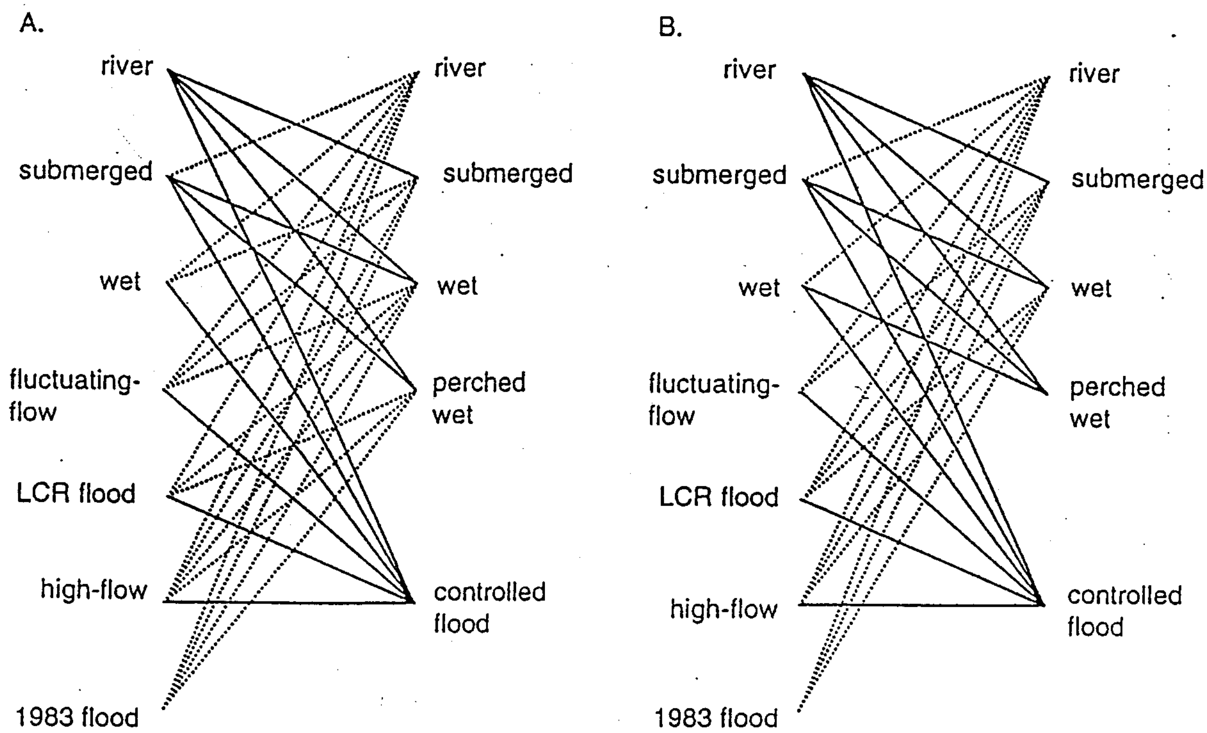
$$NNA = (A_d - A_e) / A_{pe},$$

where A_d is the area of deposition, A_e is the area of erosion, and A_{pe} is the area of the persistent eddy. These analyses all rely on the interpretation of topographic levels in the aerial photographs that are compared between years to determine areas of erosion and deposition. This type of analysis is not possible in the older photographs, which are at a less detailed scale, are of lower quality, and cannot be ground truthed.

Analysis of older photographs (1935, 1965, and 1973) required the use of the more basic measurement of the area of exposed sand in each persistent eddy. Use of this type of metric is problematic because (1) bar area is discharge dependent and discharge was not the same in all photographs and (2) the analysis does not detect changes in bar elevation. The first problem was addressed by correction of the bar area data for differences in discharge, and that method is discussed below. Because changes in bar elevation could not be determined from the older photographs, we assumed that changes in area reflect only large-scale changes in bar volume. In other words, detectable changes in bar area were assumed to indicate a corresponding shift in bar volume.

The measurements of bar area for each year that we mapped surficial geology (after correction for discharge differences) were used to calculate additional metrics.

Figure 11


A.
river
submerged
wet
fluctuating-flow
LCR flood
high-flow
1983 flood
river
submerged
wet
perched wet
controlled flood
B.
river
submerged
wet
fluctuating-flow
LCR flood
high-flow
1983 flood
river
submerged
wet
perched wet
controlled flood

These metrics were calculated only for eddies larger than 1000 m^2. The normalized bar area (or percent of eddy with exposed sand) was calculated as the ratio of the area of exposed sand in each persistent eddy to the area of that eddy. This procedurenormalizes the bar area for persistent eddies of different sizes. The degree to which each individual eddy was representative of the mean normalized bar area for a given year was estimated by the Z-score (Z), calculated as:

$$Z = \frac{X_i - \overline{X}}{s}$$

where X_i is the value for an observation, $\overline{X}$ is the mean for that year, and s is the standard deviation of the mean. This is a representation of the difference between an observation and the mean normalized by the standard deviation and is positive or negative depending on whether the observation is greater or less than the mean. The consistency of individual eddies was estimated by the average Z-score, which is the sum of the absolute values of the Z-scores for every year mapped.

Comparison Between Surficial Geologic Maps and Topographic Surveys

The surficial geologic maps were made using aerial photographs and involved several steps that introduced the possibilities for error, including transfer between map scales and the actual interpretation of the photographs. Measurements of sand bar erosion and deposition by topographic and bathymetric surveys may have survey errors and boat position errors, but are extremely accurate compared to the analysis of aerial photographs. The topographic data, therefore, are considered as a standard to which other measurements can be compared.

The measured values for areas of erosion and deposition reported by each study can not be compared directly because the measurement boundaries differ between the methods. Spatial analysis of the areas of agreement and disagreement, considering only areas of overlapping data, is most appropriate.

Because the data for each method are available in geo-referenced format, comparison of the results is best done in a geographic information system (GIS). The comparison process included three steps: (1) obtain or create ARC/INFO coverages of erosion-deposition maps for each method, (2) produce maps that overlay these maps for each site, and (3) perform a statistical analysis of the level of agreement between the methods. This process was repeated for each period of comparison for each of the 7 sites where this comparison was made.

Schmidt and Leschin (1995) and Leschin and others (1996) produced erosion-deposition maps for the study reaches for 1984-90, 1990-92, 1992-93 (LCR Confluence reach only), 1993-March 1996 (LCR Confluence reach only), 1992-March 1996 (Point Hansbrough Reach only), and March 1996-April 1996. The method used to develop these maps is discussed above, and the ARC/INFO coverages for these maps are part of the USU database. The topographic data collected by the NAU monitoring program are not, however, regularly converted into erosion-deposition maps. We created erosion-deposition maps from the NAU topographic database for the time periods that could be compared with the surficial geologic maps. For example, the March 24 to April 4, 1996 erosion-deposition maps were compared with the February 17 to April 15, 1996 topographic survey data. Measurements by different methods have rarely, or never, been made on the same day, and we must assume that no changes occurred between the nearest overlapping days (i.e. between February 17 and March 24).

The topographic data were acquired in the Arizona State Plane coordinate system. These coordinate files of irregularly spaced points were converted into a regular grid using the Delaunay triangulation with linear interpolation procedure within **Surfer** mapping software (Golden Software, Inc., 1997). These grid files were plotted and checked for accuracy. The first grid file of the comparison set was subtracted from the second grid to create a difference grid. The final difference grids were imported into ARC/INFO and converted into coverages consisting of polygons of erosion, deposition, and no significant change. Elevation differences between topographic surveys greater than 25 cm are considered significant (J.E. Hazel, pers. comun.). Thus, regions of greater than 25 cm of deposition or erosion were grouped to create the respective erosion and deposition polygons and regions of less than 25 cm of change were grouped to create the "no change" polygons. These coverages were then compared with the coverages showing erosion and deposition determined from the surficial geologic mapping.

Consistency between the surficial geologic maps and the topographic surveys was evaluated by visual inspection for areas of agreement and disagreement, computation of error matrices, and calculation of error statistics. These statistics include the areas and percentages of agreement and disagreement and calculation of the kappa coefficient, estimated by the khat statistic. This statistic is a measure of the actual agreement minus the agreement expected by chance [*Naesset,* 1996]. The possible values of khat range from $-\infty$ to 1, and values > 0.4 are considered to represent good agreement between the actual and predicted values. Khat, K, was calculated as,

$$\hat{K} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} x_{i+}x_{+j}}{N^2 - \sum_{i=1}^{r} x_{i+}x_{+j}}$$

where N is the number of observations, x_{i+} and x_{j+} are row and column sums, respectively, and,

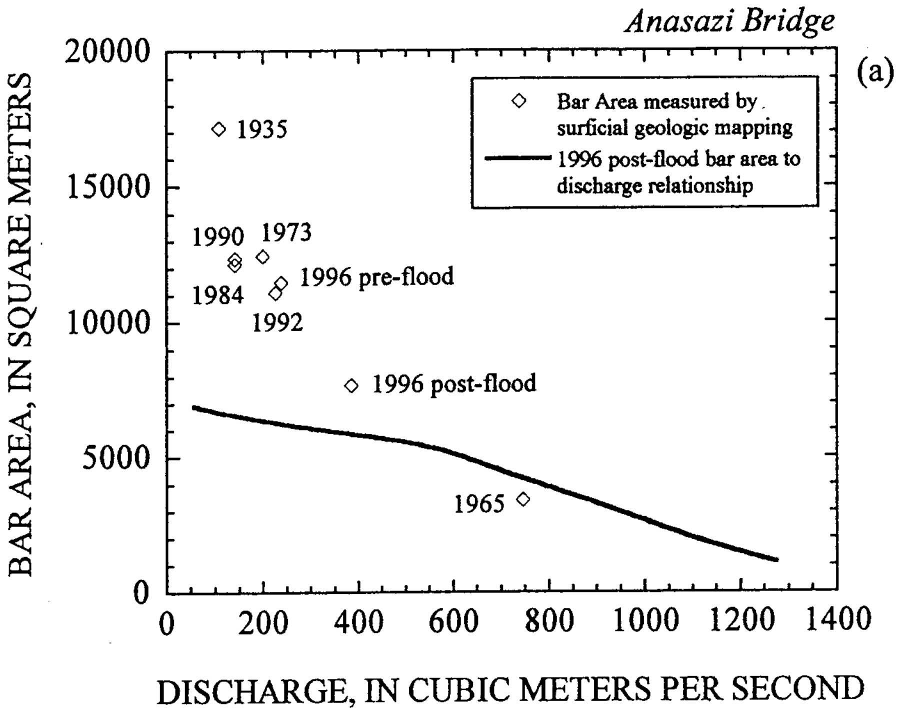
$$\sum_{i=1}^{r} x_{ii}$$

is the sum of the areas of agreement.

Correction of Surficial Geologic Maps for Discharge Differences

Many of the data incorporated in this study were derived from the analysis of aerial and oblique photographs. In all of these methods, bar area is dependent on discharge at the time of the photograph. Most of the surficial geologic maps were made from aerial photographs taken at constant known discharge (Table 1). The photographs used in the test-flow air photo study were taken at constant flows of 142 m^3/s. The oblique photographs used to make rectified images of sand bars, however, were taken at both constant and fluctuating discharges. We used the topographic data for the sites where it is available to correct for discharge differences between the surficial geologic maps. For 7 sites where detailed topographic data and stage-discharge relations were available, sand-bar area to discharge curves were created. These relations show the area of each bar as a function of discharge, based on the bar's topography following the 1996 controlled flood. On the same graph, the area of the sand bar measured from each surficial geologic map is plotted against the discharge of the aerial photography that was used to make each map (Figure 12). The estimated area of exposed sand at a common 226 m^3/s for each year of surficial geologic mapping was determined by fitting the 1996 bar area-to-discharge relationship to the area determined in each year by surficial geologic mapping. Discharge-corrected values of bar area for every eddy in each reach were calculated by determining the average of the individual site corrections in each reach for each year. The corrected and uncorrected measurements of bar area determined by surficial geologic mapping are listed in Table 4.

This approach presents the most accurate portrayal of bar size from the older photographs that is possible and is the only means of interpreting the condition of sand bars from 1965 photographs, which were taken at high discharge. This correction was applied to the surficial geologic map data only. Although the measurements from the topographic/bathymetric surveys could be used to calculate area above any discharge for every measurement, the reported values are for area above 142 m^3/s only (Kaplinski and others, 1995). The measurements made from low-altitude aerial photographs were also collected at 142 m^3/s. In summary, the time series plots contain data for bar area above 142 m^3/s for the low-altitude aerial photographs and topographic/bathymetric surveys and bar area above 226 m^3/s for the surficial geologic maps. This difference is not significant because of the normalization process used in the development of the time series. We must, however, make the additional assumption that changes in bar area exposed above the 226 m^3/s stage are proportionally similar to changes above the 142 m^3/s stage.


Anasazi Bridge
(a)
Bar Area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1935
1990
1973
1984
1996 pre-flood
1992
1996 post-flood
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
20000
15000
10000
5000
0
200
400
600
800
1000
1200
1400

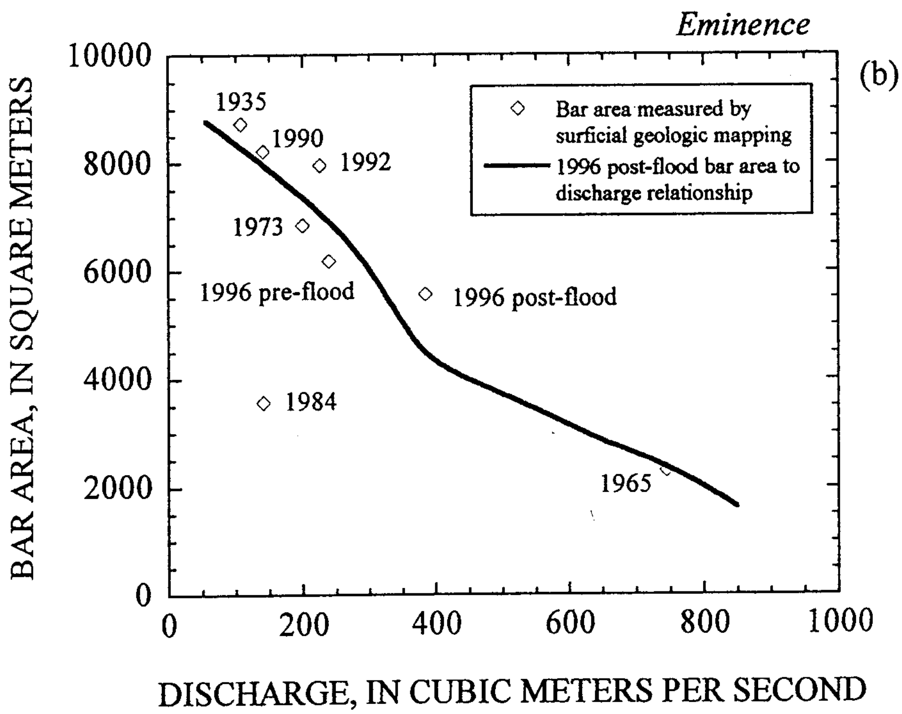
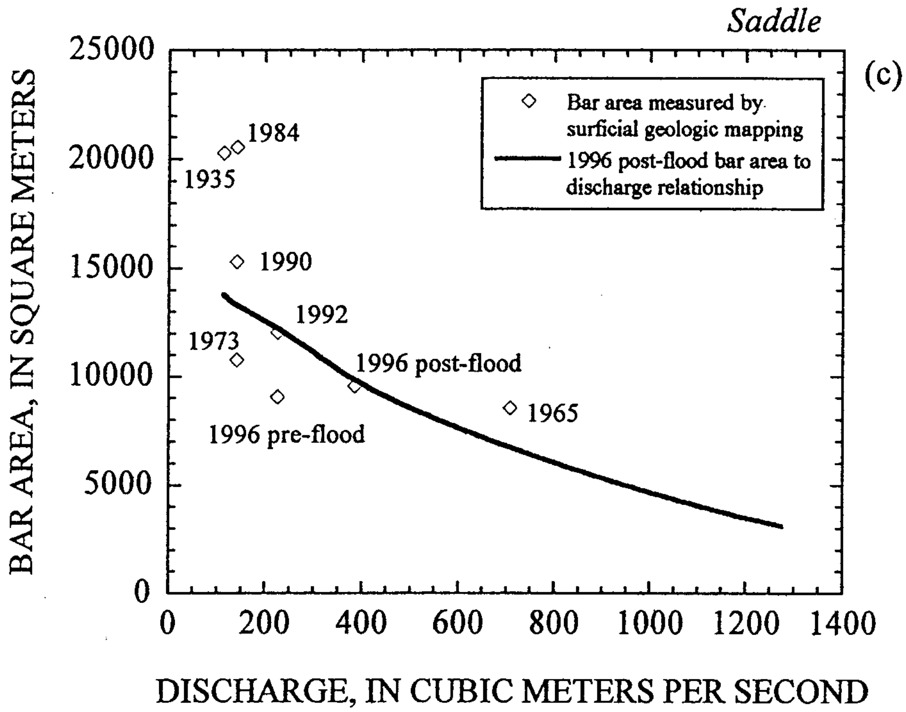

Eminence
(b)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1935
1990
1992
1973
1996 pre-flood
1996 post-flood
1984
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
10000
8000
6000
4000
2000
0
200
400
600
800
1000

Figure 12


Saddle
(c)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1984
1935
1990
1992
1973
1996 post-flood
1965
1996 pre-flood
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND

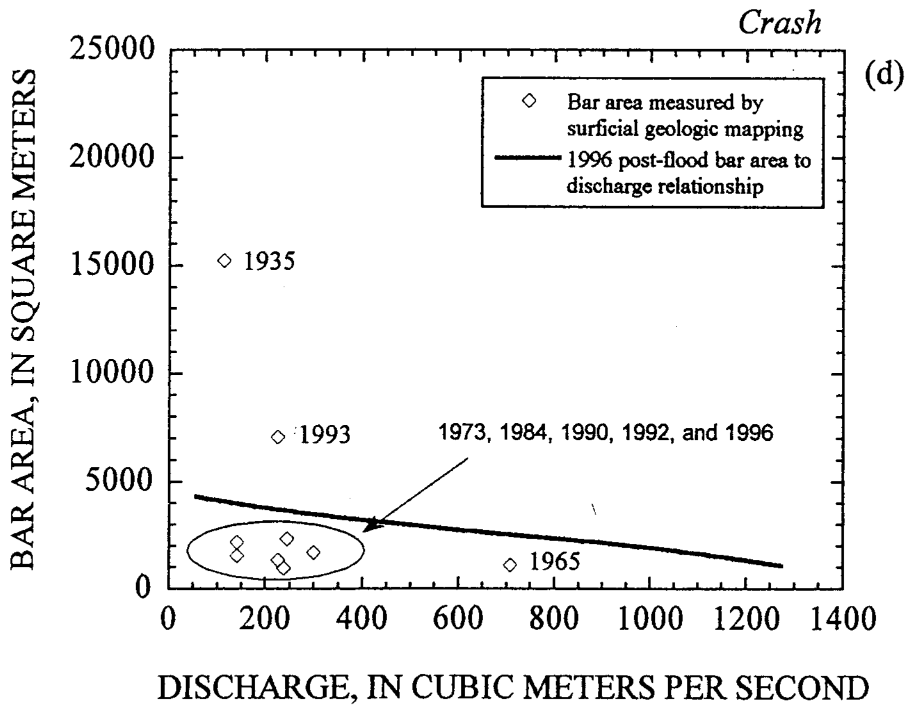
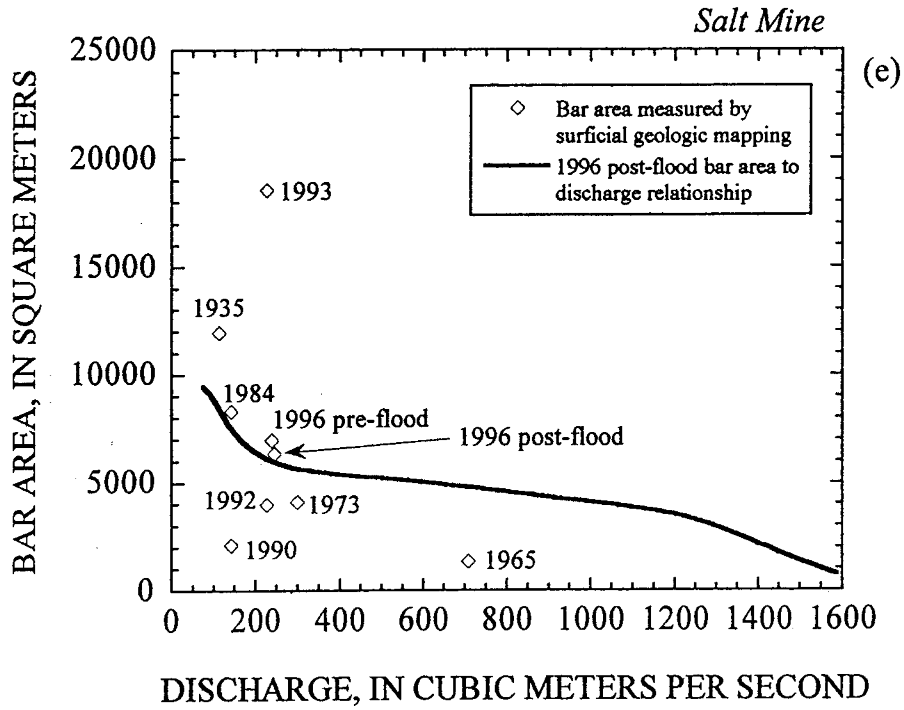
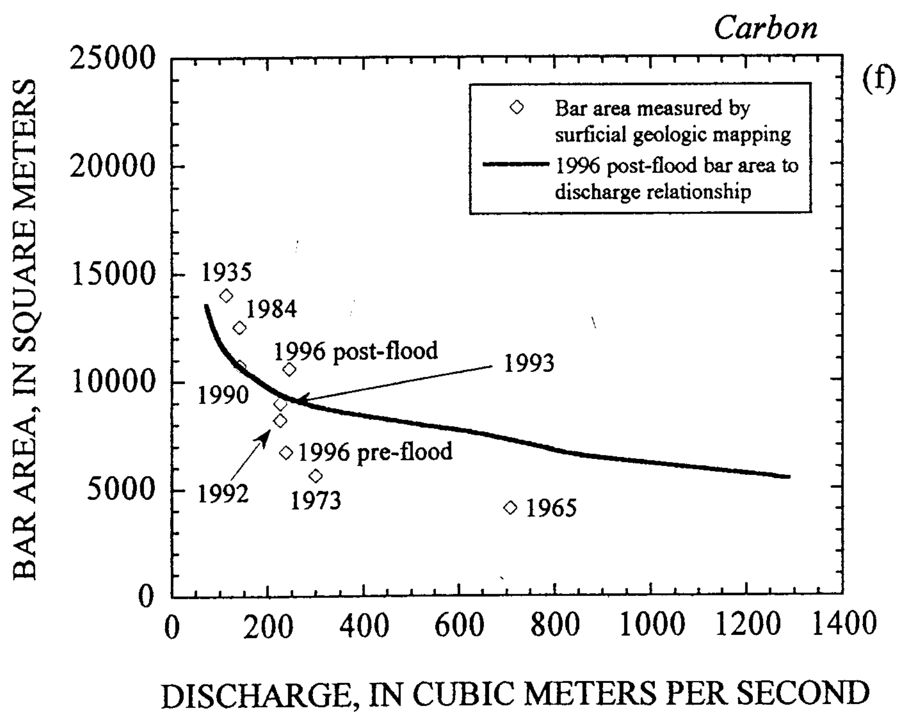

Crash
(d)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1935
1993
1973, 1984, 1990, 1992, and 1996
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND

Figure 12


Salt Mine
(e)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1993
1935
1984
1996 pre-flood
1996 post-flood
1992
1973
1990
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
1200
1400
1600


Carbon
(f)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1935
1984
1996 post-flood
1993
1990
1996 pre-flood
1992
1973
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
1200
1400

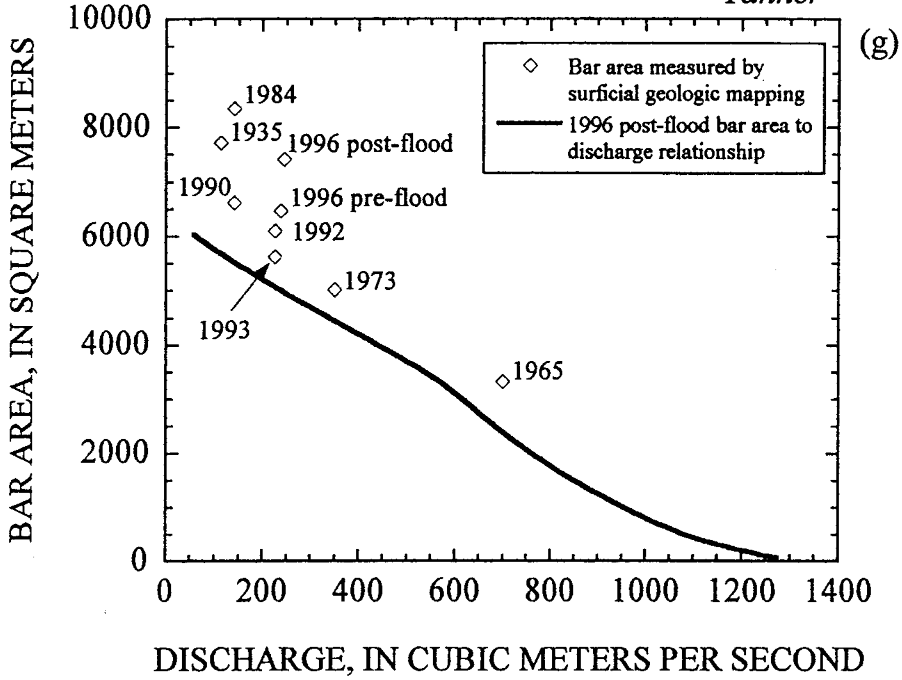

(g)
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1984
1935
1996 post-flood
1990
1996 pre-flood
1992
1973
1993
1965
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
10000
8000
6000
4000
2000
0
200
400
600
800
1000
1200
1400

Figure 12

Table 4a. Area o f exposed sand in persistent eddies larger than 1000 m^2 in the Point Hansbrough Reach from surficial geologic mapping (1935-1996).

Eddy	Eddy	Area of exposed sand, uncorrected, in thousands of square meters								Area of exposed sand, corrected, in thousands of square meters[2]							
Number	Area[1]	1935	1965	1973	1984	1990	1992	1996(a)	1996(b)	1935	1965	1973	1984	1990	1992	1996(a)	1996(b)
4	1.3	0.1	0.0	0.2	1.1	0.6	1.0	0.8	1.0	0.1	0.0	0.2	0.9	0.5	1.0	0.8	1.1
6	4.8	2.9	0.5	1.2	4.2	4.0	3.3	3.4	3.2	2.6	1.0	1.1	3.6	3.6	3.3	3.3	3.8
7	21.6	17.1	3.4	12.4	12.1	12.3	11.1	11.5	10.7	15.4	7.1	11.3	10.4	11.3	11.0	11.4	12.5
8	25.5	18.6	6.5	12.8		10.8	11.0	9.0	9.5	16.7	13.4	11.7		9.9	10.8	9.0	11.0
12	12.6	6.9	4.4	5.7	8.7	9.4	9.2	8.2	8.3	6.2	9.1	5.2	7.4	8.6	9.1	8.2	9.6
14	22.0	17.7	1.5	7.7	3.8	2.2	2.7	2.9	3.5	15.9	3.2	7.0	3.2	2.1	2.7	2.9	4.1
19	33.2	11.8	8.0	15.9	15.0	17.4	16.2	16.7	16.4	10.6	16.6	14.5	12.8	16.0	16.0	16.7	19.0
24	27.8	19.5	9.4	14.0	16.6	10.8	9.1	10.1	12.5	17.5	19.6	12.8	14.2	9.9	9.0	10.1	14.5
26	28.6	20.0	7.4	8.5	16.6	10.4	11.1	8.9	6.6	18.0	15.3	7.8	14.2	9.6	11.0	8.9	7.7
27	1.5	0.9	0.3	0.2	1.0	0.7	0.8	0.7	0.8	0.8	0.7	0.2	0.8	0.7	0.8	0.7	0.9
28	2.0	0.8	0.2	1.0	1.2	0.9	1.0	0.3	0.3	0.7	0.5	0.9	1.0	0.8	1.0	0.3	0.4
30	3.4	2.1	1.7	2.4	2.3	2.7	2.4	2.4	2.2	1.9	3.5	2.2	2.0	2.4	2.4	2.4	2.6
31	2.3	2.1	1.2	1.5	1.7	1.9	1.6	1.6	2.1	1.9	2.5	1.4	1.5	1.7	1.6	1.6	2.4
33	2.2	0.5	0.1	0.9	1.4	1.4	1.2	0.8	0.9	0.5	0.2	0.8	1.2	1.3	1.2	0.8	1.0
38	2.5	0.9	0.1	2.1	1.4	2.1	1.9	2.1	0.9	0.8	0.3	1.9	1.2	1.9	1.8	2.0	1.1
39	2.3	1.1	0.6	0.9	1.9	1.2	0.9	0.9	0.7	1.0	1.3	0.9	1.6	1.1	0.9	0.9	0.9
40	2.7	0.3	1.0	1.2	2.2	1.9	1.8	1.6	1.7	0.3	2.1	1.1	1.9	1.7	1.7	1.6	2.0
44	10.7	5.4	1.7	2.6	5.0	5.3	4.0	3.3	3.4	4.8	3.6	2.4	4.2	4.8	3.9	3.3	4.0
47	1.3	0.0	0.0	0.2	0.3	0.3	0.3	0.1	0.3	0.0	0.0	0.2	0.3	0.2	0.3	0.1	0.3
50	2.2	1.8	1.2	0.4	1.3	1.4	1.9	0.5	0.7	1.7	2.4	0.4	1.1	1.3	1.8	0.5	0.8
51	2.8	1.7	0.6	1.2	2.0	2.4	2.1	1.6	1.4	1.6	1.3	1.1	1.7	2.2	2.1	1.6	1.6
52	2.0	1.1	0.8	0.5	1.3	1.2	1.3	1.1	1.0	1.0	1.6	0.5	1.1	1.1	1.3	1.1	1.2
55	1.8	1.5	0.2	0.0	1.0	1.0	0.9	0.6	0.6	1.3	0.4	0.0	0.9	0.9	0.9	0.6	0.7
60	1.1	0.0	0.2	0.2	0.7	0.8	0.8	0.8	0.4	0.0	0.3	0.1	0.6	0.7	0.8	0.8	0.4
61	3.2	2.6	0.0	0.9	0.7	0.3	1.1	0.6	0.8	2.3	0.0	0.8	0.6	0.3	1.1	0.6	0.9
67	30.5		14.5	11.5	19.4	19.8	18.5	11.7	10.2		30.2	10.5	16.6	18.3	18.3	11.7	11.8
75	41.7	21.4	12.7	14.2	30.2	21.1	17.4	14.1	16.0	19.3	26.5	12.9	25.9	19.5	17.2	14.1	18.6
83	5.0	0.0	0.8	0.7	3.8	2.7	2.3	2.8	2.5	0.0	1.6	0.6	3.2	2.5	2.3	2.8	2.9
84	5.2	0.0	0.4	1.4	3.3	3.8	3.7	3.8	3.1	0.0	0.8	1.3	2.8	3.5	3.7	3.7	3.6
87	5.7	0.7	0.0	2.8	4.3	1.8	1.8	1.3	3.0	0.7	0.0	2.5	3.7	1.7	1.8	1.3	3.5
88	1.0	0.9	0.0	0.0	0.5	0.7	0.3	0.3	0.4	0.8	0.0	0.0	0.4	0.6	0.3	0.3	0.5
89	7.0	5.3	1.6	3.4	5.9	4.7	3.2	4.6	3.3	4.7	3.4	3.1	5.1	4.3	3.2	4.6	3.8
91	14.5	6.1	2.6	2.5	7.0	6.1	6.8	6.6	6.0	5.5	5.5	2.3	6.0	5.6	6.8	6.6	7.0
94	12.4	6.9	2.2	2.3	4.4	6.0	5.6	6.5	5.7	6.2	4.7	2.1	3.7	5.5	5.6	6.4	6.7
95	17.2	3.1	1.5	12.9	5.9	8.4	7.4	7.2	6.3	2.8	3.2	11.7	5.1	7.7	7.3	7.2	7.4
96	14.9	6.6	2.6	5.3	6.0	7.6	6.4	8.7	8.2	5.9	5.3	4.9	5.1	7.0	6.3	8.6	9.6
97	3.6	1.8	0.7	0.8	0.7	1.7	1.2	2.6	2.0	1.6	1.4	0.7	0.6	1.6	1.2	2.6	2.3

[1] Area of persistent eddy in thousands of square meters.

[2] Correction for discharge differences between aerial photographs.

Table 4b. Area o f exposed sand in persistent eddies larger than 1000 m^2 in the Tapeats Gorge Reach from surficial geologic mapping (1935-1996).

Eddy	Area	1935	1965	1973	1984	1990	1992	1993	1996(a)	1996(b)	1935	1965	1973	1984	1990	1992	1993	1996(a)	1996(b)
1	23.2	18.2	0.9	1.8	2.8	4.2	3.1	2.5	3.3	3.4	15.8	1.7	2.0	2.4	3.0	3.1	2.5	3.3	3.5
2	2.9		0.2	0.1	2.0	1.0	0.6	0.9	0.8	1.0		0.4	0.1	1.7	0.7	0.6	0.9	0.8	1.0
4	1.4		0.0	0.3	0.9	0.8	0.6	0.4	0.5	0.0		0.0	0.3	0.8	0.6	0.6	0.4	0.5	0.0
7	1.4	1.4	0.1	0.0	0.4	0.1	0.1	0.1	0.1	0.3	1.2	0.1	0.0	0.4	0.1	0.1	0.1	0.1	0.3
8	7.4	4.6	0.7	0.8	1.7	1.6	2.1	2.2	1.6	1.2	4.0	1.3	0.9	1.5	1.1	2.1	2.2	1.6	1.2
9	3.4	1.6	2.0	1.4	3.0	1.3	1.1	0.9	0.7	1.3	1.3	3.6	1.6	2.7	0.9	1.1	0.9	0.7	1.4
10	15.2	11.9	1.2	1.6	3.6	5.8	3.7	4.6	2.4	4.3	10.4	2.2	1.7	3.2	4.1	3.7	4.6	2.4	4.4
11	3.7	2.7	0.5	0.6	1.0	1.3	0.7	0.6	0.8	1.1	2.4	0.9	0.7	0.9	0.9	0.7	0.6	0.8	1.1
12	8.9	6.6	1.6	2.0	3.8	4.2	2.9	2.7	2.4	4.6	5.7	3.0	2.2	3.3	3.0	2.9	2.7	2.4	4.6
14	11.8	9.6	2.2	3.9	3.5	2.8	6.2	3.1	2.7	2.5	8.3	4.0	4.3	3.1	2.0	6.2	3.1	2.8	2.5
15	11.0	3.7	1.6	2.0	3.6	3.0	9.9	3.1	2.0	2.2	3.2	2.9	2.2	3.2	2.2	9.9	3.1	2.0	2.2
16	1.9	1.8	0.0	0.1	0.1	0.2	0.3	0.3	0.3	0.0	1.6	0.0	0.2	0.1	0.1	0.3	0.3	0.3	0.0
19	2.3	0.3	0.2	0.0	0.4	0.6	0.5	0.4	0.5	1.1	0.3	0.4	0.0	0.4	0.4	0.5	0.4	0.5	1.1
20	6.1	2.3	2.7	2.6	3.8	2.7	2.6	2.0	2.6	3.3	2.0	4.8	2.9	3.4	1.9	2.6	2.0	2.6	3.4
21	1.4	0.3	0.0	0.1	0.1	0.1	0.2	0.3	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.2	0.3	0.1	0.2
22	1.8	0.4	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.3	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1
24	1.3	0.5	0.3		0.5	0.1	0.3	0.5	0.1	0.4	0.5	0.5		0.4	0.1	0.3	0.5	0.1	0.4
25	6.8	1.4	1.1		3.2	4.0	3.3	5.0	3.8	2.5	1.2	2.1		2.8	2.9	3.3	5.0	3.8	2.5
26	10.3	8.0	0.5		1.6	0.9	1.9	6.2	4.0	0.6	7.0	0.9		1.4	0.6	1.9	6.2	4.0	0.6
27	2.7	1.9	1.2	1.6	2.0	1.7	1.8	2.0	1.5	1.8	1.6	2.2	1.7	1.8	1.2	1.8	2.0	1.5	1.8
28	5.0	3.8	1.8	2.8	3.7	2.8	2.7	3.5	1.9	2.6	3.3	3.2	3.1	3.3	2.0	2.7	3.5	2.0	2.7
30	13.6	5.3	1.3	1.5	2.9	2.5	2.9	8.5	7.1	2.8	4.6	2.3	1.7	2.6	1.7	2.9	8.5	7.2	2.8
31	18.5	15.2	1.1	1.7	2.2	1.5	1.3	7.0	0.9	2.3	13.2	1.9	1.9	1.9	1.1	1.3	7.0	0.9	2.3
32	10.1	6.0	0.7	2.8	4.5	3.0	3.8	5.2	4.2	7.0	5.2	1.2	3.2	4.0	2.2	3.8	5.2	4.3	7.1
33	5.9	3.8	0.1	0.2	0.8	0.7	2.2	1.9	1.2	1.0	3.3	0.2	0.2	0.7	0.5	2.2	1.9	1.2	1.0
35	1.8	0.2	0.0	0.9	0.7	0.5	0.8	1.3	0.0	0.0	0.1	0.1	1.0	0.6	0.4	0.8	1.3	0.0	0.0
36	32.3	11.9	1.3	4.1	8.3	2.1	4.0	18.5	6.9	6.3	10.4	2.4	4.5	7.3	1.5	4.0	18.5	7.1	6.4
39	5.4	1.4	0.6	1.0	1.8	0.9	0.9	0.7	0.4	2.2	1.2	1.1	1.1	1.6	0.6	0.9	0.7	0.4	2.2
40	6.6	3.0	0.1	0.3	1.5	0.0	0.1	0.4	0.1	1.9	2.6	0.2	0.3	1.3	0.0	0.1	0.4	0.1	1.9
41	15.2	12.8	3.0	5.4	8.2	10.0	3.0	4.1	6.5	8.4	11.1	5.5	6.0	7.2	7.1	3.0	4.1	6.6	8.5
42	7.3	5.8	0.1	1.1	0.7	0.6	0.5	2.6	0.4	2.6	5.0	0.2	1.2	0.6	0.4	0.5	2.6	0.4	2.6
43	17.6	10.3	3.7	2.7	4.1	4.0	4.3	8.4	2.1	3.7	8.9	6.6	3.0	3.7	2.8	4.3	8.4	2.1	3.8
44	1.0	0.5	0.2	0.3	0.5	0.2	0.4	0.3	0.3	0.4	0.5	0.3	0.4	0.4	0.2	0.4	0.3	0.3	0.4
45	30.8	21.2	8.9	8.4	24.1	19.3	13.9	14.2	4.7	12.5	18.5	16.1	9.4	21.3	13.7	13.9	14.2	4.8	12.7
47	16.5	8.6	1.4	3.6	7.2	5.1	2.0	4.2	0.7	1.7	7.5	2.6	4.0	6.3	3.6	2.0	4.2	0.7	1.7
49	6.8	4.7	4.8	3.7	3.3	2.8	3.5	2.4	2.4	3.5	4.1	8.6	4.1	2.9	2.0	3.5	2.4	2.5	3.6
50	1.3	1.2	0.1	0.6	1.2	0.8	0.8	1.0	0.4	0.9	1.1	0.2	0.6	1.1	0.6	0.8	1.0	0.5	0.9
51	8.4	5.0	2.4	3.4	4.8	5.1	4.6	3.6	3.5	3.3	4.4	4.4	3.7	4.3	3.6	4.6	3.6	3.6	3.4
54	19.9	14.0	4.1	5.6	12.5	10.7	8.2	9.0	6.7	10.5	12.2	7.3	6.2	11.1	7.6	8.2	9.0	6.8	10.7
56	2.8	1.6	0.0	0.1	0.5	0.9	1.8	0.4	1.5	0.2	1.4	0.1	0.2	0.4	0.6	1.8	0.4	1.6	0.2

[1] Area of persistent eddy in thousands of square meters.

[2] Correction for discharge differences between aerial photographs.

Development of the Time Series of Bar Change

Site-Specific Time Series

One of the project goals was to compile all the existing data that quantified bar size into a single expanded time series of sand bar erosion and deposition. The integration of these data must be general because each study that has quantified bar size has used different measurement methods and made those measurements within different boundary areas. The time series that we constructed rely on the primary assumption that each method, regardless of measurement area boundary and units of reported data, independently and accurately characterizes bar size for the period evaluated. In other words, even though measured values of erosion and deposition vary, each method should, for a comparable time period at a given site, show the same general response.

The values for bar area or volume for the 2 data sets were normalized to the area measured on a given date. That is, the measurements made by each method were normalized by dividing each measurement by the area measured on the date chosen for nonmalization. The date to which the data were normalized was always the date of the closest overlapping measurements. In cases where measurements were made by different methods on the same date, that date was used for normalization (the date on which the bar area would equal 1.0). In cases where a lag occurred between normalization dates, we assumed that no change occurred in this lag period. Where three data sets were compared, the same procedure was followed to add the third data series. For example, at Saddle measurements were made by topographic/bathymetric survey and low-altitude aerial photographs on September 29 and 30, 1990, respectively. The survey data were then normalized by dividing each measurement by the area measured on September 29, 1990 and the low-altitude aerial photograph data were normalized by dividing each measurement by the area measured on September 30, 1990. Bar area was not measured by surficial geologic mapping on or near these dates. The nearest overlapping measurements were surficial geologic map measurements of June 30, 1990 and survey measurements of July 14, 1990. The surficial geologic map data were therefore normalized by dividing each measured area by the area measured on June 30, 1990 and then multiplying that value by the normalized area of the bar measured by survey on July

14, 1990. The normalized data were then plotted on a common time series. Error bars have not been included in these plots because the reported data used in this study did not include individual error estimates.

Reach-Average Time Series

Average time series for each of the three study reaches were calculated from the surficial geologic map data. These time series, therefore, extend from 1935 to 1996 and do not explicitly incorporate any of the detailed measurements from specific study sites. The reach-average time series do, however, use the discharge-corrected measurements of bar area from the surficial geologic maps. The time series was constructed by averageing the normalized values of bar area for each year of mapping for each reach. The error in the average values was estimated as the 90% confidence interval.

Analysis of Older Topographic Data

Topographic data from as early as 1985 were incorporated into the site analyses for the sites where these data were available, which are Eminence Break and Saddle Canyon. These data are in the format of either hand drawn or printouts of computer-generated topographic contour maps. Some maps contain only enough points to define a set of topographic profiles and are not complete contour maps. Although the coordinate system and units of each survey are usually different, all maps include at least 2 common reference points. Comparisons between the older maps were made by constructing topographic profiles from each map. The location for the profiles we constructed from the Saddle Canyon reattachment bar and Eminence Break separation bar data were first established by the U.S. Bureau of Reclamation in 1985 (Ferrari, 1985). The profiles we constructed from the Eminence Break reattachment bar data were established in this study. Some of the more recent data collected in the NAU monitoring program were added to these profiles. The NAU topographic data were used to generate contour maps using a triangulation with linear interpolation gridding procedure with **Surfer** mapping software. These maps were printed at the same scale as the older maps and with the same common reference points so the maps could be overlain. These maps were then used to generate additional topographic profiles.

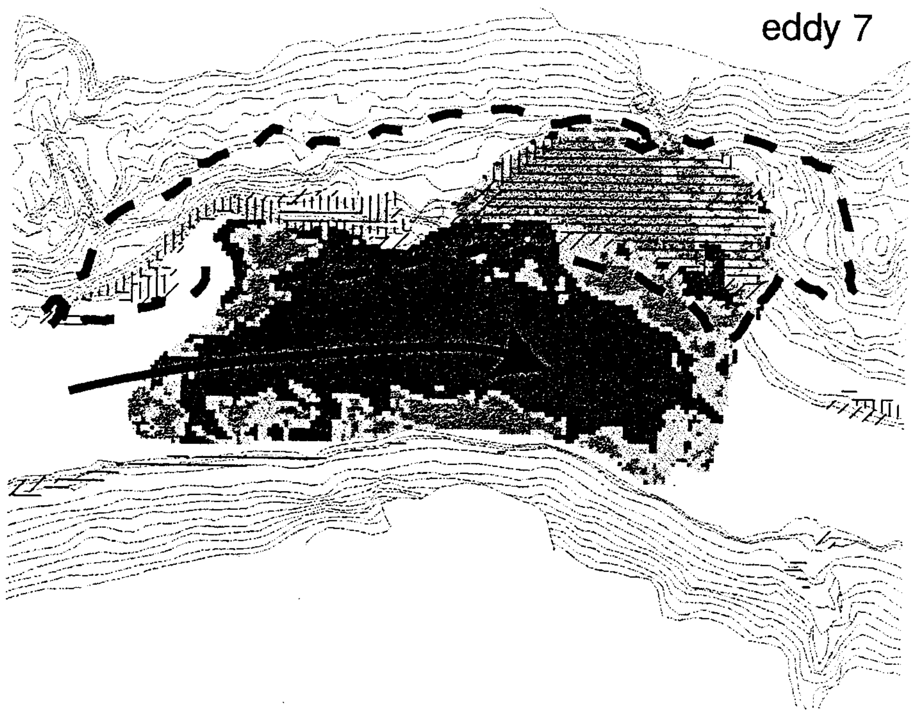
RESULTS

Comparability of Areas of Erosion and Deposition as Determined from Field Surveys and Air Photo Interpretation

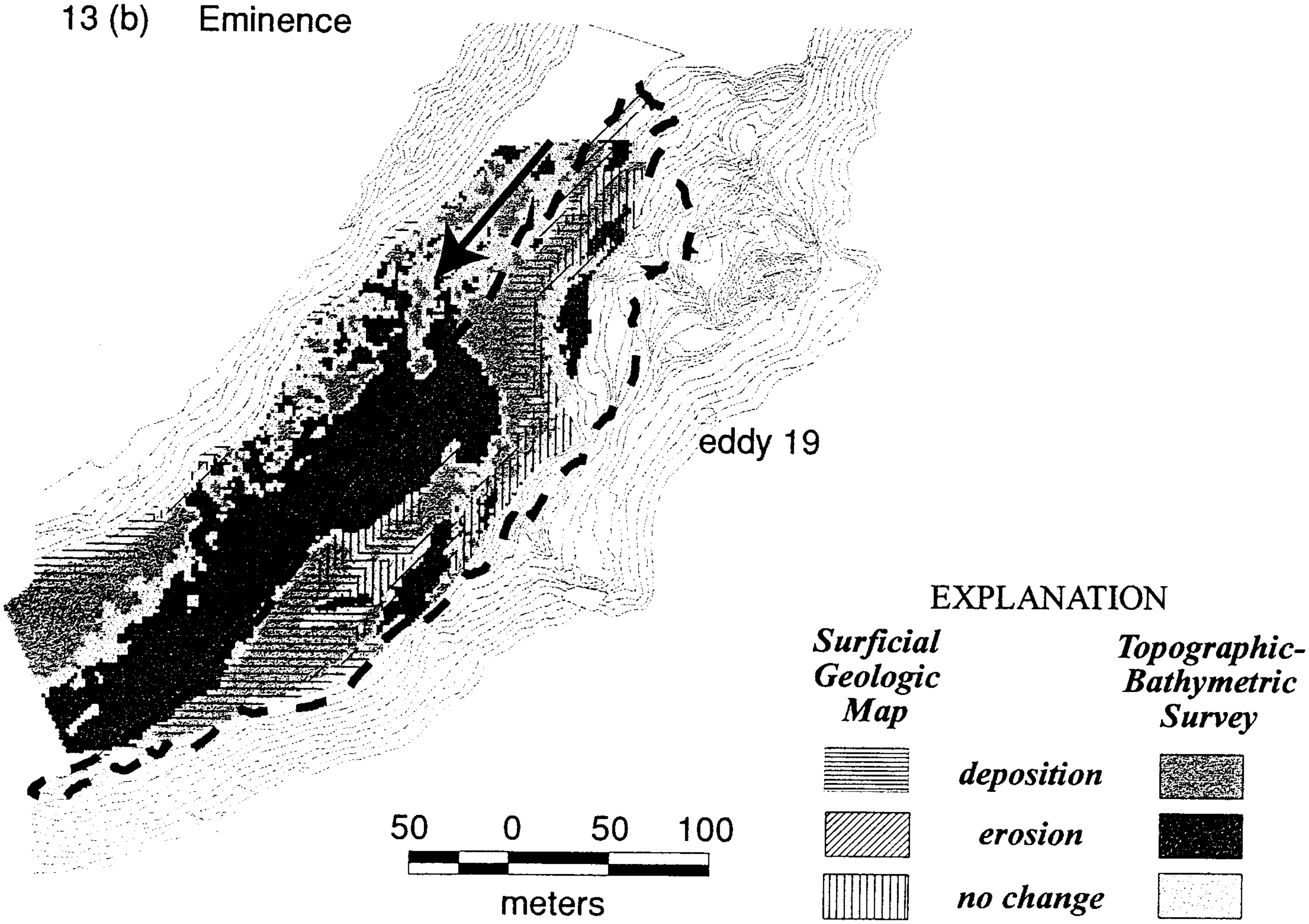
The accuracy of the surficial geologic mapping method was evaluated by comparing the maps showing areas of significant erosion and deposition (Schmidt and others, 1999), with field surveys measured by Hazel and others (1999) for similar time periods. We compared pre- and post-controlled flood maps and surveys for 6 persistent eddies. We compared areas of erosion and deposition determined from air photo analysis with areas where surveys showed topographic change greater than 0.25 m.

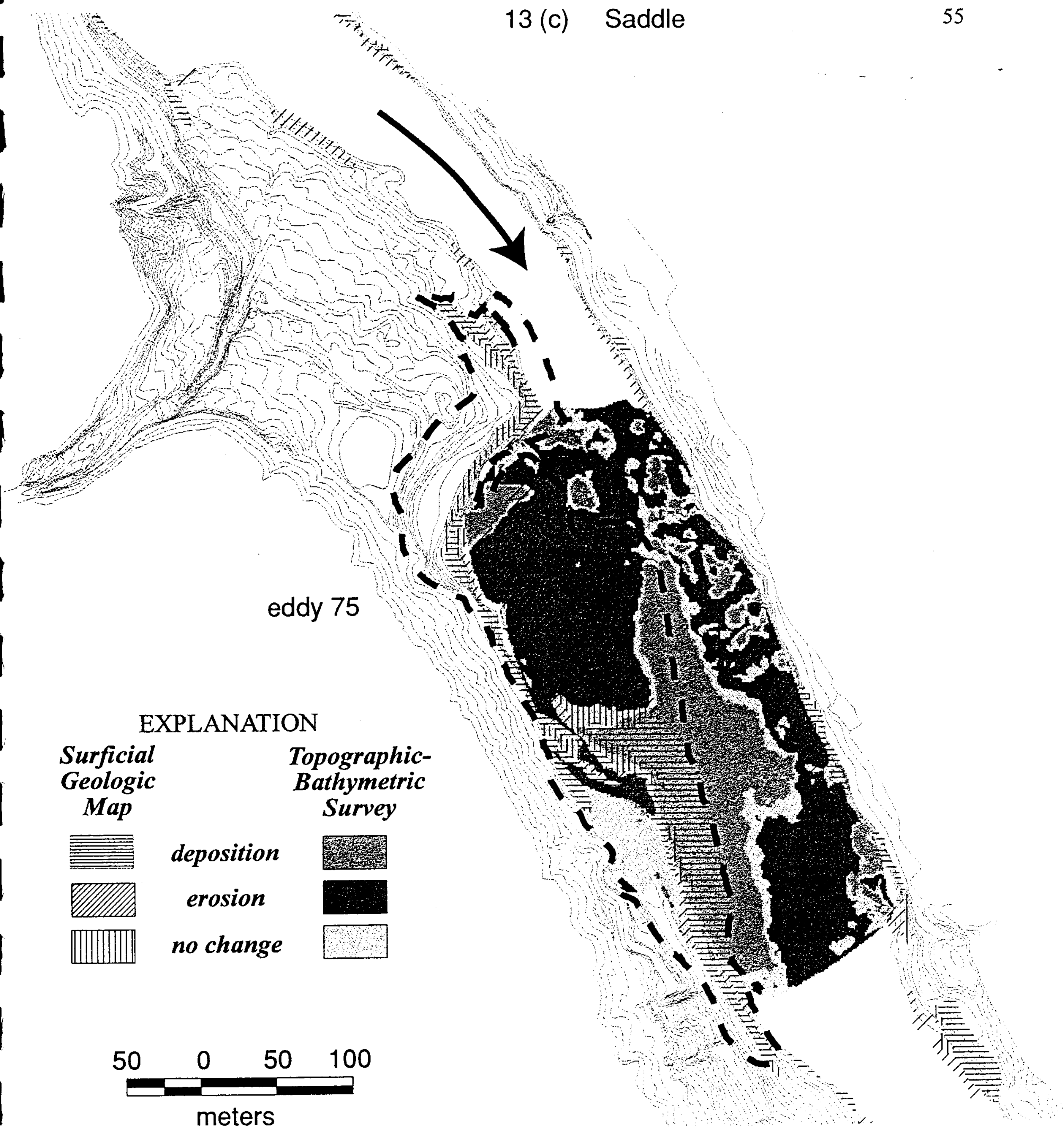
Direct comparison of the distribution of areas of significant erosion and deposition shows that the two methods predict similar distributions of topographic change (Figure 13). In general, large areas of erosion or deposition determined by surficial geologic mapping coincided with areas of erosion or deposition measured by topographic/bathymetric survey. Errors tended to occur along the margins of the areas of erosion and deposition and where areas of erosion and deposition were smallest. We also determined the percentage of the area of overlapping data where surficial geologic maps agreed with the survey data. The areas of agreement and disagreement were organized into an error matrix for each site (Table 5). The area of agreement ranged between 41 and 79% and the area of significant disagreement, e.g. where air photo analysis suggested significant erosion and surveys measured significant deposition, was between 3 and 10%. Minor disagreement, where one method measured no change and the other recorded some type of change, occurred over 16 to 53% of the area of comparison. The error matrices for each site were summed to create a compiled error matrix (Table 6). From this matrix, we calculated a khat value of 0.50 using the formulation of Hudson and Ramm (1987). The possible values of khat range from $-\infty$ to 1, and values > 0.4 are considered to represent good agreement between the actual and predicted values. Random generation of erosion, deposition, and no change values for the same polygons that were mapped yielded an average khat value of 0.00 and a maximum of 0.31 in 1000 trials. Thus the

13 (a) Anasazi Bridge

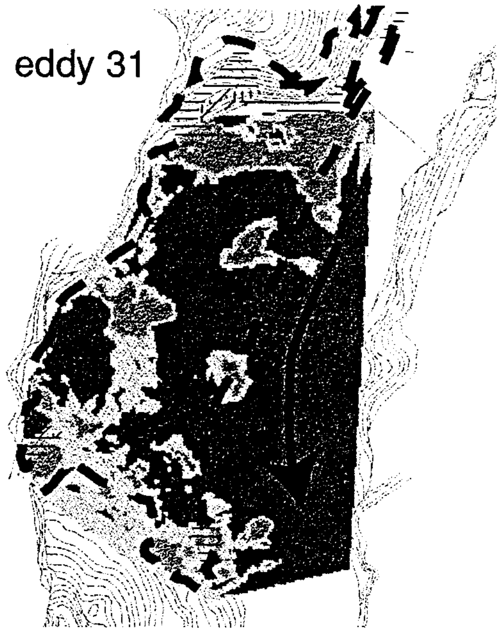


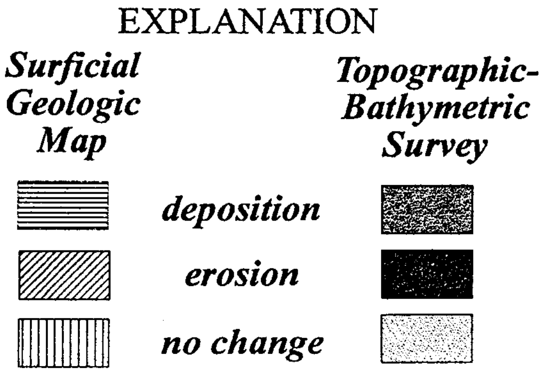
13 (b) Eminence




13 (c) Saddle
eddy 75
EXPLANATION
Surficial Geologic Map
Topographic-Bathymetric Survey
deposition
erosion
no change
50 0 50 100
meters

13 (d) Crash





13 (e) Tanner

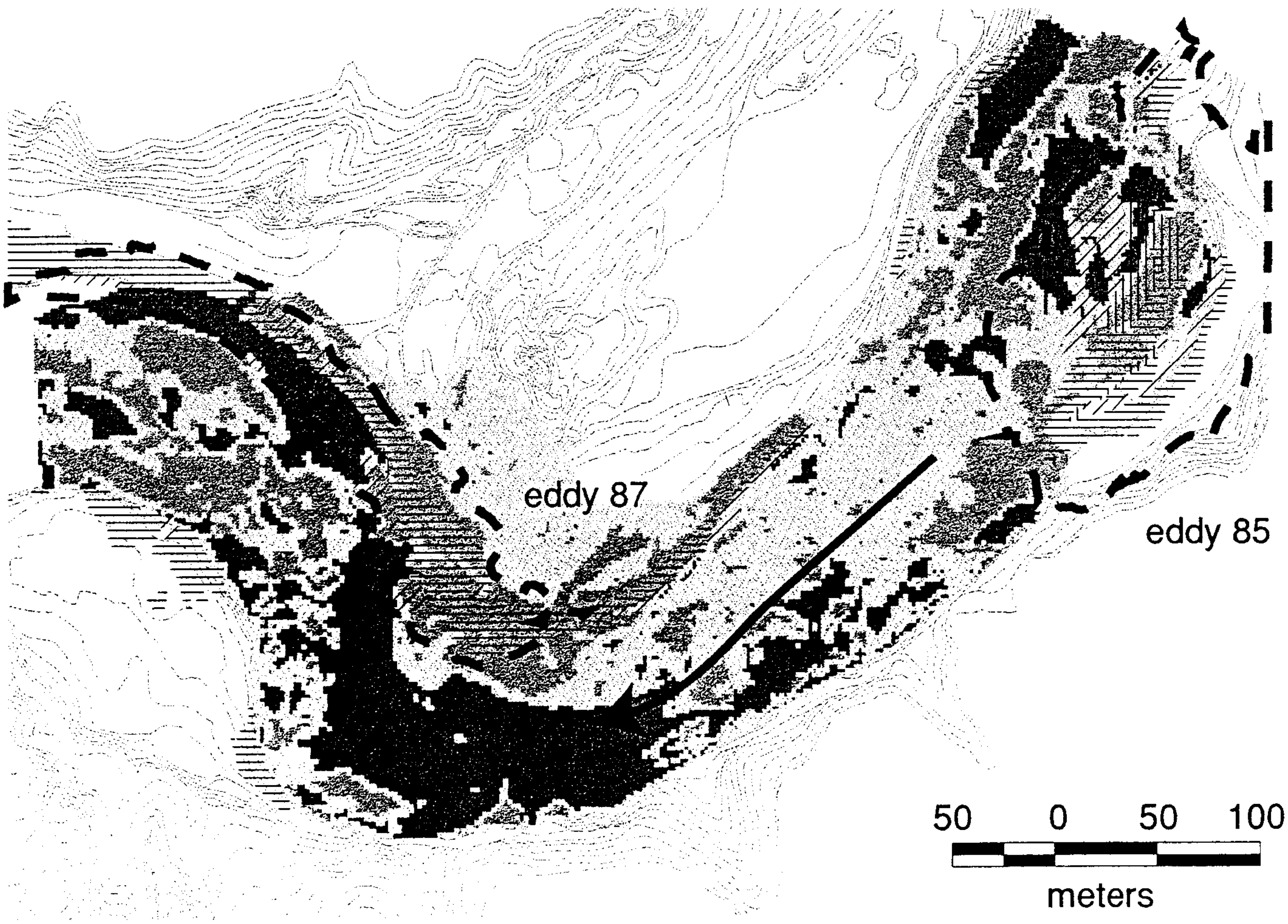


Table 5. Error matrices for each site of comparison showing erosion, deposition, and areas of no change measured by topographic/bathymetric survey (survey) and surficial geologic mapping (map).

Area of indicated response, in square meters. | Percent indicated response of total overlap area.

		Survey			*Survey*		
Anasazi Bridge		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	3638	1105	288	46	14	4
Map	No Change	459	388	160	6	5	2
	Erosion	204	444	1205	3	6	15
Eminence		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	5795	1093	183	29	5	1
Map	No Change	2184	3311	1987	11	16	10
	Erosion	716	1084	3935	4	5	19
Saddle		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	4670	1294	766	23	6	4
Map	No Change	833	3229	601	4	16	3
	Erosion	182	624	8468	1	3	41
Crash		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	279	111	34	24	10	3
Map	No Change	350	246	7	31	22	1
	Erosion	0	39	77	0	3	7
Tanner (eddy 85)		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	1223	527	13	22	10	0
Map	No Change	918	554	266	17	10	5
	Erosion	352	1203	481	6	22	9
Tanner (eddy 87)		Deposition	No Change	Erosion	Deposition	No Change	Erosion
	Deposition	4006	568	456	30	4	3
Map	No Change	2361	2358	71	17	17	1
	Erosion	963	572	2222	7	4	16

Table 6. Compiled error matrix showing erosion, deposition, and areas of no change measured by topographic/bathymetric survey (survey) and surficial geologic mapping (map).

Area of indicated response, in square meters.

All Sites

		Survey		
		Deposition	No Change	Erosion
	Deposition	19611	4699	1739
Map	No Change	7103	10085	3092
	Erosion	2418	3965	16388

Percent indicated response of total overlap area.

	Survey		
	Deposition	No Change	Erosion
Deposition	28	7	3
No Change	10	15	4
Erosion	3	6	24

mapping can be considered to predict areas of erosion and deposition significantly better than random.

Because some of the analyses rely only on the area of exposed sand and do not incorporate the calculations of erosion and deposition discussed above a separate error analysis compares the area of exposed sand measured by each method. Figure 14 shows the area of exposed sand measured by surficial geologic mapping plotted against the bar area above 226 m^3/s calculated from topographic survey data. The relationship between area of sand determined by the two methods is linear with a slope of 0.97 and an R^2 of 0.86. A perfect correlation would be indicated with a slope of 1.0, with equal variance above and below the fitted line. The surficial geologic maps tend to overpredict bar area when compared with the areas derived from topographic surveys (Figure 14). The variance between predicted (measured by surficial geologic map) and actual (measured by topographic survey) bar areas does not change significantly with increasing bar size.

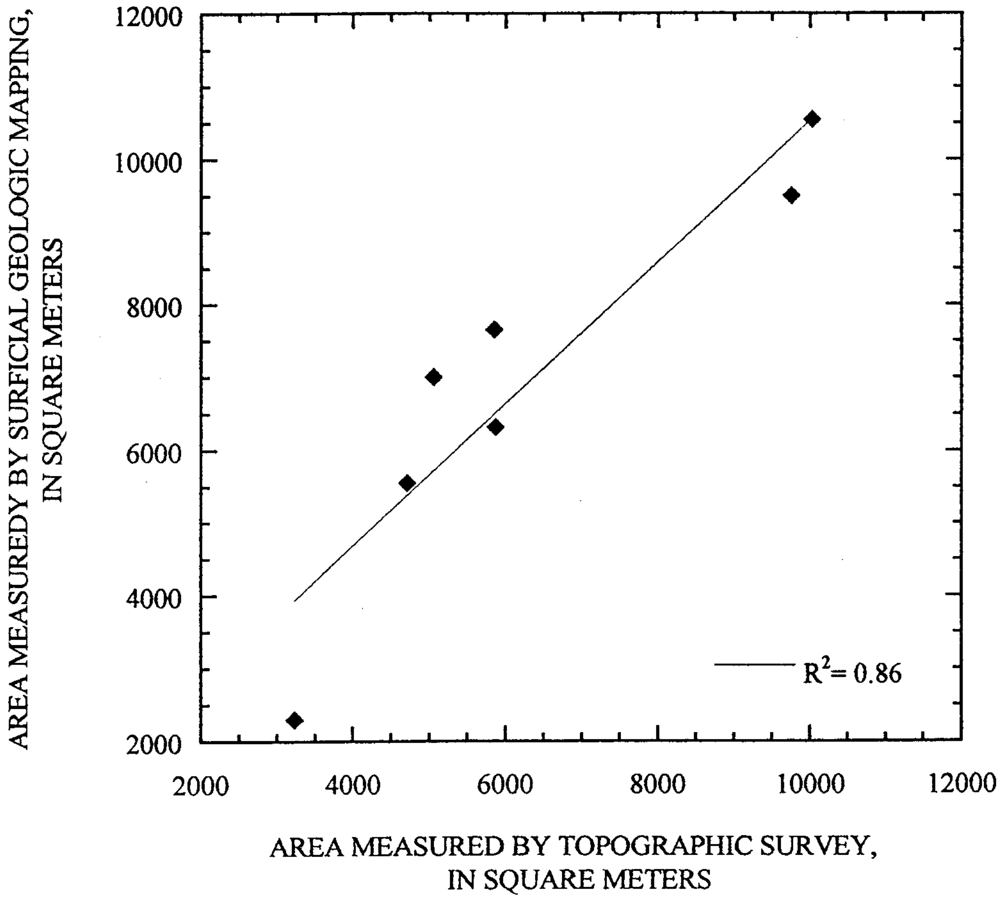
Historical Patterns of Sand Bar Change

The size of the sand bars within persistent eddies has varied greatly over time. Most bars were larger in the 1935 photographs than their average size in the post-dam era, although each measured bar has been as large at least once in the post-dam era as in 1935. No site exhibited the style of steady and progressive erosion that was measured at Badger Creek Rapids, however, we did not have historic bar elevation data as detailed as was analyzed at Badger Creek.

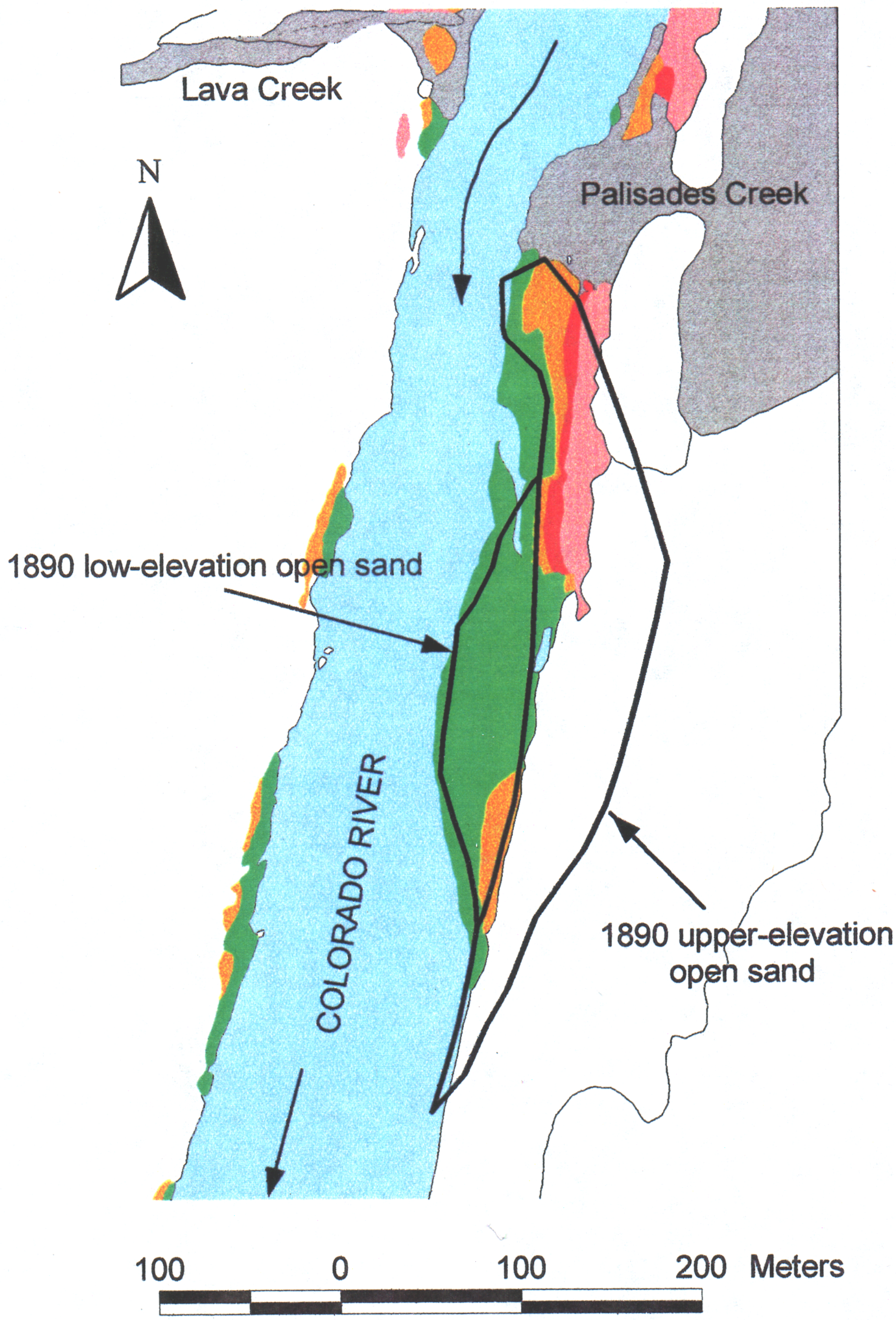
Pre-dam bar topography was interpreted at the Palisades Creek site where historic photographs are available. Photographs from 1890 show a greater area of high-elevation open sand than in 1991. The extent of exposed sand in 1890 was mapped in the field in reference to identifiable stable points (Figure 15). These maps show that the area of low-elevation sand was similar in 1935 and in 1993, but that the area of high-elevation sand was never as large in the later years as it was in 1935. Much of the loss of high-elevation sand was due to encroachment of vegetation into areas that were formerly bare sand.

A time series of normalized bar area extending between 1935 and present was developed for 8 sites (Figure 16). A time series was not developed at the Palisades Creek

Figure 14


AREA MEASUREDY BY SURFICIAL GEOLOGIC MAPPING, IN SQUARE METERS
12000
10000
8000
6000
4000
2000
2000
4000
6000
8000
10000
12000
R^2= 0.86
AREA MEASURED BY TOPOGRAPHIC SURVEY, IN SQUARE METERS

15.


Lava Creek
Palisades Creek
N
1890 low-elevation open sand
COLORADO RIVER
1890 upper-elevation open sand
100
0
100
200
Meters

16

Figure 16

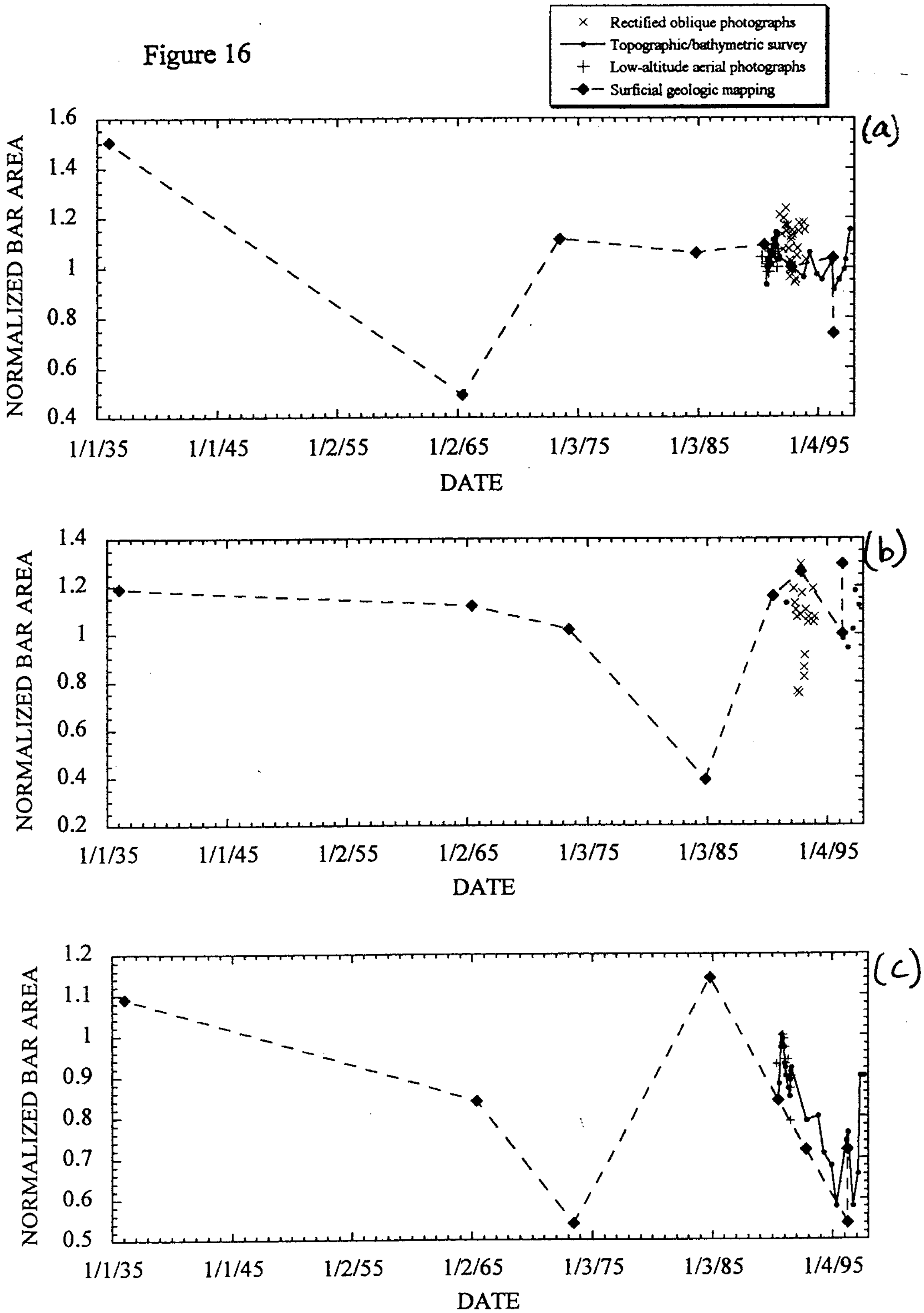
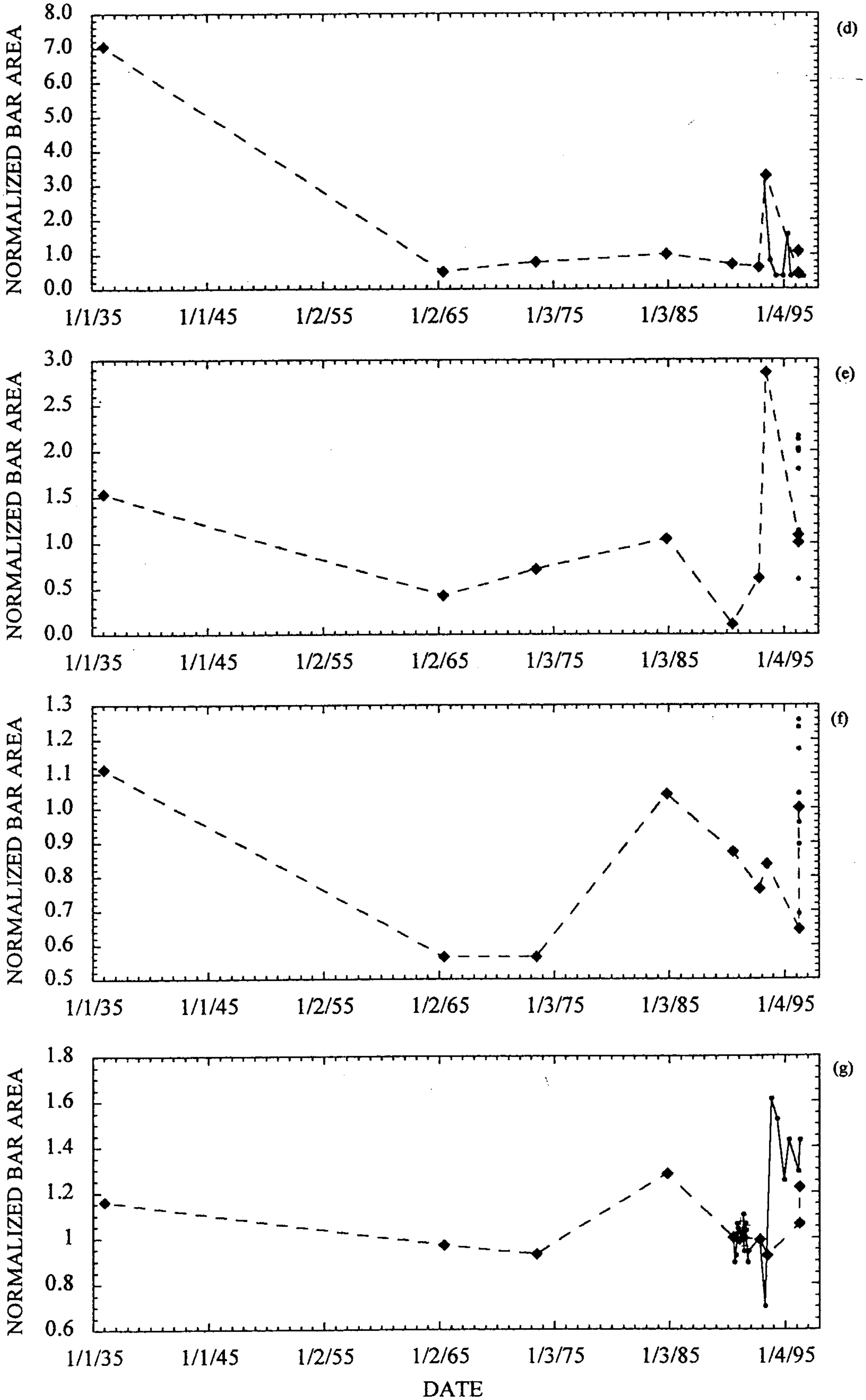

Rectified oblique photographs
Topographic/bathymetric survey
Low-altitude aerial photographs
Surficial geologic mapping
(a)
NORMALIZED BAR AREA
1.6
1.4
1.2
1
0.8
0.6
0.4
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE
(b)
NORMALIZED BAR AREA
1.4
1.2
1
0.8
0.6
0.4
0.2
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE
(c)
NORMALIZED BAR AREA
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE

Figure 16


(d)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
NORMALIZED BAR AREA
(e)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
NORMALIZED BAR AREA
(f)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
NORMALIZED BAR AREA
(g)
1.8
1.6
1.4
1.2
1
0.8
0.6
NORMALIZED BAR AREA
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE

site because measurements from topographic survey that included the entire bar were not available.

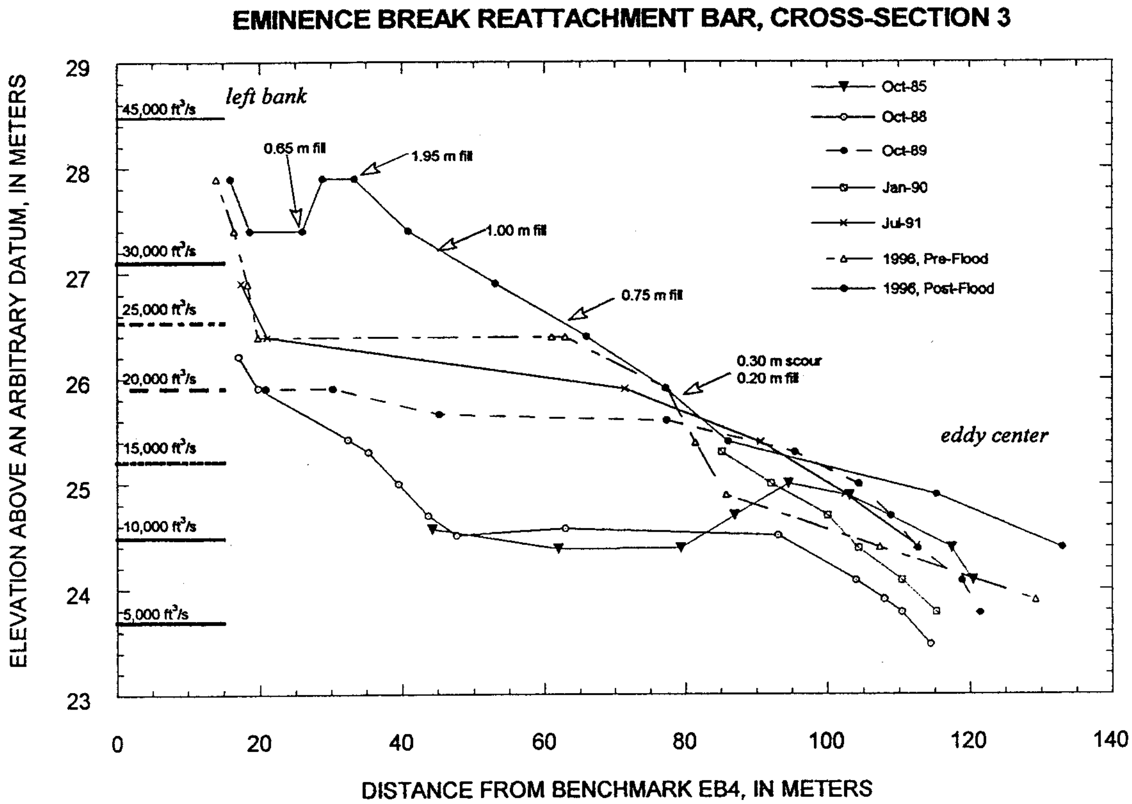
During the post-dam period, the sand bars were largest in either 1984 or 1993, except at Eminence Break. At this site, bar size was greatest in either 1991 or 1992, although that area was entirely below the 30,000 ft^3/s stage. The measurement of bar area made from the surficial geologic maps agrees with topographic measurements made at this site. These show that the reattachment bar was lowest in elevation in 1985-1988, higher in 1989 and 1996 pre-flood, and highest following the controlled flood (Figure 17).

This pattern of change is very different than the pattern of change at the nearby Saddle Canyon reattachment bar (Figure 16). Topographic profiles at this site show that the thickness of sand on the reattachment bar platform was much greater in 1985-1986 than at any other time including following the 1996 controlled flood (Figure 18). Although normalized area following the 1996-controlled flood was never the largest measured, at most sites the post-flood area was significantly larger than the pre-flood area.

The time series for Eminence Break, Saddle Canyon, Crash Canyon, and Tanner Rapid all show gradual net erosion between 1990-92 and April 1996 (Figure 16). At Crash Canyon and Tanner Rapid, however, this erosional trend is interrupted by deposition that occurred during the 1993 flood of the Little Colorado River. Other than deposition due to specific tributary flood events, there is no evident difference between the study reaches.

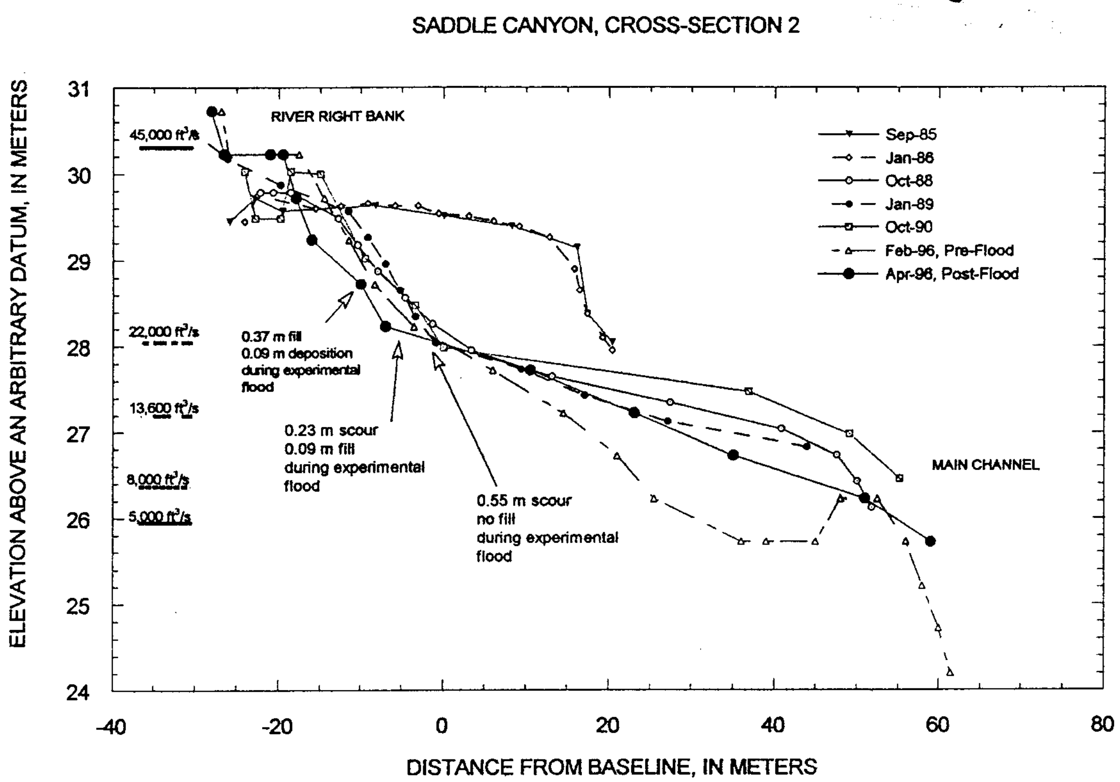
The period of net erosion from 1990 to 1996 that occurred at most sites was also a period during which monitoring data were collected at frequent intervals at some sites. These data indicate frequent erosion and deposition events that caused bar area to fluctuate widely about the size measured from the surficial geologic maps. The most frequent measurements analyzed are those derived from the low-altitude aerial photographs and the rectified oblique photographs (Figure 16a, b, c, and g). Although these bar area fluctuations indicate that significant amounts of erosion and deposition occured frequently and during normal powerplant flows, the magnitude of these fluctuations was still smaller than the longer-term bar area trends shown by the other methods collecting data at less frequent intervals.

Figure 17


EMINENCE BREAK REATTACHMENT BAR, CROSS-SECTION 3
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BENCHMARK EB4, IN METERS
left bank
eddy center
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
0.65 m fill
1.95 m fill
1.00 m fill
0.75 m fill
0.30 m scour
0.20 m fill
Oct-85
Oct-88
Oct-89
Jan-90
Jul-91
1996, Pre-Flood
1996, Post-Flood
29
28
27
26
25
24
23
0
20
40
60
80
100
120
140

18

Figure 18

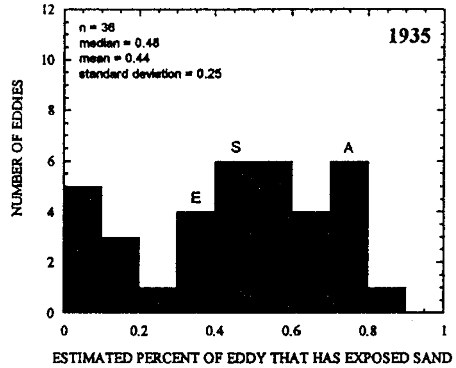

SADDLE CANYON, CROSS-SECTION 2
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BASELINE, IN METERS
RIVER RIGHT BANK
MAIN CHANNEL
Sep-85
Jan-86
Oct-88
Jan-89
Oct-90
Feb-96, Pre-Flood
Apr-96, Post-Flood
45,000 ft³/s
22,000 ft³/s
13,600 ft³/s
8,000 ft³/s
5,000 ft³/s
0.37 m fill
0.09 m deposition
during experimental
flood
0.23 m scour
0.09 m fill
during experimental
flood
0.55 m scour
no fill
during experimental
flood
31
30
29
28
27
26
25
24
-40
-20
0
20
40
60
80

Relationship between Site Specific and Reach-Scale Bar Behavior

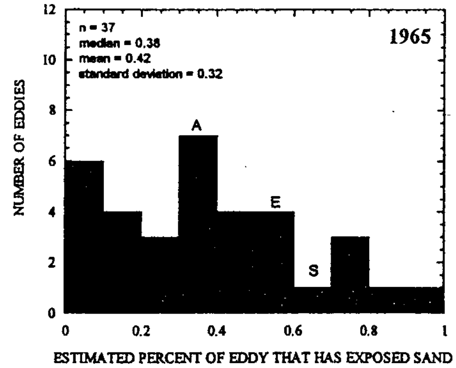
The substantial variability in response from site to site requires that a substantial number of the eddies in a reach be measured in order to develop an average history of bar change. The only way to do this is to utilize the data from comprehensive maps, which include all the eddies in a given reach. The difficulty with these data is that they have limited temporal resolution. If reach-average histories can be developed, then these data may also be used to evaluate the degree to which individual eddies are representative of the reach-average response.

Sand bar size, expressed by the normalized bar area, was highly variable in all of the study reaches in most years of aerial photographic coverage (Figures 19-21). In most years some eddies were nearly full of sand while others were devoid of sand. Often a central tendency occured, indicating an average condition, but in some years the distribution was flat or skewed, indicating that the mean value did not accurately represent the sand bars in that reach. Normal and moderately skewed distributions were most common in the Point Hansbrough reach (Figure 19) while flat and strongly skewed distributions were more frequent in the Tapeats Gorge (Figure 20) and Big Bend (Figure 21) reaches. Despite the variability in the shape of the distributions, the mean and median values were similar, defining an "average" condition for the reach.

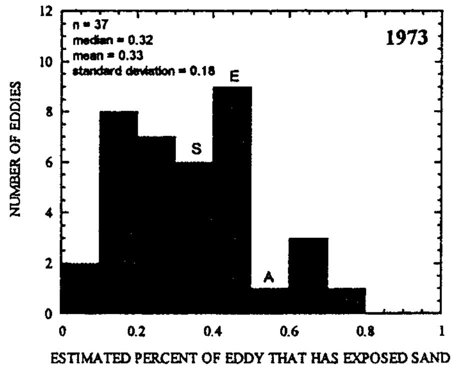
The sites where detailed measurements have been made were sometimes representative of reach average response but sometimes behaved differently than the reach average response. In most years where a strong central tendency occurred, at least one detailed site was representative of the reach-average response (Figure 19). The consistency with which individual persistent eddies were representative of the reach average sand bar sizes for all mapped years was quantified by the average Z-score (Table 7). In the Point Hansbrough Reach, the detailed measurement sites all exhibited behaviors that were generally consistent with the reach-average. These three sites are, therefore, probably good indicators of reach average conditions. The behavior of the detailed measurement sites in the Tapeats Gorge and Big Bend reaches was much less consistent. These sites were frequently very different from the reach-average condition. There are two possible explanations for this: (1) all sand bars in this reach are less stable (no single bar tends to always lie in the center of the distribution) and therefore a greater sample size is required to capture average behavior, or (2) these are particularly poor monitoring sites and other locations in the reach would better represent the average response.



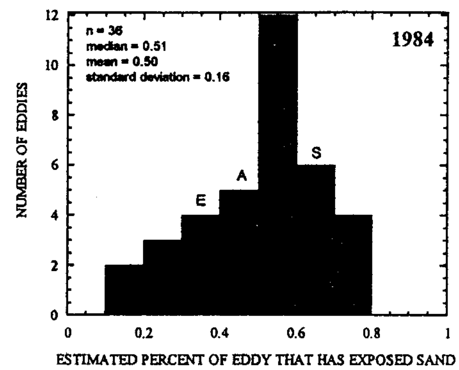
19a



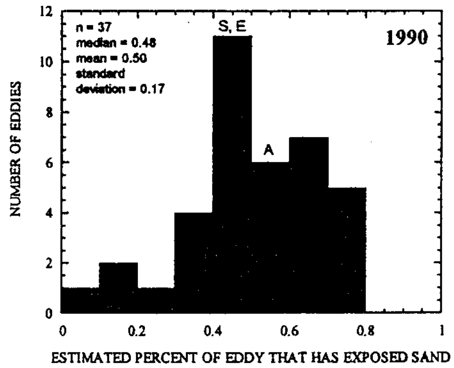
19b



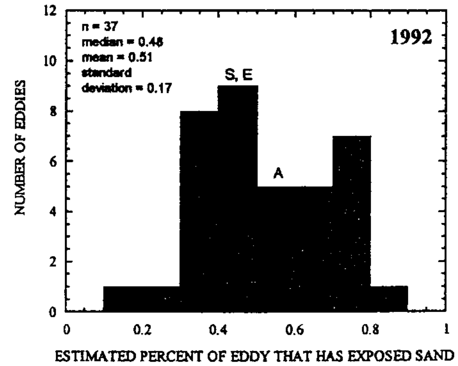
19c



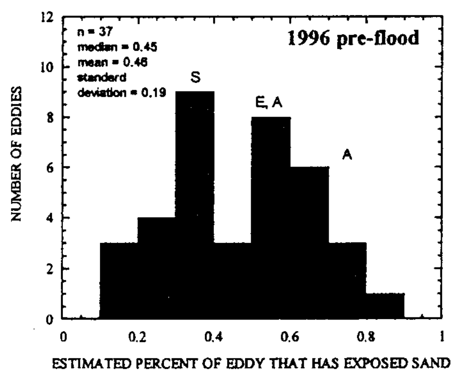
19d



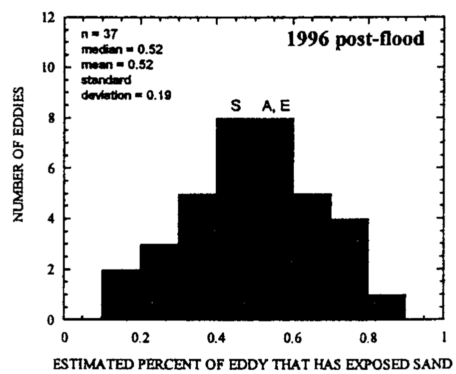
19e



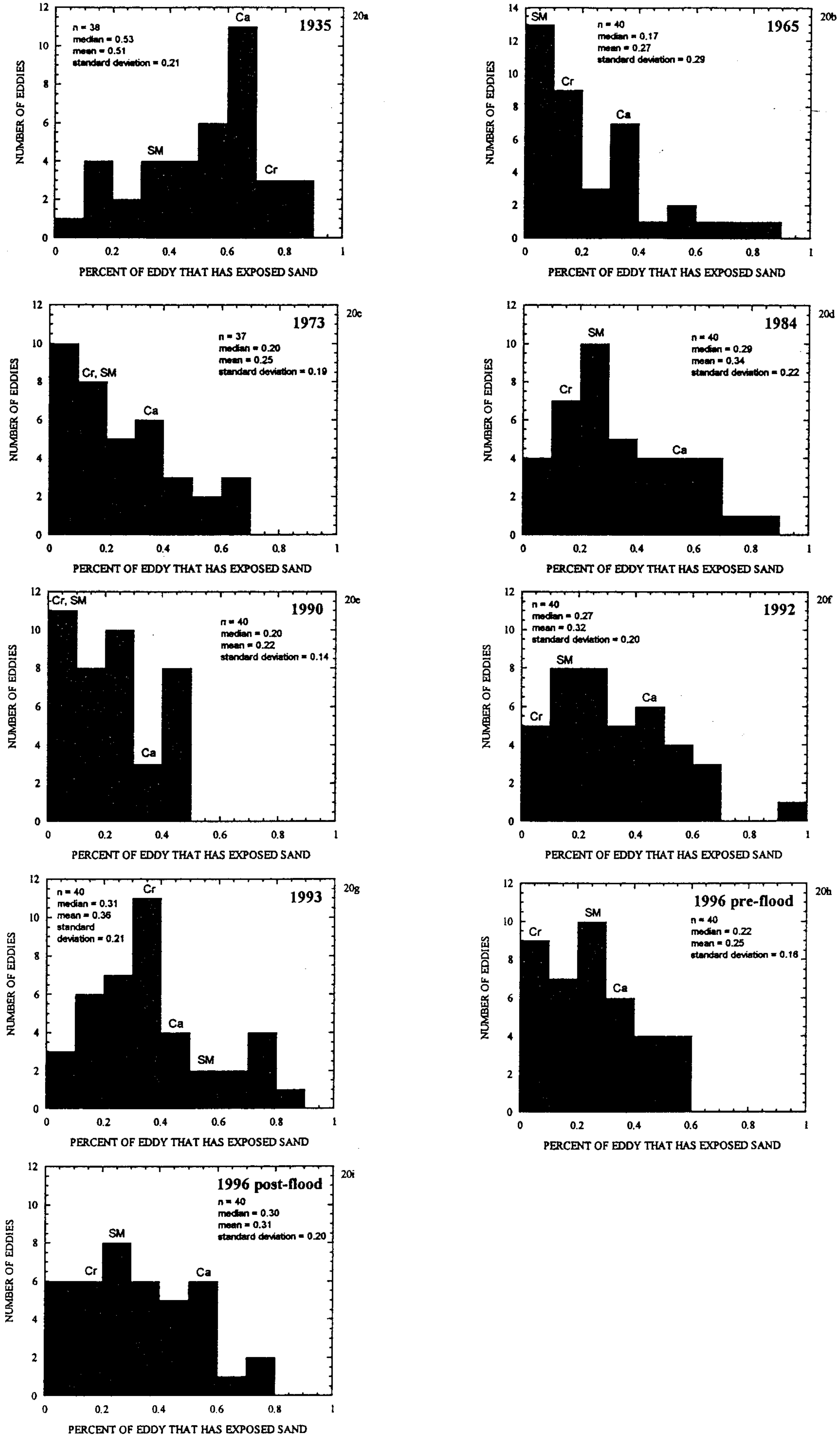
19f

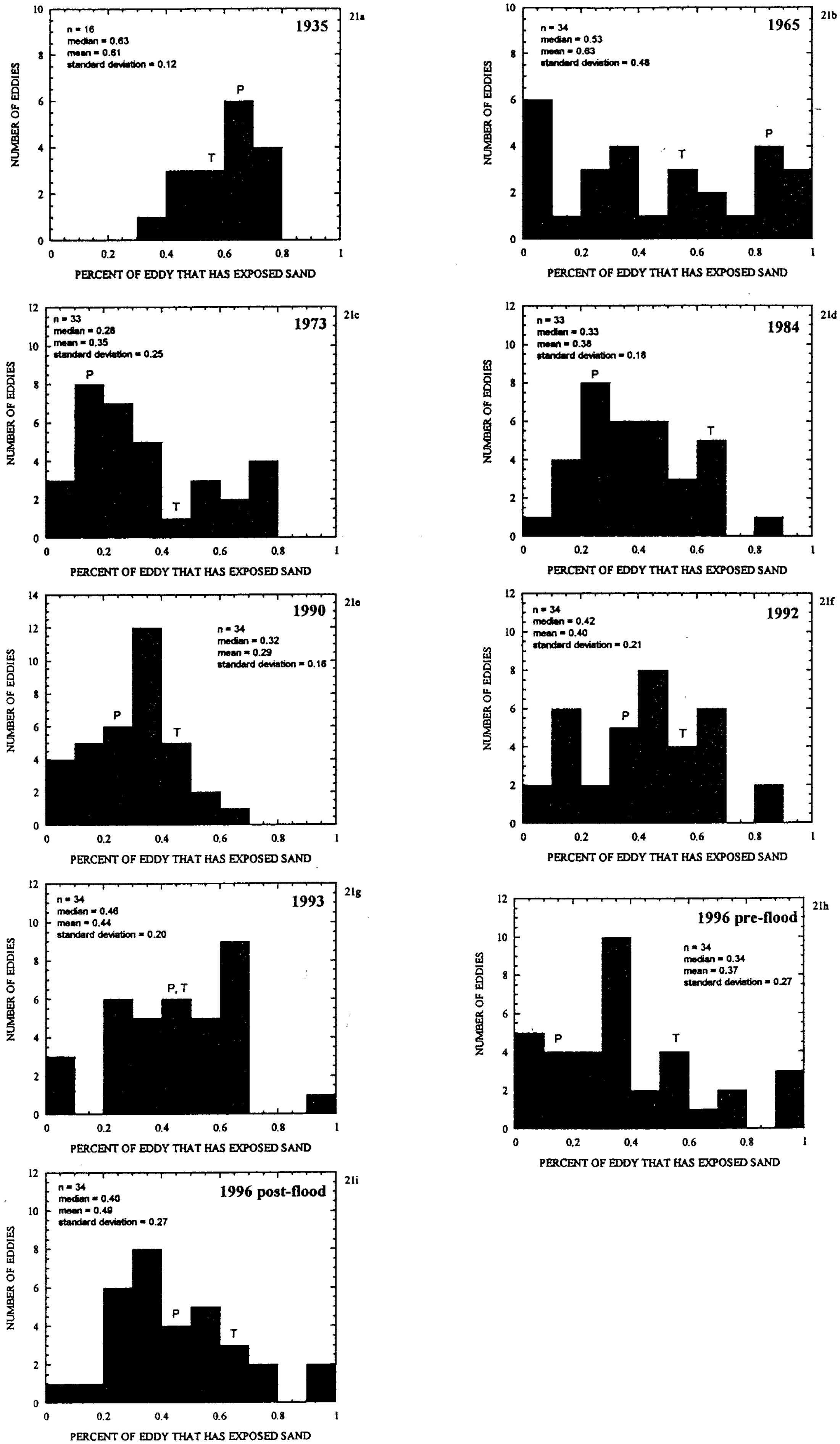


19g



19h


20a
1935
n = 38
median = 0.53
mean = 0.51
standard deviation = 0.21
Ca
SM
Cr
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20b
1965
n = 40
median = 0.17
mean = 0.27
standard deviation = 0.29
SM
Cr
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20c
1973
n = 37
median = 0.20
mean = 0.25
standard deviation = 0.19
Cr, SM
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20d
1984
n = 40
median = 0.29
mean = 0.34
standard deviation = 0.22
SM
Cr
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20e
1990
n = 40
median = 0.20
mean = 0.22
standard deviation = 0.14
Cr, SM
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20f
1992
n = 40
median = 0.27
mean = 0.32
standard deviation = 0.20
SM
Ca
Cr
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20g
1993
n = 40
median = 0.31
mean = 0.36
standard deviation = 0.21
Cr
Ca
SM
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20h
1996 pre-flood
n = 40
median = 0.22
mean = 0.25
standard deviation = 0.16
SM
Cr
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
20i
1996 post-flood
n = 40
median = 0.30
mean = 0.31
standard deviation = 0.20
SM
Cr
Ca
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND



21a
1935
n = 16
median = 0.63
mean = 0.61
standard deviation = 0.12
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21b
1965
n = 34
median = 0.53
mean = 0.63
standard deviation = 0.48
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21c
1973
n = 33
median = 0.28
mean = 0.35
standard deviation = 0.25
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21d
1984
n = 33
median = 0.33
mean = 0.38
standard deviation = 0.18
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21e
1990
n = 34
median = 0.32
mean = 0.29
standard deviation = 0.16
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21f
1992
n = 34
median = 0.42
mean = 0.40
standard deviation = 0.21
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21g
1993
n = 34
median = 0.46
mean = 0.44
standard deviation = 0.20
P, T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21h
1996 pre-flood
n = 34
median = 0.34
mean = 0.37
standard deviation = 0.27
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND
21i
1996 post-flood
n = 34
median = 0.40
mean = 0.49
standard deviation = 0.27
P
T
NUMBER OF EDDIES
PERCENT OF EDDY THAT HAS EXPOSED SAND

Table 7a. Point Hansbrough Reach

Persistent Eddy	Eddy Area (m²)	n[1]	Normalized Bar Area, 1935-96[2] Mean	Standard Deviation	Average Z-Score	Rank of Indicated Value[3] Eddy Area	Mean	Standard Deviation	Average Z-Score
27	1530	8	0.46	0.14	0.35	33	17	17	1
19	33213	8	0.46	0.08	0.35	2	18	2	2
91	14469	8	0.39	0.10	0.37	11	28	5	3
96	14890	8	0.44	0.11	0.41	10	21	9	4
7	21567	8	0.52	0.11	0.43	8	12	6	5
75	41724	8	0.46	0.12	0.43	1	16	10	6
94	12443	8	0.41	0.13	0.44	13	25	12	7
33	2236	8	0.38	0.17	0.47	28	29	21	8
39	2342	8	0.45	0.11	0.51	26	19	8	9
44	10733	8	0.36	0.08	0.54	14	32	1	10
52	1967	8	0.57	0.16	0.59	31	9	19	11
55	1758	8	0.42	0.22	0.61	32	23	27	12
24	27778	8	0.48	0.14	0.62	5	13	16	13
89	7034	8	0.57	0.11	0.65	15	7	7	14
26	28646	8	0.40	0.13	0.66	4	26	14	15
83	4995	8	0.40	0.23	0.66	18	27	30	16
28	2046	8	0.35	0.14	0.71	30	33	15	17
51	2786	8	0.59	0.13	0.72	23	4	13	18
67	30510	7	0.55	0.22	0.77	3	11	28	19
97	3647	8	0.41	0.19	0.78	20	24	23	20
95	17179	8	0.38	0.17	0.83	9	30	20	21
12	12631	8	0.63	0.12	0.84	12	3	11	22
8	25469	7	0.46	0.10	0.90	6	15	4	23
60	1097	8	0.42	0.27	0.91	36	22	33	24
40	2697	8	0.57	0.22	0.93	24	8	26	25
88	1004	8	0.37	0.27	0.95	37	31	34	26
84	5205	8	0.47	0.29	0.97	17	14	35	27
6	4836	8	0.58	0.23	1.02	19	5	31	28
87	5678	8	0.33	0.23	1.04	16	34	29	29
50	2161	8	0.58	0.32	1.11	29	6	36	30
38	2472	8	0.56	0.26	1.15	25	10	32	31
30	3360	8	0.72	0.15	1.23	21	2	18	32
4	1271	8	0.45	0.35	1.27	35	20	37	33
61	3221	8	0.26	0.21	1.32	22	35	25	34
31	2340	8	0.78	0.17	1.52	27	1	22	35
14	22043	8	0.23	0.21	1.55	7	36	24	36
47	1346	8	0.14	0.09	1.58	34	37	3	37

[1] Indicates the number of years the bar was mapped.

[2] The mean, standard deviation, and average Z-Score of the normalized bar area for the indicated eddy as mapped from aerial photographs. See text for explanation of Z-Score calculation.

[3] The rows are sorted from lowest to highest Z-Score. Lower scores indicate greater tendency for the area of the indicated site to be near the mean area of the reach.

Table 7b. Tapeats Gorge Reach

Persistent Eddy	Eddy Area (m²)	n[1]	Normalized Bar Area, 1935-96[2] Mean	Standard Deviation	Average Z-Score	Rank of Indicated Value[3] Eddy Area	Mean	Standard Deviation	Average Z-Score
44	1000	9	0.35	0.09	0.28	40	14	4	1
12	8941	9	0.37	0.13	0.37	15	13	12	2
11	3674	9	0.28	0.15	0.38	26	19	16	3
8	7377	9	0.24	0.13	0.39	17	27	11	4
43	17641	9	0.27	0.14	0.44	6	20	14	5
24	1314	8	0.27	0.12	0.45	38	23	10	6
10	15219	9	0.27	0.17	0.47	9	24	22	7
14	11838	9	0.34	0.17	0.50	11	15	24	8
2	2879	8	0.27	0.17	0.52	28	22	21	9
47	16478	9	0.22	0.13	0.52	7	28	13	10
32	10062	9	0.40	0.17	0.60	14	12	25	11
33	5877	9	0.21	0.18	0.61	23	29	26	12
15	10960	9	0.31	0.23	0.65	12	16	32	13
54	19857	9	0.44	0.10	0.67	4	9	7	14
39	5389	9	0.20	0.10	0.67	24	32	5	15
36	32305	9	0.21	0.16	0.73	1	30	20	16
19	2291	9	0.19	0.12	0.76	31	33	9	17
42	7345	9	0.21	0.22	0.78	18	31	30	18
45	30753	9	0.45	0.16	0.79	2	8	18	19
30	13596	9	0.28	0.18	0.80	10	17	27	20
4	1369	8	0.28	0.20	0.82	37	18	29	21
51	8366	9	0.47	0.05	0.82	16	5	1	22
1	23168	9	0.18	0.19	0.85	3	36	28	23
41	15234	9	0.43	0.16	0.88	8	11	19	24
9	3358	9	0.47	0.28	0.89	27	6	39	25
31	18453	9	0.19	0.22	0.89	5	34	31	26
56	2845	9	0.26	0.23	0.93	29	26	33	27
26	10320	8	0.27	0.25	0.94	13	21	35	28
20	6127	9	0.46	0.15	0.94	22	7	17	29
40	6556	9	0.12	0.14	1.00	21	38	15	30
21	1369	9	0.10	0.07	1.04	36	39	3	31
49	6823	9	0.55	0.29	1.04	19	4	40	32
7	1414	9	0.19	0.27	1.05	35	35	37	33
25	6760	8	0.44	0.17	1.06	20	10	23	34
16	1876	9	0.17	0.26	1.08	32	37	36	35
35	1798	9	0.26	0.27	1.12	33	25	38	36
28	5000	9	0.57	0.11	1.28	25	3	8	37
22	1777	9	0.05	0.06	1.32	34	40	2	38
50	1254	9	0.60	0.25	1.59	39	2	34	39
27	2742	9	0.64	0.10	1.60	30	1	6	40

[1] Indicates the number of years the bar was mapped.

[2] The mean, standard deviation, and average Z-Score of the normalized bar area for the indicated eddy as mapped from aerial photographs. See text for explanation of Z-Score calculation.

[3] The rows are sorted from lowest to highest Z-Score. Lower scores indicate greater tendency for the area of the indicated site to be near the mean area of the reach.

Table 7c. Big Bend Reach

Persistent Eddy	Eddy Area (m²)	n[1]	Normalized Bar Area, 1935-96[2] Mean	Standard Deviation	Average Z-Score	Rank of Indicated Value[3] Eddy Area	Mean	Standard Deviation	Average Z-Score
97	8866	8	0.35	0.11	0.31	14	25	5	1
95	10563	9	0.50	0.14	0.34	12	9	12	2
115	36950	8	0.40	0.23	0.39	1	18	23	3
64	28142	9	0.39	0.23	0.40	3	21	22	4
62	19697	9	0.47	0.20	0.40	7	15	18	5
85	22023	9	0.45	0.13	0.44	5	16	8	6
112	10365	8	0.38	0.11	0.46	13	23	4	7
96	5573	9	0.38	0.14	0.50	18	22	11	8
113	3831	8	0.26	0.14	0.53	21	30	13	9
111	4587	8	0.27	0.13	0.54	20	27	9	10
87	11817	9	0.53	0.08	0.56	11	7	3	11
76	20308	9	0.41	0.25	0.56	6	17	26	12
120	28692	8	0.39	0.28	0.63	2	20	27	13
119	3562	8	0.27	0.16	0.67	22	29	14	14
107	1076	8	0.28	0.21	0.67	33	26	20	15
89	2255	9	0.59	0.14	0.68	25	6	10	16
70	25168	9	0.50	0.17	0.70	4	10	17	17
83	12789	9	0.52	0.24	0.73	10	8	25	18
103	1024	8	0.50	0.42	0.76	34	11	34	19
126	16236	8	0.23	0.07	0.77	8	31	2	20
122	8129	7	0.49	0.13	0.78	16	13	6	21
123	2323	8	0.36	0.38	0.78	24	24	32	22
68	1679	9	0.39	0.23	0.80	26	19	21	23
109	1083	8	0.50	0.41	0.81	32	12	33	24
98	8314	7	0.68	0.30	0.90	15	3	28	25
82	1570	8	0.67	0.23	1.01	27	4	24	26
92	1281	9	0.27	0.20	1.02	30	28	19	27
84	4835	9	0.67	0.16	1.12	19	5	15	28
91	1321	9	0.49	0.37	1.18	29	14	31	29
104	15073	8	0.72	0.13	1.30	9	2	7	30
69	5837	9	0.21	0.35	1.40	17	32	30	31
86	1453	9	0.11	0.16	1.43	28	33	16	32
102	1163	8	0.06	0.07	1.45	31	34	1	33
108	3495	8	0.99	0.34	2.25	23	1	29	34

[1] Indicates the number of years the bar was mapped.

[2] The mean, standard deviation, and average Z-Score of the normalized bar area for the indicated eddy as mapped from aerial photographs. See text for explanation of Z-Score calculation.

[3] The rows are sorted from lowest to highest Z-Score. Lower scores indicate greater tendency for the area of the indicated site to be near the mean area of the reach.

DISCUSSION

Measurement and Data Analysis Strategies

Data collected at large spatial scales (e.g. Schmidt and others, 1999) indicate variability among eddies in the same reach for the same time period. Data collected at frequent temporal intervals (e.g. Andrews and others, 1999; Cluer and Dexter, 1994) indicate a high degree of variability for the same eddy over a course of days. Together, these data suggest that frequent (daily to weekly) measurements of hundreds of sites could be required to encompass temporal and site-to-site variability. Such an approach would not only be cost prohibitive, but would likely constitute an unacceptable level of intrusion to Grand Canyon National Park. The data analyzed in this study indicate that, despite short-term fluctuations, long-term trends in bar size are detectable by yearly or less frequent measurements. The challenges lie in selecting the appropriate level of measurement detail, a representative selection of monitoring sites, and the appropriate monitoring frequency.

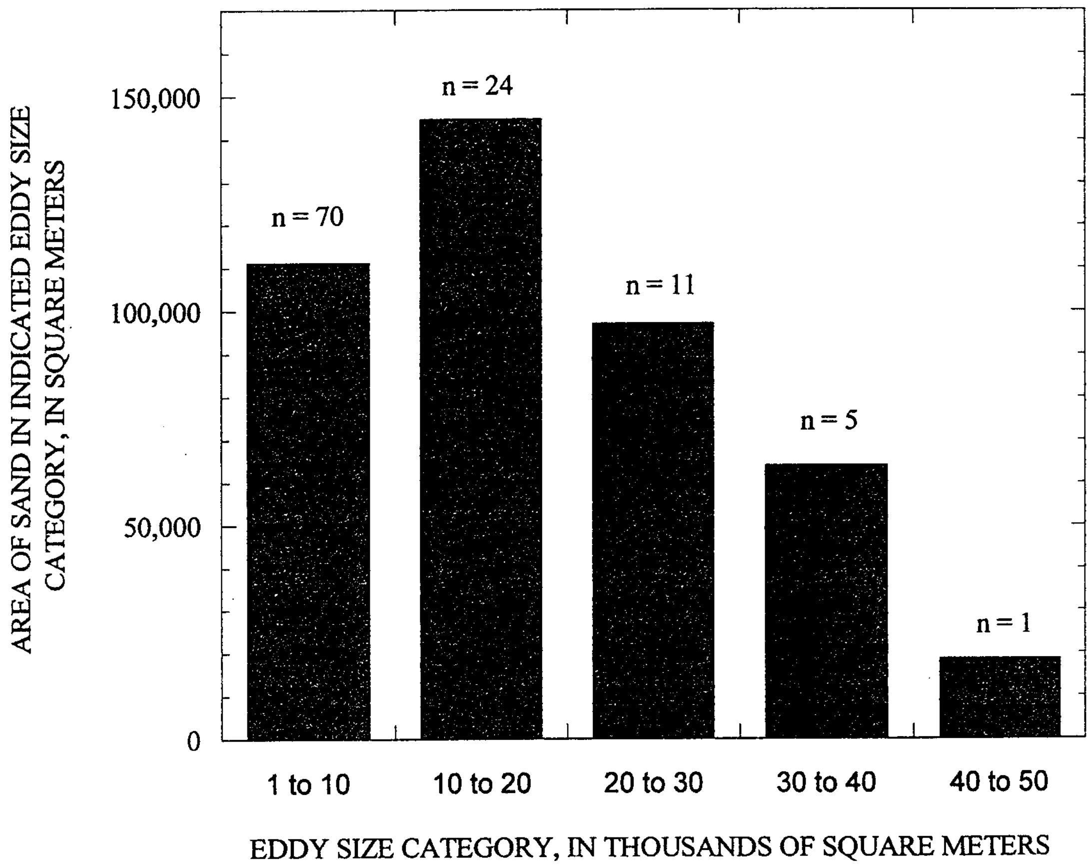
The reach-scale measurements made by surficial geologic mapping characterize reach variability by measuring all of the eddies in a reach. These measurements do not, however, provide sufficiently detailed measurements of depths of erosion and deposition or information regarding the submerged portions of the eddy and channel. These maps made from aerial photographs are not, therefore, a substitute for detailed measurements of bar and channel topography and bathymetry.

The behaviors of the individual detailed monitoring sites are sometimes reflective of the reach-average response (Figures 19-21). The agreement is best in the Point Hansbrough reach and is often very poor in the Tapeats Gorge and Big Bend reaches. While the good fit of the detailed sites in the Point Hansbrough reach appears convenient if the primary interest is the "average" condition, use of these sites alone could miss the variability in the reach. Using the reach-scale data as a guide, it may be best from a monitoring perspective to choose as monitoring sites some locations that tend to agree with the reach average and some locations that tend to define the extremes of the distribution.

The distribution of response within a reach can only be determined by methods that measure all or a representative sample of the eddies within a given reach. Because, as the data presented in this report show, the distribution of normalized sand bar areas does not always contain a strong central tendency, measuring a representative sample is problematic. The data of Schmidt and others (1999) indicate that an average of 3.8 eddies larger than 1000 m^2 occur per km in the 3 reaches they studied. If this average is applied to all of Grand Canyon, there may be nearly 1400 persistent eddies larger than 1000 m^2 between Lees Ferry and Diamond Creek. These data also indicate that there are approximately 500 eddies larger than 10,000 m^2 between Less Ferry and Diamond Creek. Analysis of the area of exposed sand after the 1996 controlled flood indicates that the greatest proportion of sand is in eddies smaller than 20,000 m^2 (Figure 22). However, the average size of the detailed monitoring sites in the reaches included in this analysis is about 25,000 m^2. Thus, the current distribution of monitoring sites, with emphasis on large sand bars, may not be representative of the bulk of sand storage locations in Grand Canyon. It must be recognized that monitoring certain types of bars may or may not accurately reflect changes that occur in the bulk of sand storage locations. Even if large bars are selected as a target for monitoring, a larger sample size may be required. Reach-scale data (i.e. Schmidt and others, 1999) could be utilized in the process of selecting sites for detailed study, dependent upon management objectives.

In summary a comprehensive monitoring program must include reliable and repeatable detailed measurements and also take into account the variability in bar response that we know occurs. This could be accomplished either by (1) choosing an appropriate number of monitoring sites <u>randomly</u> from among all the eddies in Grand Canyon or by (2) use of a multi-tiered monitoring program similar to that employed during the 1996 controlled flood. Given the large number of eddies and the large variance in bar size, the first option would likely require a much larger set of monitoring sites than currently exist. Moreover, a random sample would likely result in excluding sites of special interest and sites with a long historical record. The second option would allow continued use of the current "biased" set of monitoring sites but would include reach scale data that define the

22.


AREA OF SAND IN INDICATED EDDY SIZE CATEGORY, IN SQUARE METERS
150,000
100,000
50,000
0
n = 70
n = 24
n = 11
n = 5
n = 1
1 to 10
10 to 20
20 to 30
30 to 40
40 to 50
EDDY SIZE CATEGORY, IN THOUSANDS OF SQUARE METERS

variability for each reach. This has worked well for the reaches included in this study, but reach-scale data have only been collected for a portion of Grand Canyon.

While infrequent measurements will adequately monitor trends in sand storage, significant new insights regarding processes of erosion and deposition will require frequent and precise measurements, such as the daily topographic surveys made during the controlled flood (Andrews and others, 1999; Schmidt, 1999). Daily photographs taken by remote camera are potentially very useful for the same reasons, although their utility to date has been hampered by analysis difficulties, which include the mechanics of photo rectification and fluctuating discharges between photographs. Some of the techniques presented here to correct the aerial photographs for discharge may be applicable to these oblique photographs.

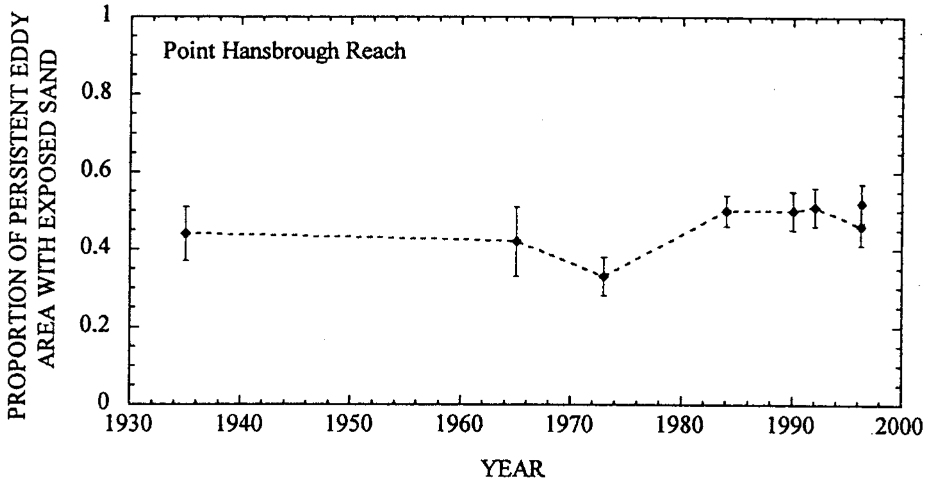
Time Series of Sand Bar Size

The data analyzed in this study demonstrate the variable nature of sand bar change in Grand Canyon. These data also suggest that "average" conditions can be difficult to determine. Nevertheless, the need remains to characterize trends in sand bar size and identify responses to specific management actions. Because of the large variability, many of the changes that have been measured can not be considered significant, however, some trends in average bar area can be detected (Figure 23).

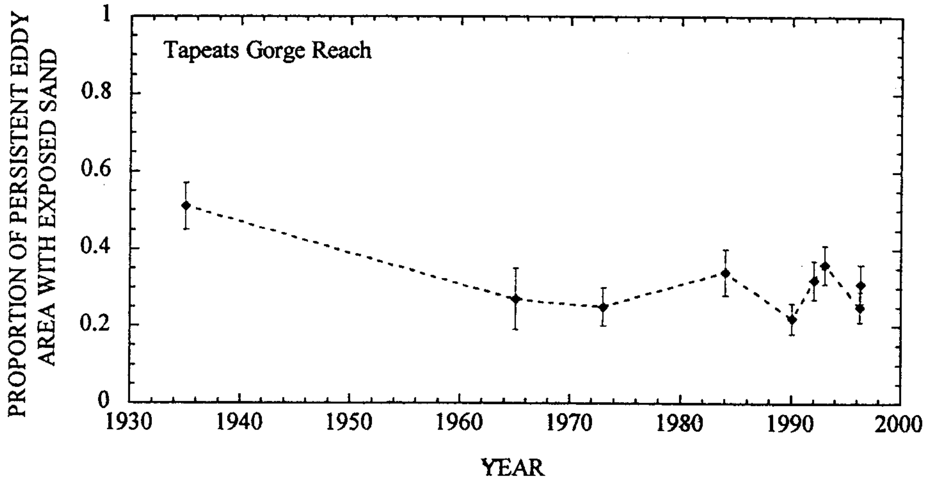
There are several trends that are consistent between the reaches. The area of exposed sand declined between 1935 and 1965-73. Whether most of the change occurred between 1935 and 1965 or between 1965 and 1973 is less certain because of the higher error in the 1965 measurements. There was also a consistent increase between 1973 and 1984, although this increase was only significant in the Point Hansbrough reach. Finally, increase in normalized bar area occurred during the 1996 controlled flood in all reaches. In the two reaches that are downstream from the LCR confluence, there was deposition between 1990 and 1993 attributable to floods from the Little Colorado River.

The characteristics of the distribution of normalized bar area are very different between reaches and between years (Figures 19-21). Consistent responses in a reach, indicated by a normal distribution, are most common in the Point Hansbrough reach

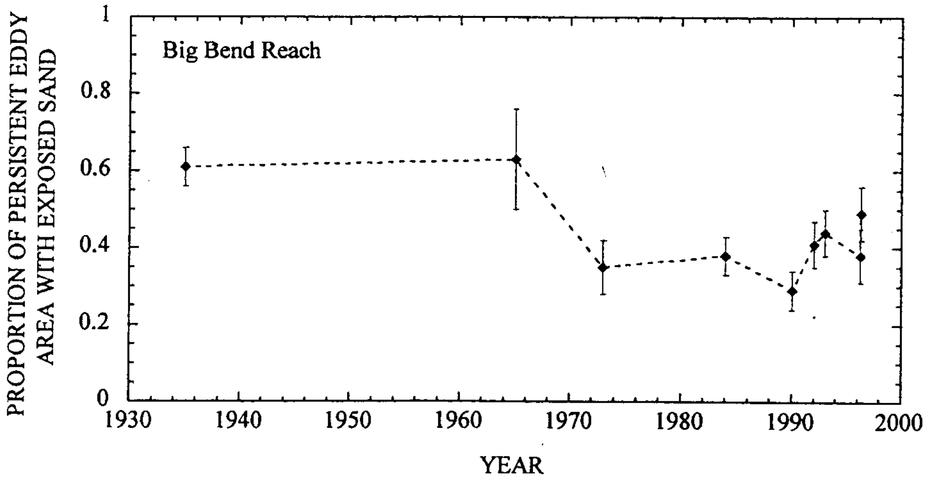
Figure 23



Point Hansbrough Reach
PROPORTION OF PERSISTENT EDDY AREA WITH EXPOSED SAND
YEAR
0
0.2
0.4
0.6
0.8
1
1930
1940
1950
1960
1970
1980
1990
2000



Tapeats Gorge Reach
PROPORTION OF PERSISTENT EDDY AREA WITH EXPOSED SAND
YEAR
0
0.2
0.4
0.6
0.8
1
1930
1940
1950
1960
1970
1980
1990
2000



Big Bend Reach
PROPORTION OF PERSISTENT EDDY AREA WITH EXPOSED SAND
YEAR
0
0.2
0.4
0.6
0.8
1
1930
1940
1950
1960
1970
1980
1990
2000

(Figure 19). The flat and multi-peaked distributions that are most common in the Tapeats Gorge and Big Bend reaches may be indicative of the higher sediment concentrations that typically occur in the reaches downstream from the LCR confluence. When sediment concentrations are high, eddies may completely fill with sand. Once eddies are filled, they are then more likely subject to rapid erosion events that evacuate sand from the eddies. This type of behavior would be likely to result in a distribution in which some eddies are filled and others are nearly empty and some are in the process of filling. Rapid erosion events were documented in the Tapeats Gorge reach during the 1996 controlled flood (Andrews and others, 1999). If this hypothesis is correct, a normal distribution would indicate lower sediment concentrations because very few eddies would be completely filled with sand and subject to evacuation events.

CONCLUSIONS

Integrating data from air and ground photography and from ground surveys, we developed 60-100 year time series of sand bar change at seven sites located between Lees Ferry and Phantom Ranch. We also measured the characteristics of sand bar change in every sand bar along 31 km of the river for periods between aerial photos by mapping the distribution of sand and analyzing change within a GIS framework. The topographic data are used to ground truth and calibrate the measurements made by aerial photographs. The photographic and topographic measurement methods are generally consistent when the spatial and temporal extent of the measurements are similar.

No long-term trends of sand bar degradation were identified at these sites, which are located more than 95 km downstream from Glen Canyon Dam. The area of low-elevation sand in eddies in these reaches has varied widely in both the pre- and post-dam era. We found at least one time between 1984 and 1996 at each of the nine sites when bar area was as great as in 1935. Reach-average time series for the 3 study reaches show decline in the area of exposed sand at 226 m^3/s between 1935 and 1965-1973 and between 1984 and 1996 prior to the controlled flood. Consistent depositional trends occurred between 1973 and 1984, between 1990 and 1993 in reaches downstream from the Little Colorado River, and during the 1996 controlled flood.

Although reach-average trends were identified, the variability of bar change between nearby eddies within a reach is very large; there are always extremes whose magnitude of erosion or deposition exceeds the reach average. Furthermore, the variability differs between reaches and differs from year to year. The only means of describing this variability are by analysis of spatial-rich data of the nature presented in this report.

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APPENDICIES

A. Eminence Detailed Site Report

ABSTRACT

The sand bed of the persistent eddy at Eminence Break was entirely exposed in December 1935 and has never been at such a uniform high elevation in any subsequent year for which records are available. However, the separation and reattachment bar parts of this eddy have been at high elevations at other times during the post-dam era.

The separation bar has been a large campsite throughout the period covered by photographic record, and this bar typically experiences scour and fill during flows that exceed powerplant capacity. Parts of the separation bar that are below the stage of 25,000 ft^3/s were most extensive immediately after recession from the 1996 controlled flood. Some parts of the same bar above that level were more extensive in the mid-1980's.

During the post-dam era, high-elevation parts of the reattachment bar that are emergent at maximum powerplant discharge have never projected far into the eddy. The changes in area of the reattachment bar have typically occurred at lower elevation. The largest area of high-elevation sand above powerplant capacity was surveyed here immediately after the 1996 controlled flood. These low-elevation parts of the reattachment bar were smallest during photography taken in October 1984. These low-elevation areas aggrade during fluctuating flows, and were most extensive and highest in 1991. Thus, the reattachment bar has not been a site where extensive, high-elevation deposition typically occurs. The 1996 controlled flood added more sand volume to this persistent eddy than had ever been measured since 1985, despite the fact that erosion offshore was extensive.

INTRODUCTION

The Eminence Break site is an informally named fan-eddy complex located on river left at River Mile 44.0 in the Point Hansbrough reach of Marble Canyon. The persistent eddy that is part of this complex occurs in the channel expansion downstream from the constriction formed by the Eminence Break debris fan (Figure 1). Schmidt and Leschin (1995) defined a persistent eddy to be the largest area of emergent bars that have occurred in a fan-eddy complex in all years of available aerial photography. In the Point

Hansbrough reach, Schmidt and Leschin (1995) mapped emergent bars on 8 sets of aerial photographs taken between 1935 and 1996. They found that the Eminence Break persistent eddy is 33,200 m^2 and is the second largest in the reach; only the Saddle Canyon eddy is larger.

The Eminence Break debris fan is large, and the Colorado River channel is constricted to a slightly greater extent than elsewhere. The ratio of the channel width at the constriction to the average upstream channel width is 0.42 at 5,000 ft^3/s, which is smaller than the average ratio of 0.49 for large debris fans in Grand Canyon (Schmidt and Graf, 1990). The constriction ratio increases to 0.58 at 45,000 ft^3/s, and the size of the eddy increases. There is a small high-elevation reattachment bar that Leschin and Schmidt (1995) mapped as having formed during the high flows of 1983 flood; this evidence indicates that the eddy persists at discharges at least as high as 90,000 ft^3/s. The area of the separation bar that forms at these high discharges is more extensive than is the area of the reattachment bar.

The direction of surface currents within the eddy were mapped in the field during the 1996 controlled flood. These maps show that the size of the eddy increases as discharge increases from 8,000 to 45,000 ft^3/s (Figure 2). The recirculation zone length increases by 24%, from 330 m to 410 m (Figure 2). At low discharges, there is a single recirculating cell with many areas of weak and stagnant flow (Figure 2a). At 45,000 ft^3/s, smaller secondary cells of recirculating current develop downstream from the separation point, and currents are stronger throughout the eddy (Figure 2b) Andrews (unpubl. data) measured the direction and speed of surface floats during the 1996 controlled flood, but those data are unavailable at present. Excavations, and sedimentologic analyses of the separation and reattachment deposits were made in 1985 and 1996 and these data demonstrate that bedform migration directions consistent with deposition by recirculating flow (J.C. Schmidt and D.M. Rubin, unpublished data).

Measurements of the water-surface profile were made in 1985 at 3 discharges and show that a steep slope in the constriction persists at discharges between 3,100 and 41,000 ft^3/s. The elevation of the drop in the rapid is between 0.4 to 0.5 ft (Figure 3). A large gravel bar upstream from the Eminence Break debris fan on river right is emergent at baseflow, and a low-gradient backwater pool does not exist upstream from the fan at these low discharges (Figure 3). On river left, the water surface profile reflects flow conditions in the persistent eddy. The upstream, or reverse, gradient of the eddy is steeper at 45,000 ft^3/s than at 28,000 ft^3/s (Figure 3).

AVAILABLE MONITORING DATA

The area and volume of the sand bars in the persistent eddy prior to 1985 were interpreted from historical aerial and oblique photographs. The quality of the aerial photographs and the discharge at which they were taken varies considerably. Leschin and Schmidt (1995; 1996) used these photographs and more recent photographs to map surficial geology of the reach that includes Eminence Break. From these maps, area of exposed sand in each year was calculated, and these measured areas vary greatly because discharge at the time of photography varies greatly (Tables 1 and 2). Our analysis of bar change had to account for these differences in discharges.

The separation and reattachment bars at Eminence Break have been the subject of numerous monitoring activities and scientific investigations since 1985. Most studies have focused on monitoring by repeat topographic and bathymetric surveys (Tables 1 and 2). The site has also been used as a type example in the eddy bar classification scheme of Schmidt and Graf (1990), and the topography of the persistent eddy has been used as initial conditions for a linked numerical model of streamflow and sediment transport (Nelson and McDonald, unpublished manuscript).

At least one topographic survey of the separation bar has been made in every year, except 1987, since 1985 (Table 1). Topographic data collected between 1985 and January 1990 were used to construct 5 topographic profiles of the separation bar (Figure 1). From October 1991 to present, integrated topographic and bathymetric data have been used to calculate net area and volume changes within specified boundaries on the separation bar only (Kaplinski and others, 1995; Hazel and others, 1999). For comparison purposes, the more recent data were compared to the original topographic profiles.

Detailed surveys of the reattachment bar were also made between 1985 and 1991 (Schmidt and Graf, 1990; Kaplinski and others, 1995). Bathymetric surveys document changes on the reattachment bar between April 1985 and January 1986 (Schmidt and Graf, 1990). Ground-based topographic surveys were conducted between October 1985 and July 1991 (Schmidt, unpublished data; Kaplinski and Hazel, 1995). The topographic data collected between 1985 and 1991 were used to construct 3 profiles of the reattachment bar, and these data were compared. The location of these profiles are shown on Figure 1. The bathymetric data collected by Schmidt and Graf (1990, Figure 15) in 1985 and 1986 could not be compared with subsequent data, because we could not determine the relationship between these data and reference points used in other surveys. McDonald and Nelson (unpublished manuscript) surveyed the only topographic or bathymetric data of the reattachment bar collected between 1991 and February 1996. These data are not yet in a format suitable for comparison with other data. Since February 1996, the reattachment bar has been part of the sand bar monitoring program of Hazel and others (1999).

Inventories of Grand Canyon campsites were conducted in 1973, 1983, 1991, 1994, and in 1996 before, after, and 6 months after the controlled flood (Weeden, 1973; Brian and Thomas, 1984; Kearsley and Warren, 1993; Kearsley and others, 1994; and Kearsley and Quartaroli, 1997). These inventories include a semi-quantitative evaluation of the size of the Eminence Break camp, which is on the separation bar; they based their estimate on the number of persons who could use this area for camping and they also measured the total campable area in some years (Table 1).

Two additional data sets measured the area of emergent sand from aerial photographs. The "test-flow air photo study" measured the area of exposed sand from low-altitude aerial photographs taken during the 1990 to 1991 test-flow period (Cluer, 1992). These data have the disadvantage that they did not distinguish between the separation and reattachment bars, and therefore we cannot use these data to detect changes in either of the bars individually. Cluer and others (1994) made area measurements for the separation and reattachment bars individually from spatially-rectified images of oblique photographs taken by a remote camera since 1992. These measurements were made of selected photographs from an original data set that includes daily images.

PHOTOGRAPHIC HISTORY: 1935 TO 1984

Photographs taken in December 1935 show that the persistent eddy was completely filled with sand (Figure 4). In subsequent years, the reattachment bar projected farther into the main channel but had a similar total area; the upstream portion of the eddy never had emergent sand in any subsequent air photo or survey (Figure 4). Thus, the area that comprises backwater habitat at low discharge in the post-dam era was filled with sand in 1935. The 1935 photographs were taken at about 4,000 ft^3/s, and the deposits occur at a range of elevations that extend to elevations that must have formed by the 105,000 ft^3/s flood that occurred in June 1935. Thus, the 1935 photographs document the maximum probable extent of sand bars in this eddy. The separation bar is obscured by shadow in the 1935 photographs.

Only a small area of sand is exposed in the 1965 photographs, because the Colorado River was at high discharge at the time of the photos. The deposits that are exposed appear to be freshly reworked and likely were deposited by the 45,000 ft^3/s bypass-tube test flow of May 8, 1965. These deposits occur along the bank and do not project into the eddy; these deposits do not create a large return current backwater channel. The area of exposed sand on the separation bar is smaller in 1965 than in subsequent years.

The 1973 photograph shows a reattachment bar that projects farther into the eddy and towards the main channel; this emergent bar creates a well-defined eddy return current channel (Figure 5). The area of the reattachment bar exposed in 1984 is much smaller than in 1973, and occurs downstream from the 1973 location. The smaller reattachment bar in 1984 does not project as far into the channel but does have a large return current channel (Figure 4). The photographs in 1973 and 1984 were both taken at about 5,000 ft^3/s, and measured areas reflect real changes in bar size. The size of the separation bar is very similar in 1973 and 1984. The 1984 photographs show the establishment of new vegetation on the separation bar just downstream from the old high-water vegetation (Figure 5). The separation bar was classified as a large campsite in 1973, 1984, and 1991.

TOPOGRAPHIC SURVEYS: 1985 TO 1991

Reattachment Bar

Bathymetric surveys of the eddy made in April and September 1985 and January 1986 show that the reattachment bar was progressively eroded during this period (Schmidt and Graf, 1990). Most of this erosion occurred between April and September when about 0.6 m of sand was eroded from bar crest (Schmidt and Graf, 1985, table 8). Erosion was less than 0.3 m on the upstream end of the reattachment bar and as much as 1.2 m at the downstream end of the bar.

The first ground-based topographic survey of the reattachment bar was made in October 1985 after most of the erosion determined from the bathymetric surveys had already occurred. The bar was also photographed at this time (Fig 6a). Most of the reattachment bar platform was sufficiently low in elevation that it was entirely submerged at 3,000 ft^3/s (Figure 7c). The elevation of the reattachment bar platform was somewhat lower when surveyed in October 1988 (Figure 7c). Between October 1988 and October 1989, deposition occurred over much of the reattachment bar and was about 1.5 m along CS-3 between CS-1 and CS-2 (Figure 7c). The bar crest aggraded so that upstream parts of the bar near the center of the eddy were emergent at flows less than 20,000 ft^3/s. Deposition along CS-1 between October 1989 and January 1990 increased the width of the reattachment bar emergent at 15,000 ft^3/s, but erosion near the eddy center decreased the total bar length. Aggradation continued over most of the bar through July 1991. The elevation of the bar crest increased so that downstream parts of it were emergent at 25,000 ft^3/s (Figure 7c), and the return channel was partially filled in at CS-1 and CS-2 (Figs. 7a and 7b).

Repeat topographic surveys of the reattachment bar were not made during the test flows that occurred in 1990 and 1991. Measurements of exposed bar area were made from low-altitude aerial photographs, but these data cannot be used to asses the individual behavior of the separation and the reattachment bar, as discussed above (Table 1). Visual inspection of the outlines of exposed bar area indicate that erosion and deposition during this period occurred along the margins of the reattachment bar and that no large-scale erosion or deposition occurred (Figure 8). This is consistent with the topographic data that bracket the test-flow period, which shows some deposition and erosion along bar margins but no large-scale changes.

Based on these data, relatively little net change occurred between July 1991 and February 1996 (Figure 7). Some aggradation occurred on the upstream portion of the bar, increasing the area emergent at 25,000 ft^3/s and partially filling the return-current channel (Figure 7a and 7c). Some erosion also occurred during this period, reducing the length of the bar projecting upstream (Figure 7c).

Separation Bar

Topographic profiles were established on the separation bar in October 1985. These profiles were resurveyed in January 1986 following 4 months of fluctuating flows. Daily fluctuations were typically between about 2,000 and 20,000 ft^3/s with a few peaks as high as 30,000 ft^3/s. Up to 40 cm of sand was deposited at the 30,000 ft^3/s stage at profiles B and E and up to 1 m of bank retreat occurred at profile D below the 30,000 ft^3/s stage (Figure 9). The effects of sustained releases at 45,000 ft^3/s during May and June 1986 were documented by a resurvey of the profiles in October 1988. All of the profiles show 40 to 50 cm of deposition above the 30,000 ft^3/s stage and from 1 to 3 m of bank retreat below that stage (Figure 9). The deposition must have occurred during the 1986 bypass release, although the erosion may have occurred then or during high fluctuating flows of summer 1986 to fall 1988. Continued bank erosion occurred at all profiles through February 1996 (Figure 9). At most profiles, the amount of bank retreat that occurred between July 1991 and February 1996 was similar to or less than the erosion that occurred between October 1988 and July 1991, indicating that erosion rates declined as parts of the bar became armored.

The separation bar was resurveyed twice monthly during the 1990-91 test-flow period. These surveys documented frequent erosion and deposition, but there was no relationship between the magnitude or direction of change and flow regime (Figure 10). For example, erosion and deposition occurred during periods of low- and high-fluctuating flows. For the low- and high-fluctuating and constant flows evaluated during the 1990-91 test-flow period, there was a good correlation ($R^2 = 0.70$) between the change in volume and the antecedent bar volume, however (Figure 10); the greatest amounts of erosion occurred when the bar contained the most sand. The much less frequent surveys made during the interim flow period do not follow this relationship, however (Figure 10). Thus, 6- to 12-month measurement intervals may not be frequent enough to reliably determine antecedent bar condition that could explain bar behavior.

The net change at the separation bar between 1990 and 1992 was evaluated both by repeat topographic surveys and by analyzing surficial geologic maps. Both methods documented erosion along the bank at the upstream and downstream margins of the separation bar (Figure 11). Continued erosion was measured between September 1991 and February 1996 (Figure 12). This erosion rate was highest between September 1991 and October 1992. Erosion rates declined with time on the upstream portion of the separation bar, as documented by rephotography showing the development of armoring bank material (Kaplinski and others, 1995).

Bar area was also measured from rectified oblique photographs in 1992 and 1993. These data show a much greater range in bar area than determined from the topographic survey data. For comparison in Figure 12, the measurements from the rectified oblique photographs and the topographic surveys were normalized to a common datum. The topographic data are adjusted to reflect our estimates of bar area above the 5,000 ft^3/s stage and are normalized to the topography of October 19, 1992. The data from the rectified oblique photographs for exposed bar area are normalized to bar size photographed on October 12, 1992. This comparison assumes, therefore, that the bar did not change significantly in the intervening period and that both methods adequately characterize bar area, although the exact areas of measurement differ. The data from the rectified oblique photographs have a much wider scatter than the topographic data for any period of measurement, including the twice-monthly surveys made in 1990-91 (Figure 12). However, only 2 of the photographs used for the areal measurements were taken during steady known discharge, and the scatter of these data is likely due largely to water stage differences (Figure 11).

CONTROLLED FLOOD

Reattachment Bar

The largest changes measured by topographic surveys at the reattachment bar during the entire period of record occurred during the 1996 controlled flood. The upstream portion of the bar aggraded to as high as the 40,000 ft^3/s stage along CS-2. Scour chains buried in the bar before the flood and excavated following the event showed that as much as 2 m of fill occurred, and that very little scour occurred (Figure 6c). Deposition also occurred on the upstream portion of the bar but at lower elevations. The elevation of the bar crest at the upstream end of the reattachment bar along CS-1 was approximately the same in the pre- and post-flood surveys (Figure 7a).

Areas of erosion and deposition were determined by analysis of the pre- and post-flood topographic/bathymetric surveys and by comparison of pre- and post-flood aerial photographs (Figure 13). These methods yielded generally consistent results although the aerial photograph analysis did not detect the large amounts of erosion that occurred in the channel. The area of sand above the 20,000 ft^3/s stage increased 19%, from 1700 to 2000 m^2, while the area of the bar above the 5,000 ft^3/s stage did not change significantly (Hazel and others, 1999). The increase in bar volume above the 20,000 ft^3/s stage was the most significant change, increasing from 550 to 2450 m^3 (Hazel and others, 1999).

Daily measurements of erosion and deposition were made during the controlled flood (Andrews and others, unpubl. manuscript). These data indicate that the largest volumes of scour occurred during the first days of the flood and that fill volumes varied during the flood but did not systematically increase or decrease (Table 3). Consistent with the February and April topographic surveys (Figure 12), these measurements show net erosion in the eddy and net deposition at higher elevations.

Separation Bar

The net effect of the 1996 controlled flood was aggradation over most of the separation bar below the 30,000 ft^3/s stage; there were small areas of erosion at high elevations (Figure 13). Increases in bar thickness of up to 1 m occurred over the upstream portion of the separation bar at profiles CS-A, CS-B, and CS-C (Figure 9), resulting in a greater amount of sand below the 30,000 ft^3/s stage than occurred in any previous measurements. Deposition also occurred below the 30,000 ft^3/s stage at the downstream profiles, but did not aggrade the bar to 1985-86 levels (Figure 9d and 9e). Up to about 0.5 m of erosion only occurred at the 35,000 to 45,000 ft^3/s stage along profile CS-B (Figure 9).

TIME SERIES OF BAR CHANGE

Reattachment Bar

The combined time-series of reattachment bar area shows that the various monitoring methods, except for the rectified oblique photos, yield generally consistent results (Fig 14). Thus, the changes measured by field survey and corrected surficial geologic map monitoring programs can be evaluated in relation to pre-dam conditions as depicted on aerial photographs. As discussed above, differences in measurement methods preclude direct comparisons of bar area (Table 2). Direct comparisons can only be conducted where data sets are georeferenced. As discussed above, the measurements of areas of erosion and deposition determined from surficial geologic maps agree well with the data obtained from topographic maps (Figure 11 and Figure 13). The time series (Figure 14) was constructed by applying the normalization procedure described above to each of the 3 data sets. The surficial geologic maps and rectified oblique photographs were normalized to October 11, 1992, a date that both kinds of measurements were made (Table 2). The closest overlap between the surficial geologic maps and the topographic data occurred on the measurements of February 17 and March 24, 1996 (Table 1). The topographic survey data were normalized so that the February 17 measurement equaled the normalized area determined by surficial geologic map on March 24. The final underlying assumption in this normalization is that each method independently characterizes bar area, even though measurement areas are not equivalent.

The values of sand bar area determined by surficial geologic mapping plotted in Figure 14 were corrected for the differences in area that are solely due to differences in discharge at the time of photography. The discharge bias was accounted for by plotting the exposed bar area against the discharge and comparing these data to the area-discharge relationship for the bar determined from topographic survey data collected in April 1996 (Figure 15). The difference between the bar area that was measured from photographs and the area-discharge relation is a measure of the bar area in those years in relation to the area following the controlled flood. We estimated the area of exposed sand at 8,000 ft^3/s in all years for which surficial geologic map data are available by fitting the 1996 bar area-to-discharge relationship to the area determined in each year by surficial geologic mapping (Figure 15). This approach presents the most accurate portrayal of bar size from the older photographs that is possible and is the only means of interpreting the 1965 photographs.

The time series shows a large decrease in size of the reattachment bar between 1965 and 1984 (Figure 14). The bar area increased in area dramatically between 1984 and 1990 to a size comparable with the 1935 condition. Large-scale deposition on the reattachment bar was also measured by the topographic surveys made in October 1988 and October 1989, indicating that the 1984-90 deposition measured by the surficial geologic maps occurred during wide-ranging fluctuating flows between 2,000 and 30,000 ft^3/s. Flows did not exceed 30,000 ft^3/s during this time. The bar was largest in 1991.

Separation Bar

The topographic survey data show that normalized changes in bar area track changes in bar volume fairly well at the separation bar (Figure 12). However, the areal changes are small enough relative to the total bar area that photographic methods that only measure area do not adequately describe bar condition. Changes in area due to discharge differences between photographs outweigh real changes in bar area (Figure 12). We cannot correct for the errors associated with different discharges at the time of measurements, as was employed for the reattachment bar, because the surficial geologic maps include a much larger area of the high-elevation portion of the bar than do the topographic surveys, resulting in much larger values.

CONCLUSIONS

The sand bed of the persistent eddy at Eminence Break was entirely exposed in December 1935 and has never been at such a uniform high elevation in any subsequent year. However, the separation and reattachment bar parts of this eddy have been at high elevation at other times during the post-dam era.

The separation bar has been a large campsite throughout the period covered by this study, and this bar typically experiences scour and fill during flows that exceed powerplant capacity. Low-elevation parts of the separation bar that are below the stage of 25,000 ft^3/s were most extensive immediately after recession from the 1996 controlled flood. Some high-elevation parts of this same bar were more extensive in the mid-1980's.

During the period in 1990-91 when the separation bar was surveyed twice monthly, there was correlation between the change in volume and the antecedent bar volume; the greatest amounts of erosion occurred when the bar contained the most sand. The much less frequent surveys made during the interim flow period do not follow this relationship, indicating that 6- to 12-month measurement intervals may not be frequent enough to reliably determine antecedent bar condition that could explain bar behavior.

During the post-dam era, high-elevation parts of the reattachment bar that are emergent at maximum powerplant discharge have never projected far into the eddy. The changes in area of the reattachment bar have typically occurred at lower elevation. The largest area of high-elevation sand above powerplant capacity was surveyed here immediately after the 1996 controlled flood. These low-elevation parts of the reattachment bar were smallest during photography taken in October 1984. These low-elevation areas aggrade during fluctuating flows, and were most extensive and highest in 1991. Thus, the reattachment bar has not been a site where extensive, high-elevation deposition typically occurs. The 1996 controlled flood added more sand volume to this persistent eddy than had ever been measured since 1985, despite the fact that erosion offshore was extensive.

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LIST OF FIGURES

30,000 ft^3/s. Low fluctuating flows also occurred during the test period with minimums between 2,000 and 10,000 ft^3/s and maximums between 13,000 and 20,000 ft^3/s. Constant flows of 5,000 ft^3/s occurred during the test-flow period for evaluation purposes. Interim flows began following the test-flow period with minimums of 5,000 to 10,000 ft^3/s and maximums of 14,000 to 18,000 ft^3/s.

Figure 11. Map showing areas of significant aggradation and degradation measured by topographic/bathymetric survey (between October 12, 1990 and October 19, 1992) and surficial geologic mapping (between June 30, 1990 and October 11, 1992) downstream from Saddle Canyon. Areas of erosion, deposition, and less than 0.3 m of change are shown by red, green, and blue, respectively. Areas shaded by diagonal lines are erosion measured by surficial geologic maps. The solid thick line shows the area of the persistent eddy.

Figure 12. Plot showing area and volume of sand in the separation bar above the 5,000 ft^3/s stage as measured by topographic/bathymetric survey (Hazel and others, 1999) and area of sand measured by rectified images of oblique photographs (Cluer, 1994). The measurements from the rectified oblique photographs area normalized to October 12, 1992 and the measurements from the topographic/bathymetric surveys are normalized to October 19, 1992.

Figure 13. Map showing areas of significant aggradation and degradation measured by topographic/bathymetric survey (between February 17 and April 15, 1996) and surficial geologic mapping (between March 24 and April 4, 1996) downstream from Eminence Break. Areas of erosion, deposition, and less than 0.3 m of change are shown by red, green, and blue, respectively. Areas shaded by diagonal lines are erosion measured by surficial geologic maps. The thick line shows the area of the persistent eddy.

Figure 14. Time-series plot of normalized sand bar area from 1935 to present for the Eminence Break reattachment bar. See text for description of normalization procedure and correction applied to surficial geologic map data. Note shift in horizontal scale at 1990.

Figure 15. Plot showing the relationship between measured sand bar area and discharge. The diamonds are the bar area above the indicated discharge calculated from the post-1996 flood topographic data (Hazel and others, 1999). The line is a logarithmic best fit (R^2= 0.98) to these points. The squares show area of exposed sand above the indicated discharge measured from surficial geologic maps (Schmidt and Leschin, 1995). Six additional curves parallel to the bold fitted curve were used to estimate the area of exposed sand at 8,000 ft^3/s from the areas measured at various discharges. For example, the estimated area of sand exposed at 8,000 ft^3/s in 1984 is 2,400 m^2, read as the point where the curve that passes through the 1984 measured area intersects the 8,000 ft^3/s line.

Table 1. Sand bar monitoring data available for the separation bar at Eminence Break Camp (RM 44L).

Date	Method	Reference	Area[1], in m^2	Corrected Area[2], in m^2	Normalized area[3]	Discharge[4], in ft^3/s
1/17/1890	Stanton photo #347	Melis and others (1995)				na
1973	campsite inventory	Weeden (1973)	L			na
1983	campsite inventory	Brian and Thomas (1984)	L			na
1991	campsite inventory	Kearsley and Warren (1993)	L			na
1994	campsite inventory	Kearsley (1995)	L			na
12/31/35	surficial geologic map	Schmidt and Leschin (1995)	3085		0.29	4000
5/14/65	surficial geologic map	Schmidt and Leschin (1995)		9500		25000
6/16/73	surficial geologic map	Schmidt and Leschin (1995)	9731	10500	0.93	5000
10/21/84	surficial geologic map	Schmidt and Leschin (1995)	11358	14000	1.08	5000-8000
5/26/85	oblique photograph	Schmidt (personal communication)				na
8/5/85	oblique photograph	Schmidt (personal communication)				na
10/13/85	topographic map (profiles)	Schmidt (personal communication)				na
10/13/85	oblique photograph	Schmidt (personal communication)				na
1/16/86	topographic map (profiles)	Schmidt (personal communication)				na
4/22/87	oblique photograph	Schmidt (personal communication)				na
Oct-88	topographic map (profiles)	Schmidt (personal communication)				na
1/19/89	oblique photograph	Schmidt (personal communication)				na
1/20/89	topographic map (profiles)	Schmidt (personal communication)				na
Oct-89	topographic map (profiles)	Schmidt (personal communication)				na
1/22/90	topographic map (profiles)	Schmidt (personal communication)				na
1/22/90	oblique photograph	Schmidt (personal communication)				na
5/5/90	test-flow air photographs	Cluer (1992)	19059			
6/30/90	surficial geologic map	Schmidt and Leschin (1995)	11340	14000	1.08	5000
9/30/90	test-flow air photographs	Cluer (1992)	19030			
10/12/90	topographic/bathymetric survey	Kaplinski and others (1995)	2578		1.04	na
10/26/90	topographic/bathymetric survey	Kaplinski and others (1995)	2417		0.97	na
11/9/90	topographic/bathymetric survey	Kaplinski and others (1995)	2551		1.03	na
11/11/90	test-flow air photographs	Cluer (1992)	19131			
12/14/90	topographic/bathymetric survey	Kaplinski and others (1995)	2611		1.05	na
12/17/90	test-flow air photographs	Cluer (1992)	18270			
12/28/90	topographic/bathymetric survey	Kaplinski and others (1995)	2722		1.10	na
12/30/90	test-flow air photographs	Cluer (1992)	18725			
1/11/91	topographic/bathymetric survey	Kaplinski and others (1995)	2688		1.08	na
1/12/91	test-flow air photographs	Cluer (1992)	19243			
1/25/91	topographic/bathymetric survey	Kaplinski and others (1995)	2577		1.04	na
1/26/91	test-flow air photographs	Cluer (1992)	18461			
2/8/91	topographic/bathymetric survey	Kaplinski and others (1995)	2604		1.05	na
2/9/91	test-flow air photographs	Cluer (1992)	19651			
4/19/91	topographic/bathymetric survey	Kaplinski and others (1995)	2623		1.06	na
4/20/91	test-flow air photographs	Cluer (1992)	19082			
5/2/91	topographic/bathymetric survey	Kaplinski and others (1995)	2633		1.06	na
5/17/91	topographic/bathymetric survey	Kaplinski and others (1995)	2632		1.06	na
5/19/91	test-flow air photographs	Cluer (1992)	18564			
6/2/91	test-flow air photographs	Cluer (1992)	21340			
6/3/91	topographic/bathymetric survey	Kaplinski and others (1995)	2674		1.08	na
6/28/91	topographic/bathymetric survey	Kaplinski and others (1995)	2646		1.07	na
6/30/91	test-flow air photographs	Cluer (1992)	19615			
7/12/91	topographic/bathymetric survey	Kaplinski and others (1995)	2675		1.08	na
7/26/91	topographic/bathymetric survey	Kaplinski and others (1995)	2585		1.04	na
7/27/91	test-flow air photographs	Cluer (1992)	20480			
9/26/91	topographic/bathymetric survey	Kaplinski and others (1995)	2656		1.07	na
9/26/91	topographic map (profiles)	Schmidt (personal communication)				na
3/15/92	rectified oblique photograph	Cluer and Dexter (1994)	876		1.12	na
4/19/92	rectified oblique photograph	Cluer and Dexter (1994)	794		1.02	na
5/16/92	rectified oblique photograph	Cluer and Dexter (1994)	678		0.87	na
6/14/92	rectified oblique photograph	Cluer and Dexter (1994)	751		0.96	na
7/19/92	rectified oblique photograph	Cluer and Dexter (1994)	505		0.65	na

8/16/92	rectified oblique photograph	Cluer and Dexter (1994)	406		0.52	na
9/13/92	rectified oblique photograph	Cluer and Dexter (1994)	616		0.79	na
10/11/92	surficial geologic map	Schmidt and Leschin (1995)	10480	12500	1.00	8000
10/12/92	rectified oblique photograph	Cluer and Dexter (1994)	782		1.00	8000
10/19/92	topographic/bathymetric survey	Kaplinski and others (1995)	2479		1.00	na
11/12/92	rectified oblique photograph	Cluer and Dexter (1994)	658		0.84	na
12/19/92	oblique photograph	Schmidt (personal communication)				na
1/17/93	rectified oblique photograph	Cluer and Dexter (1994)	460		0.59	na
2/20/93	rectified oblique photograph	Cluer and Dexter (1994)	519		0.66	na
2/23/93	Stanton photo #347	Melis and others (1995)				na
3/14/93	rectified oblique photograph	Cluer and Dexter (1994)	748		0.96	na
4/18/93	rectified oblique photograph	Cluer and Dexter (1994)	819		1.05	na
5/31/93	rectified oblique photograph	Cluer and Dexter (1994)	652		0.83	8000
7/18/93	rectified oblique photograph	Cluer and Dexter (1994)	620		0.79	na
9/12/93	rectified oblique photograph	Cluer and Dexter (1994)	709		0.91	na
10/10/93	topographic/bathymetric survey	Kaplinski and others (1995)	2498		1.01	na
10/16/93	rectified oblique photograph	Cluer and Dexter (1994)	898		1.15	na
11/14/93	rectified oblique photograph	Cluer and Dexter (1994)	658		0.84	na
12/19/93	rectified oblique photograph	Cluer and Dexter (1994)	411		0.53	na
4/11/94	topographic/bathymetric survey	Kaplinski and others (1995)	2550		1.03	na
11/22/94	topographic/bathymetric survey	Kaplinski and others (1995)	2485		1.00	na
4/27/95	topographic/bathymetric survey	Kaplinski and others (1995)	2450		0.99	na
2/17/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	2390		0.96	na
Mar-96	campsite inventory	Kearsley and Quartaroli (1997)	870*			na
3/24/96	surficial geologic map	Schmidt and others (1998)	12371	14000	1.18	8000
Apr-96	campsite inventory	Kearsley and Quartaroli (1997)	1230*			na
4/4/96	surficial geologic map	Schmidt and others (1998)	5826	13500	0.56	13600
4/15/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	2950		1.19	na
Sep-96	campsite inventory	Kearsley and Quartaroli (1997)	1080*			na
9/16/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)				na
2/16/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)				na
4/23/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)				na
8/27/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)				na

[1] The values for area are those reported for each respective measurement that included areal data. The boundary in which area is measured is not consistent between methods and for the photographic methods, discharge varies between some measurements. Thus, these numbers are not directly comparable. For the topographic/bathymetric surveys, the area reported is the area above the 5000 ft^3/s stage.

[3] Measurements of sand bar area determined from surficial geologic maps are corrected for discharge differences. Listed, is estimated area above the 8,000 ft^3/s stage.

[3] Normalized bar area is the area for the given normalized to the area for a chosen reference measurement. The surficial geologic maps and the rectified oblique photographs were normalized to October 11 and 12, 1992, respectively. The bar areas from the topographic/bathymetric surveys were normalized to October 19, 1992, which assumes no change occurred between these dates.

[3] Discharge is reported only for the methods for which bar area is a function of discharge and discharge at the time of photography is known

Table 2. Sand bar monitoring data available for the reattachment bar at Eminence Break Camp (RM 44L).

Date	Method	Reference	Area[1], in m^2	Normalized area[2]	Discharge[3], in ft^3/s
12/31/35	surficial geologic map	Schmidt and Leschin (1995)	7000	0.89	
5/14/65	surficial geologic map	Schmidt and Leschin (1995)	6200	0.78	
6/16/73	surficial geologic map	Schmidt and Leschin (1995)	5700	0.72	
10/21/84	surficial geologic map	Schmidt and Leschin (1995)	2400	0.30	
4/16/85	bathymetric survey	Schmidt and Graf (1990)			21000
5/26/85	oblique photograph	Schmidt (personal communication)			44000
8/5/85	oblique photograph	Schmidt (personal communication)			27000
9/2/85	bathymetric survey	Schmidt and Graf (1990)			
10/13/85	oblique photograph	Schmidt (personal communication)			23500
10/13/85	topographic map	?			23500
1/16/86	bathymetric survey	Schmidt and Graf (1990)			10500
4/22/87	oblique photograph	Schmidt (personal communication)			14500
Oct-88	topographic map	?			
1/19/89	oblique photograph	Schmidt (personal communication)			
1/19/89	topographic map	Middlebury College			14500
Oct-89	topographic map	?			
1/22/90	oblique photograph	Schmidt (personal communication)			
1/22/90	topographic map	Middlebury College			
5/5/90	test-flow air photographs	Cluer (1992)	19059		
6/30/90	surficial geologic map	Schmidt and Leschin (1995)	7000	0.89	
9/30/90	test-flow air photographs	Cluer (1992)	19030		
11/11/90	test-flow air photographs	Cluer (1992)	19131		
12/17/90	test-flow air photographs	Cluer (1992)	18270		
12/30/90	test-flow air photographs	Cluer (1992)	18725		
Jan-91	topographic map	?			
1/12/91	test-flow air photographs	Cluer (1992)	19243		
1/26/91	test-flow air photographs	Cluer (1992)	18461		
2/9/91	test-flow air photographs	Cluer (1992)	19651		
4/20/91	test-flow air photographs	Cluer (1992)	19082		
5/19/91	test-flow air photographs	Cluer (1992)	18564		
6/2/91	test-flow air photographs	Cluer (1992)	21340		
6/30/91	test-flow air photographs	Cluer (1992)	19615		
7/26/91	topographic/bathymetric survey	Kaplinski and others (1995)	6570	0.88	
7/27/91	test-flow air photographs	Cluer (1992)	20480		
3/15/92	rectified oblique photo	Cluer and Dexter (1994)	5288	0.95	
4/12/92	rectified oblique photo	Cluer and Dexter (1994)	4993	0.89	
5/10/92	rectified oblique photo	Cluer and Dexter (1994)	4870	0.87	
6/14/92	rectified oblique photo	Cluer and Dexter (1994)	4732	0.85	
7/12/92	rectified oblique photo	Cluer and Dexter (1994)	3362	0.60	
8/16/92	rectified oblique photo	Cluer and Dexter (1994)	3303	0.59	
9/20/92	rectified oblique photo	Cluer and Dexter (1994)	4770	0.85	
10/11/92	rectified oblique photo	Cluer and Dexter (1994)	5580	1.00	8000
10/11/92	surficial geologic map	Schmidt and Leschin (1995)	7900	1.00	
10/18/92	rectified oblique photo	Cluer and Dexter (1994)	5733	1.03	
11/15/92	rectified oblique photo	Cluer and Dexter (1994)	5190	0.93	
12/19/92	oblique photograph	Schmidt (personal communication)			11600
1/20/93	rectified oblique photo	Cluer and Dexter (1994)	3824	0.69	
1/21/93	rectified oblique photo	Cluer and Dexter (1994)	3623	0.65	
2/7/93	rectified oblique photo	Cluer and Dexter (1994)	4017	0.72	
3/14/93	rectified oblique photo	Cluer and Dexter (1994)	4890	0.88	
5/16/93	rectified oblique photo	Cluer and Dexter (1994)	4640	0.83	
5/31/93	rectified oblique photo	Cluer and Dexter (1994)	4748	0.85	8000
10/17/93	rectified oblique photo	Cluer and Dexter (1994)	5279	0.95	
11/14/93	rectified oblique photo	Cluer and Dexter (1994)	4640	0.83	
12/12/93	rectified oblique photo	Cluer and Dexter (1994)	4754	0.85	
2/17/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	5819	0.78	
3/24/96	surficial geologic map	Schmidt and others (1998)	6200	0.78	
4/4/96	surficial geologic map	Schmidt and others (1998)	7300	0.92	

4/15/96 topographic/bathymetric survey	Hazel and Kaplinski (1998)	5696	0.76
9/16/96 topographic/bathymetric survey	Hazel and Kaplinski (1998)	5454	0.73
2/16/97 topographic/bathymetric survey	Hazel and Kaplinski (1998)	5912	0.79
4/23/97 topographic/bathymetric survey	Hazel and Kaplinski (1998)	6838	0.92
8/27/97 topographic/bathymetric survey	Hazel and Kaplinski (1998)	6512	0.87

[1] The values for area are those reported for each respective measurement that included areal data. The boundary in which area is measured is not consistent between methods and for the photographic methods, discharge varies between some measurements. Thus, these numbers are not directly comparable. For the topographic/bathymetric surveys, the area reported is the area above the 5000 ft^3/s stage.

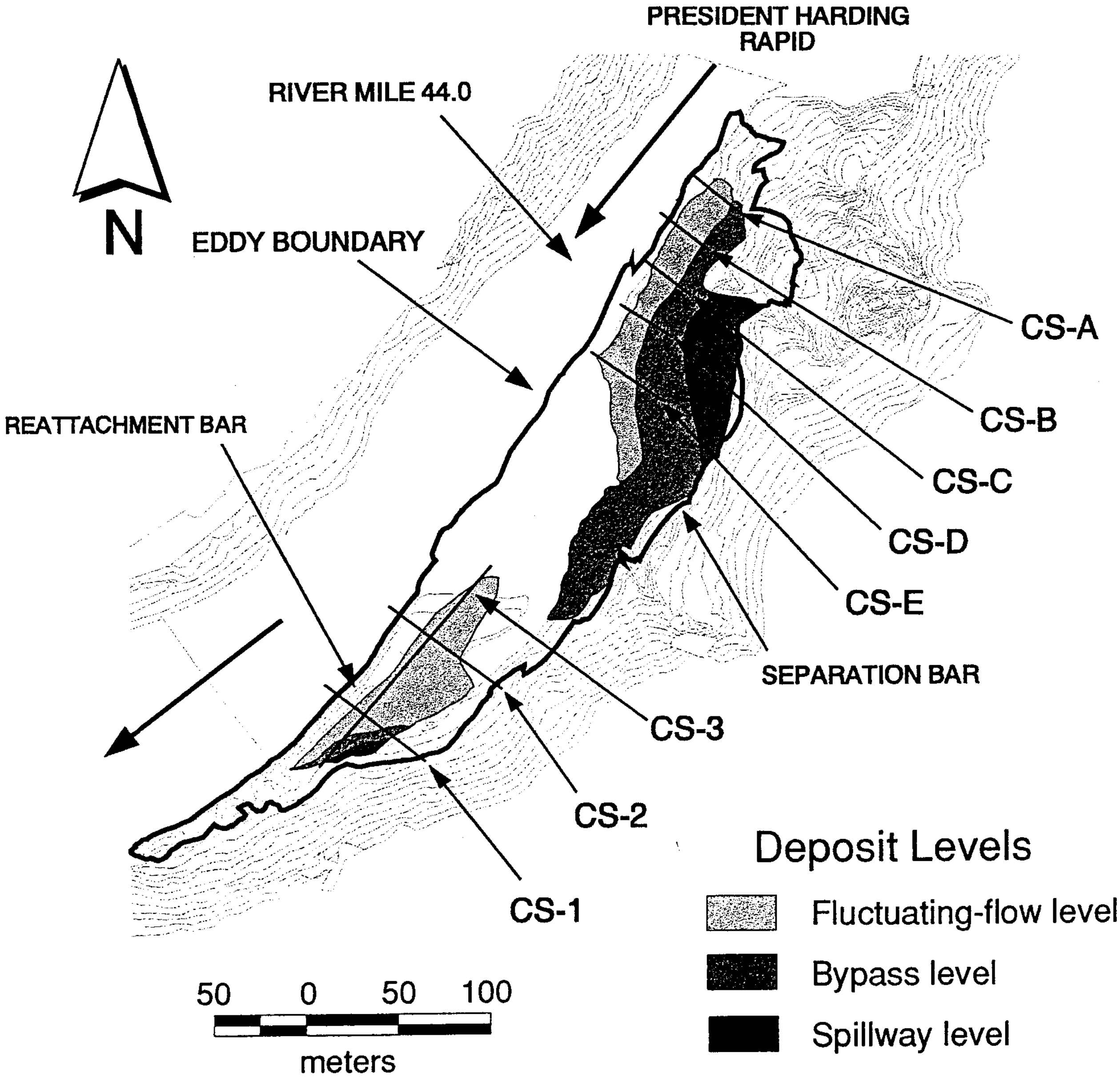
[2] Normalized bar area is the area for the given normalized to the area for a chosen reference measurement. The surficial geologic maps and the rectified oblique photographs were normalized to October 11, 1992. The bar areas from the topographic/bathymetric surveys were normalized such that the area on February 17, 1996 equalled the area measured by surficial geologic map on March 24, 1996, which assumes no change occurred between these dates.

[3] Discharge is reported only for the methods for which bar area is a function of discharge.

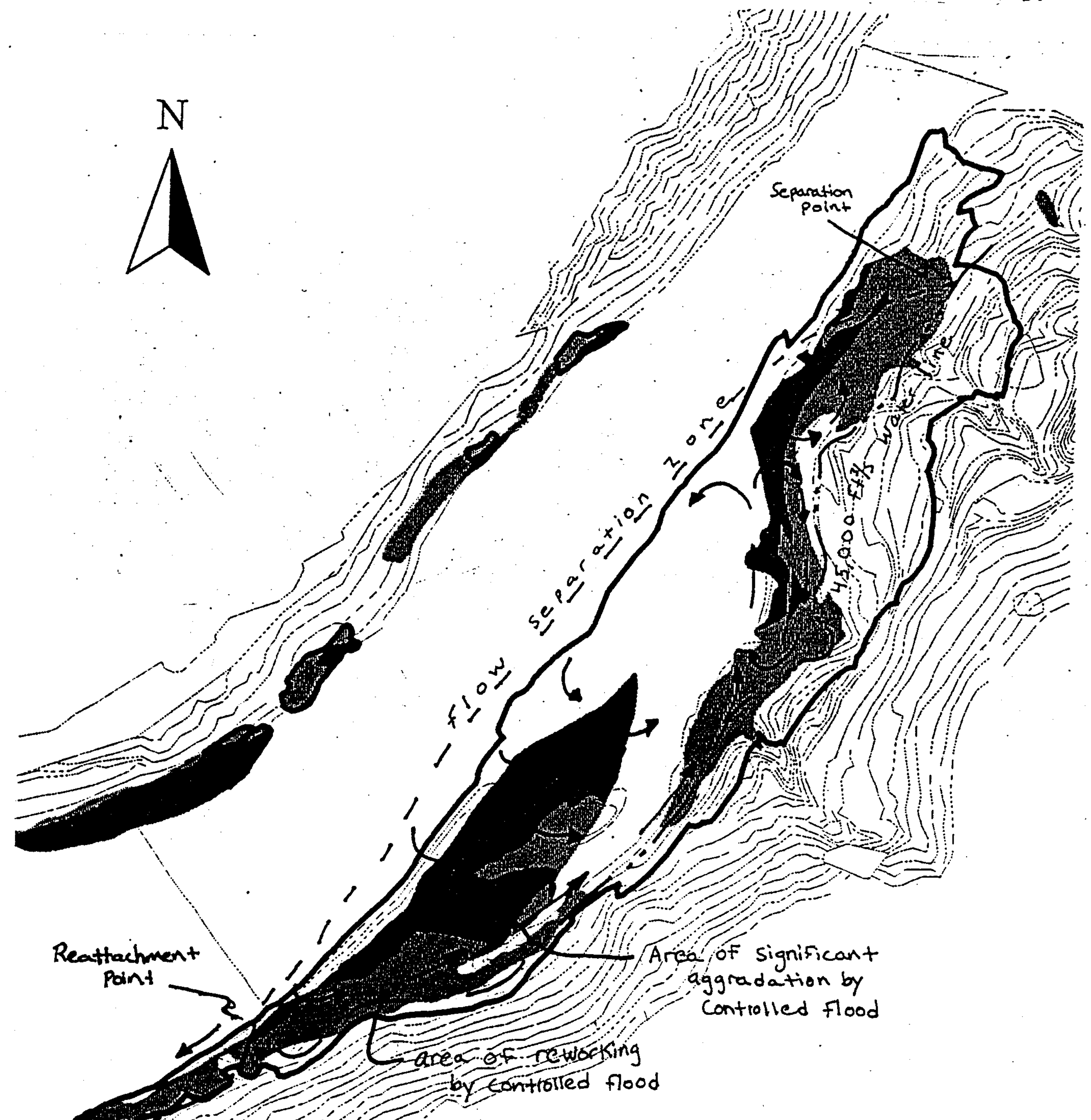
Table 3. Volume of sand scoured and filled in the eddy downstream from Eminence Break, March 25 to April 6, 1996 (Andrews, 1998).

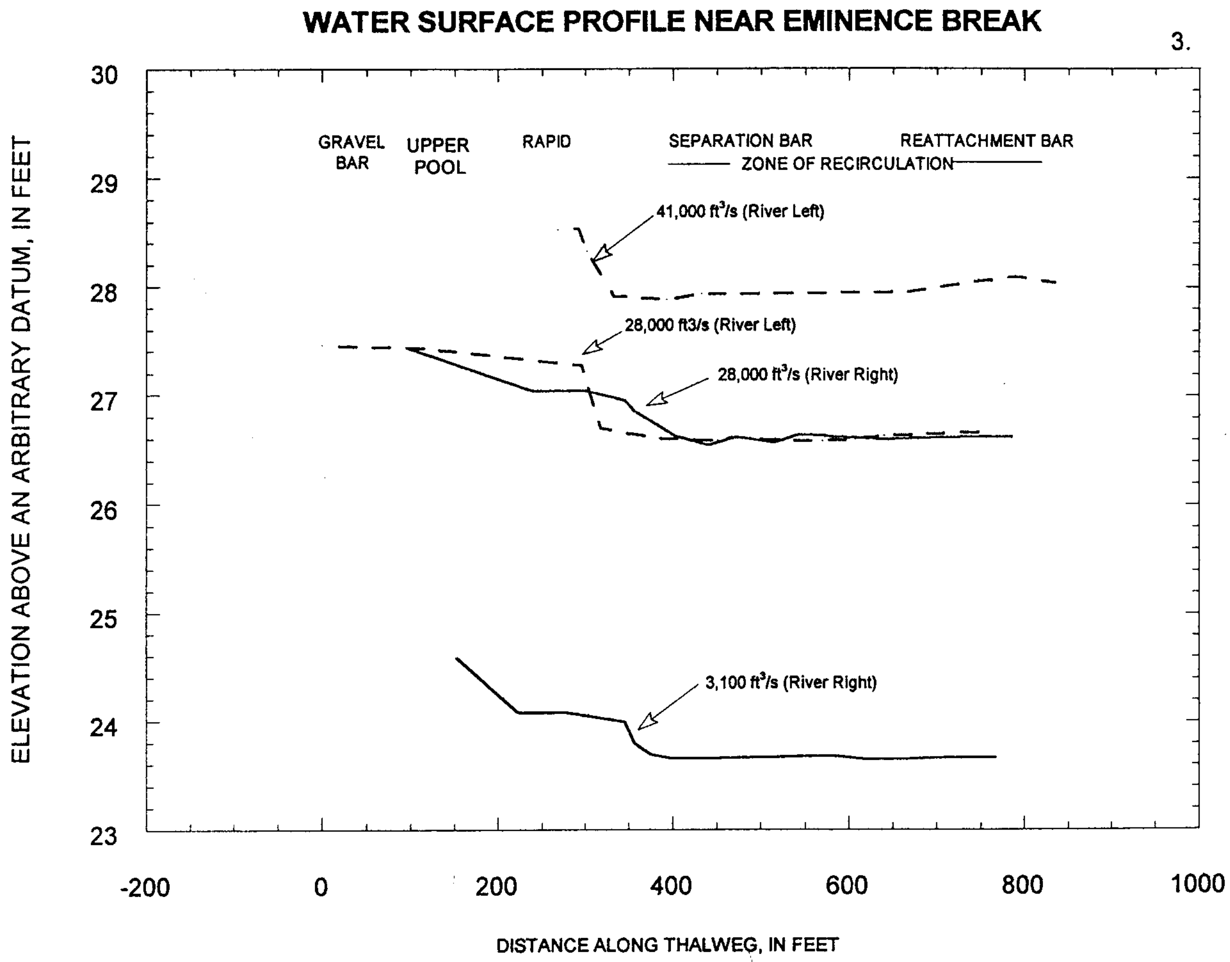
Period ending	Scour (m^3)	Fill (m^3)	Net change (m^3)
entire eddy			
Day 1	-22900	4800	-18100
Day 2	-8750	6350	-2400
Day 3	-8720	4280	-4440
Day 4	-5090	6130	1040
Day 5	-6020	3970	-2050
Day 6	-5140	3370	-1770
Day 7	-5490	3830	-1660
Post-flood	-2020	8340	6320
Pre- to post-flood	-37300	12500	-24800
above 8,000 ft^3/s stage only			
Pre- to post-flood	-5330	7090	1760

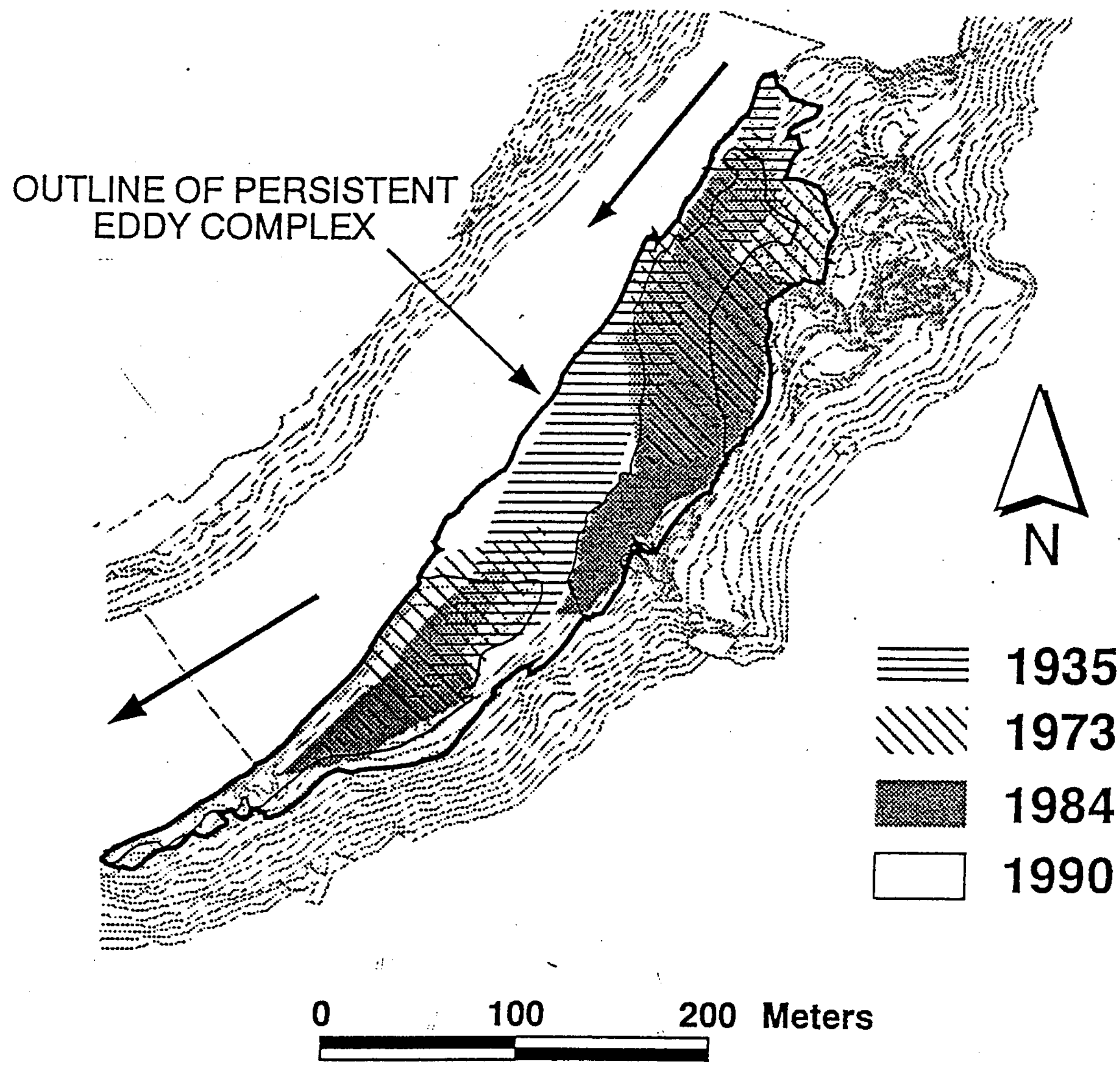
1.


PRESIDENT HARDING
RAPID
RIVER MILE 44.0
N
EDDY BOUNDARY
REATTACHMENT BAR
CS-A
CS-B
CS-C
CS-D
CS-E
SEPARATION BAR
CS-3
CS-2
CS-1
Deposit Levels
Fluctuating-flow level
Bypass level
Spillway level
50
0
50
100
meters

2b.


N
Separation Point
flow separation zone
Reattachment Point
Area of significant aggradation by Controlled Flood
area of reworking by Controlled flood
30 0 30 60 Meters

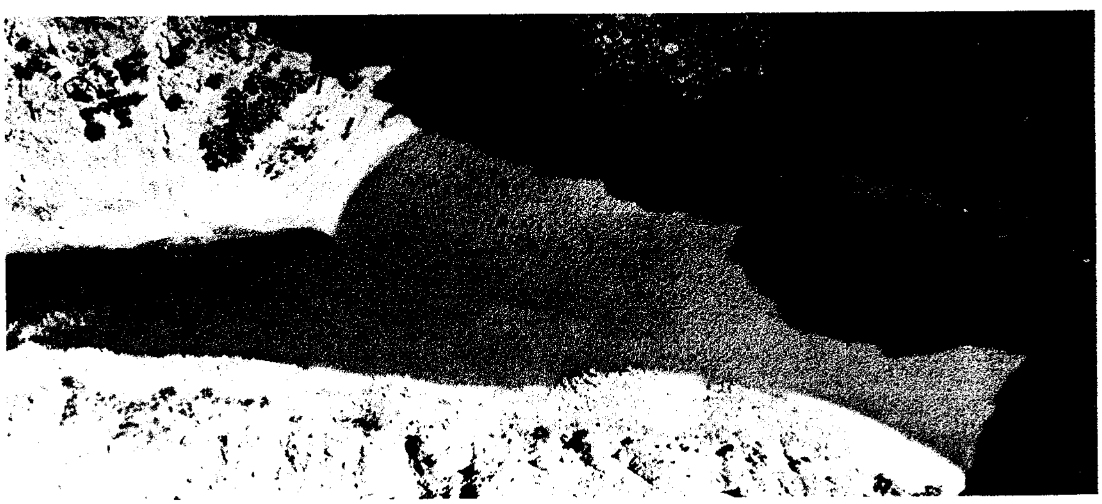

WATER SURFACE PROFILE NEAR EMINENCE BREAK
3.
GRAVEL BAR
UPPER POOL
RAPID
SEPARATION BAR
REATTACHMENT BAR
ZONE OF RECIRCULATION
41,000 ft³/s (River Left)
28,000 ft3/s (River Left)
28,000 ft³/s (River Right)
3,100 ft³/s (River Right)
ELEVATION ABOVE AN ARBITRARY DATUM, IN FEET
DISTANCE ALONG THALWEG, IN FEET
30
29
28
27
26
25
24
23
-200
0
200
400
600
800
1000


OUTLINE OF PERSISTENT
EDDY COMPLEX
N
1935
1973
1984
1990
0
100
200 Meters

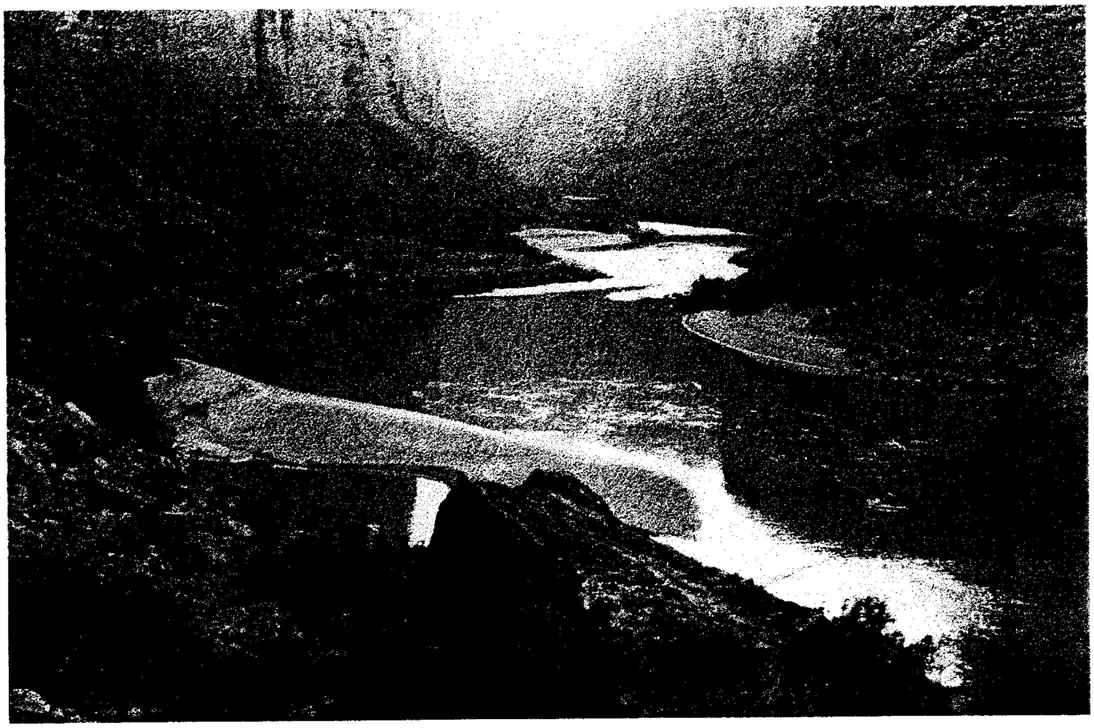
5a.

5b.

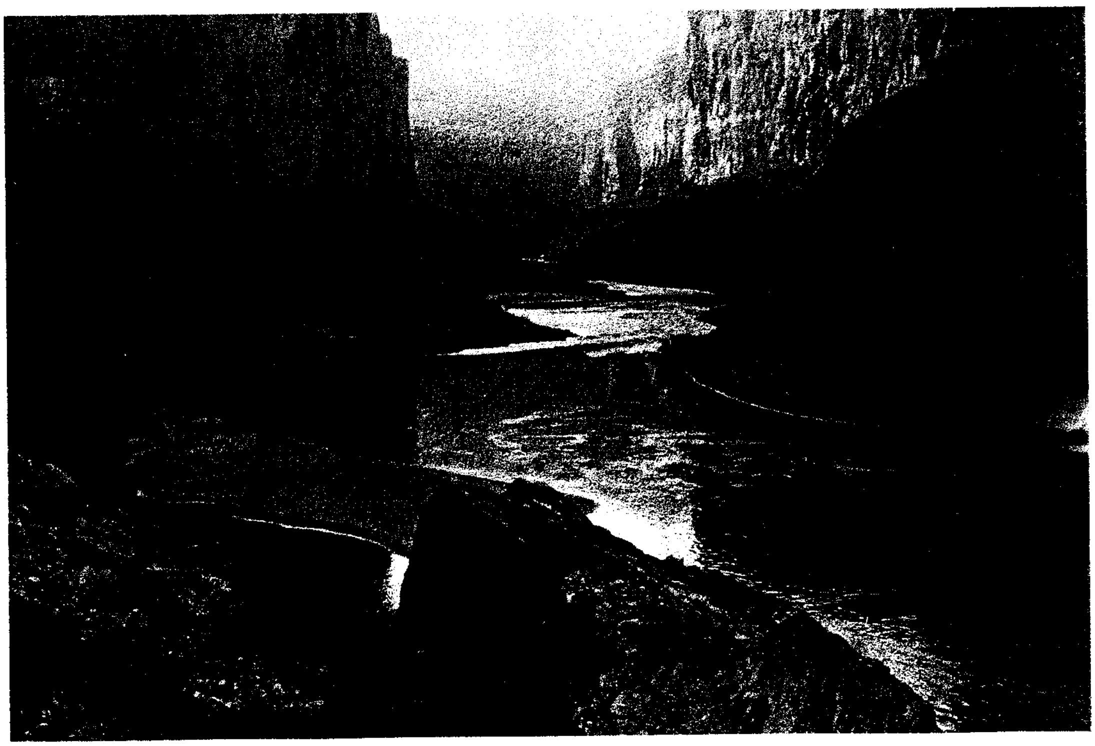
5c.

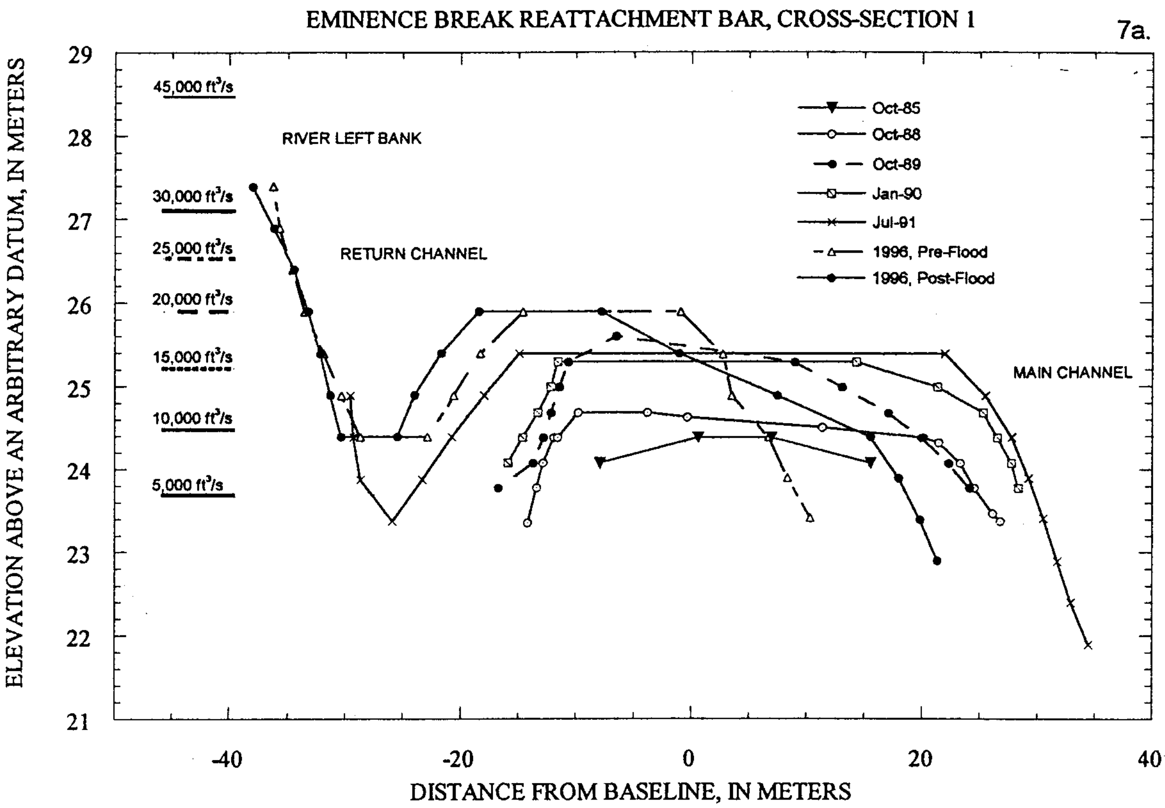


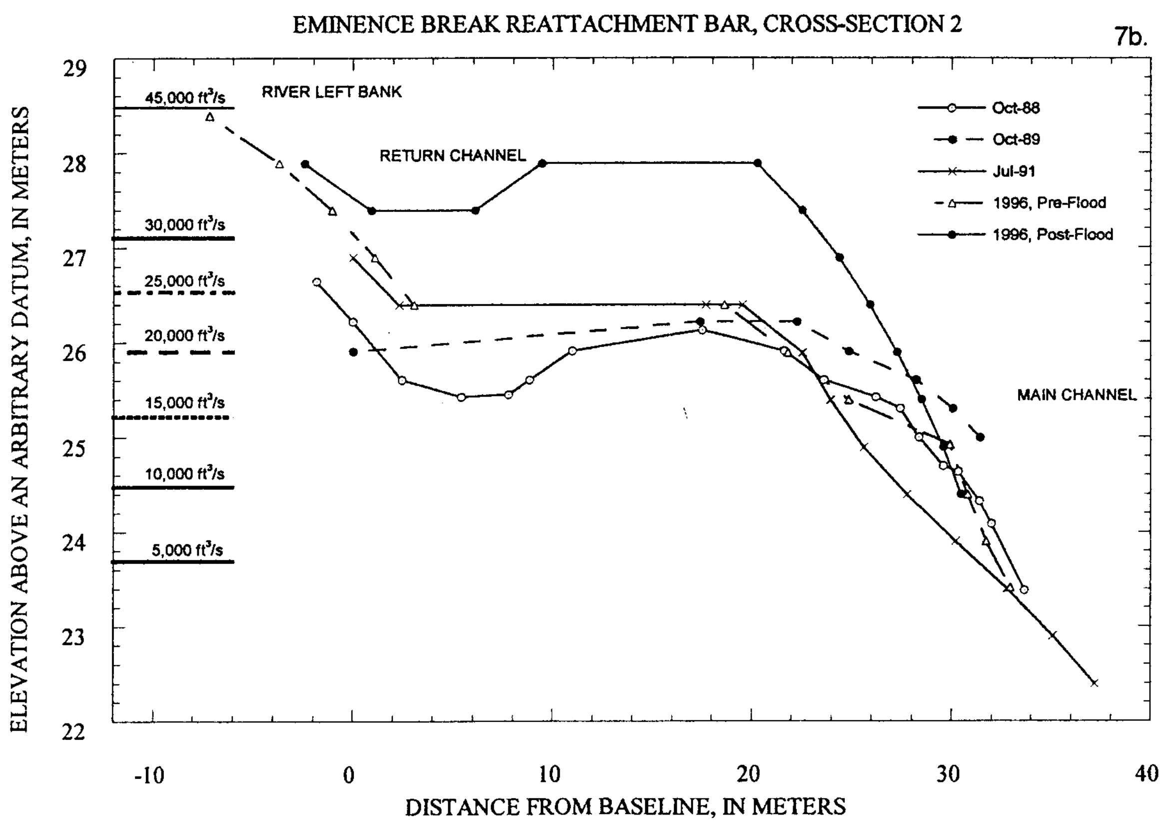
6a.

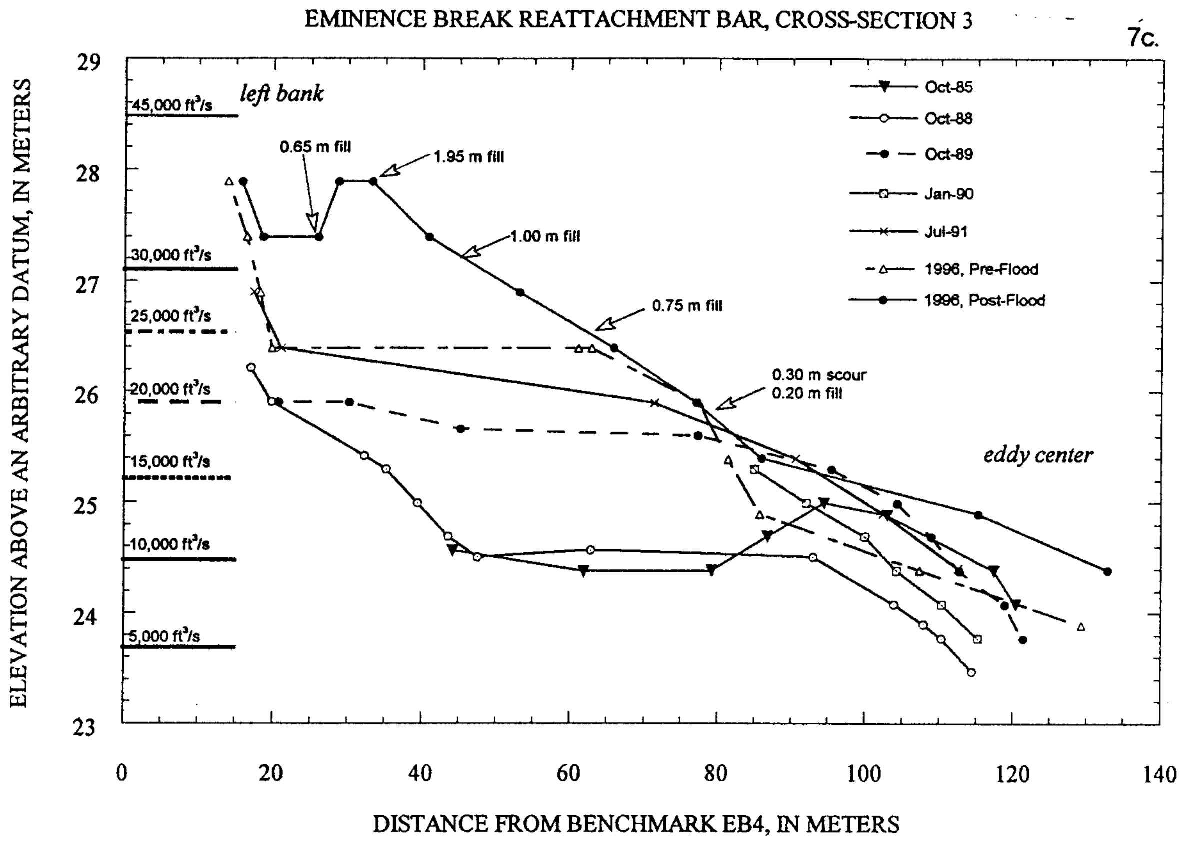


6b.



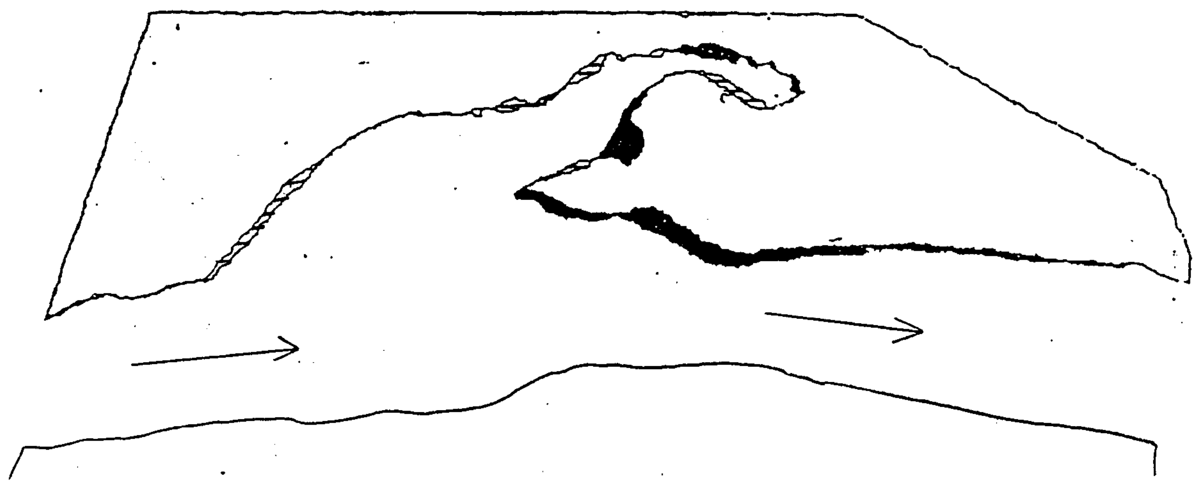

EMINENCE BREAK REATTACHMENT BAR, CROSS-SECTION 1
7a.
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BASELINE, IN METERS
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
RIVER LEFT BANK
RETURN CHANNEL
MAIN CHANNEL
Oct-85
Oct-88
Oct-89
Jan-90
Jul-91
1996, Pre-Flood
1996, Post-Flood
29
28
27
26
25
24
23
22
21
-40
-20
0
20
40


EMINENCE BREAK REATTACHMENT BAR, CROSS-SECTION 2
7b.
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BASELINE, IN METERS
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
RIVER LEFT BANK
RETURN CHANNEL
MAIN CHANNEL
Oct-88
Oct-89
Jul-91
1996, Pre-Flood
1996, Post-Flood
29
28
27
26
25
24
23
22
-10
0
10
20
30
40

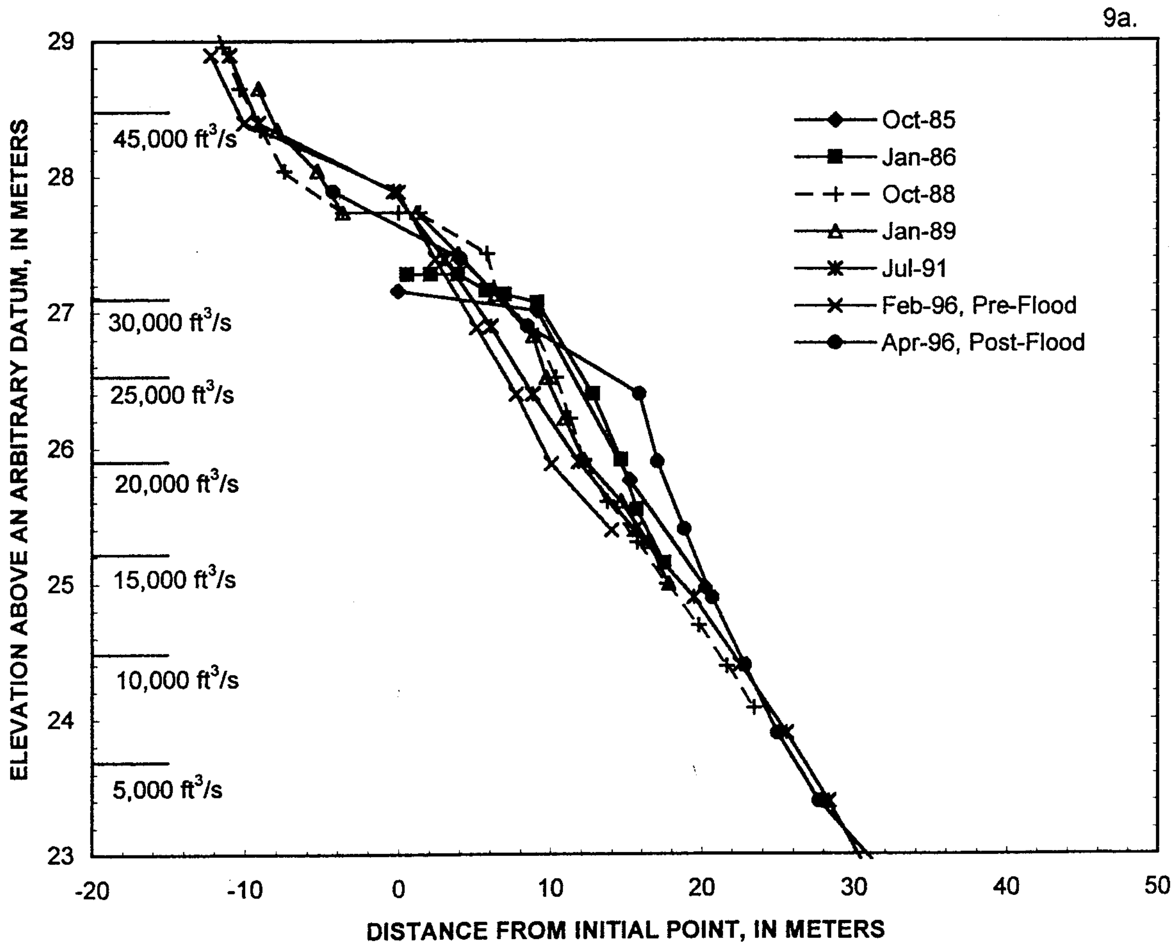


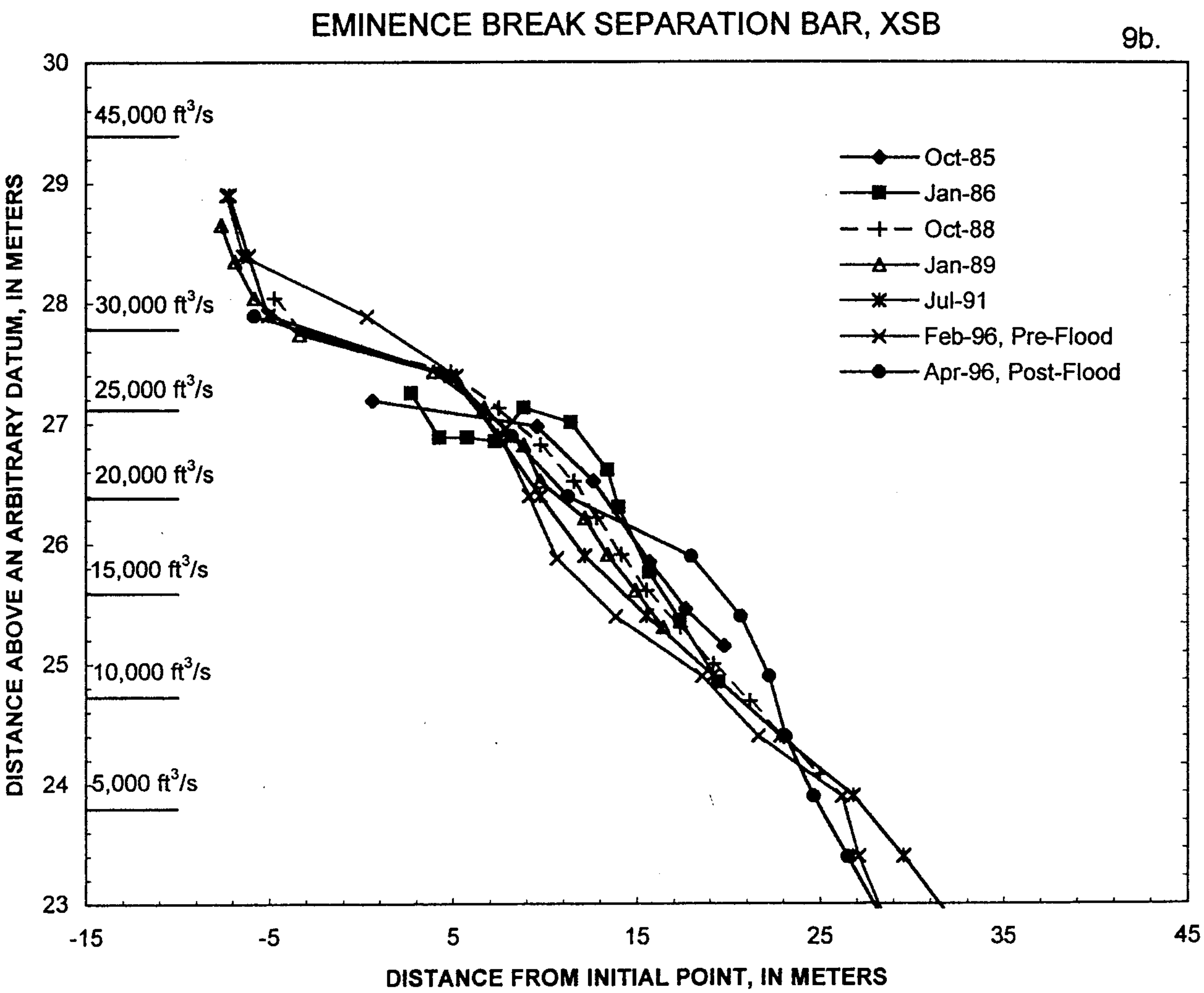
EMINENCE BREAK REATTACHMENT BAR, CROSS-SECTION 3
7c.
left bank
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
0.65 m fill
1.95 m fill
1.00 m fill
0.75 m fill
0.30 m scour
0.20 m fill
eddy center
Oct-85
Oct-88
Oct-89
Jan-90
Jul-91
1996, Pre-Flood
1996, Post-Flood
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BENCHMARK EB4, IN METERS

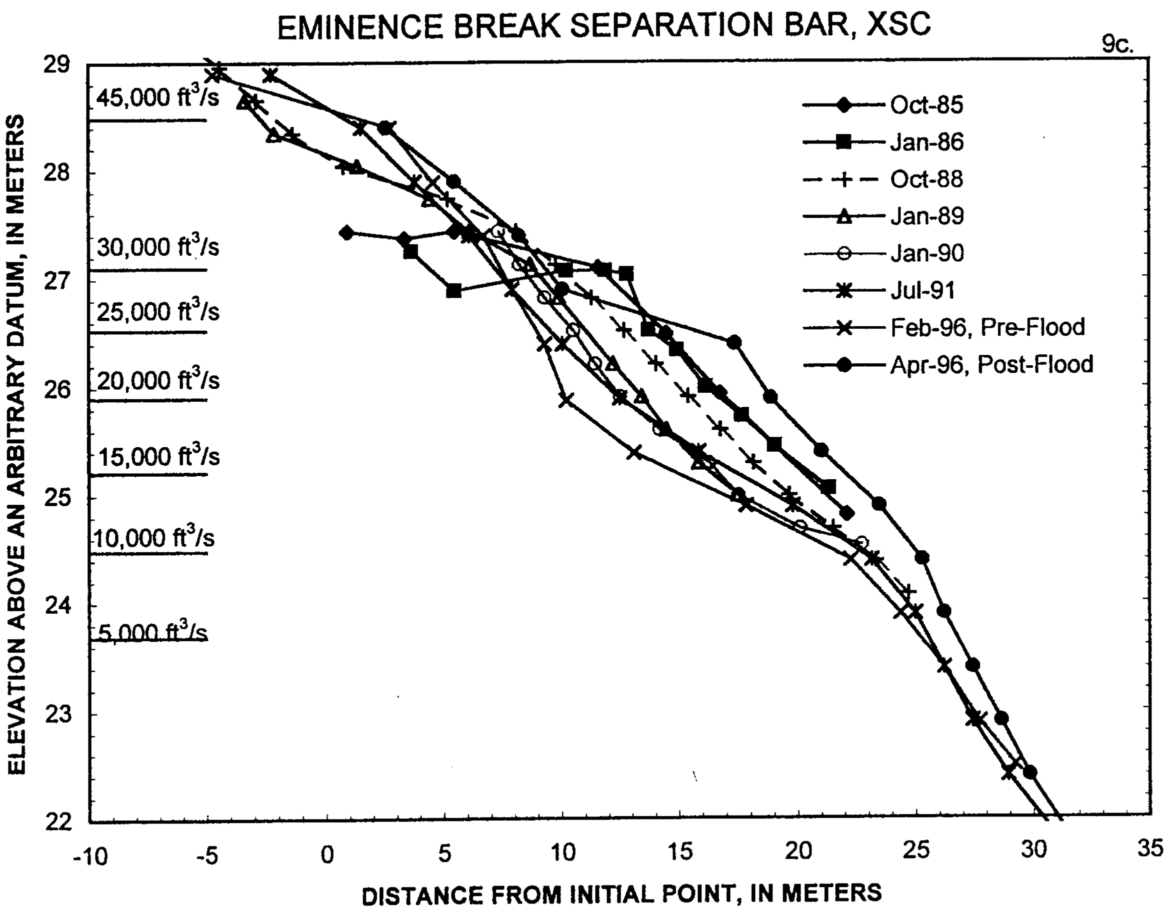
8.



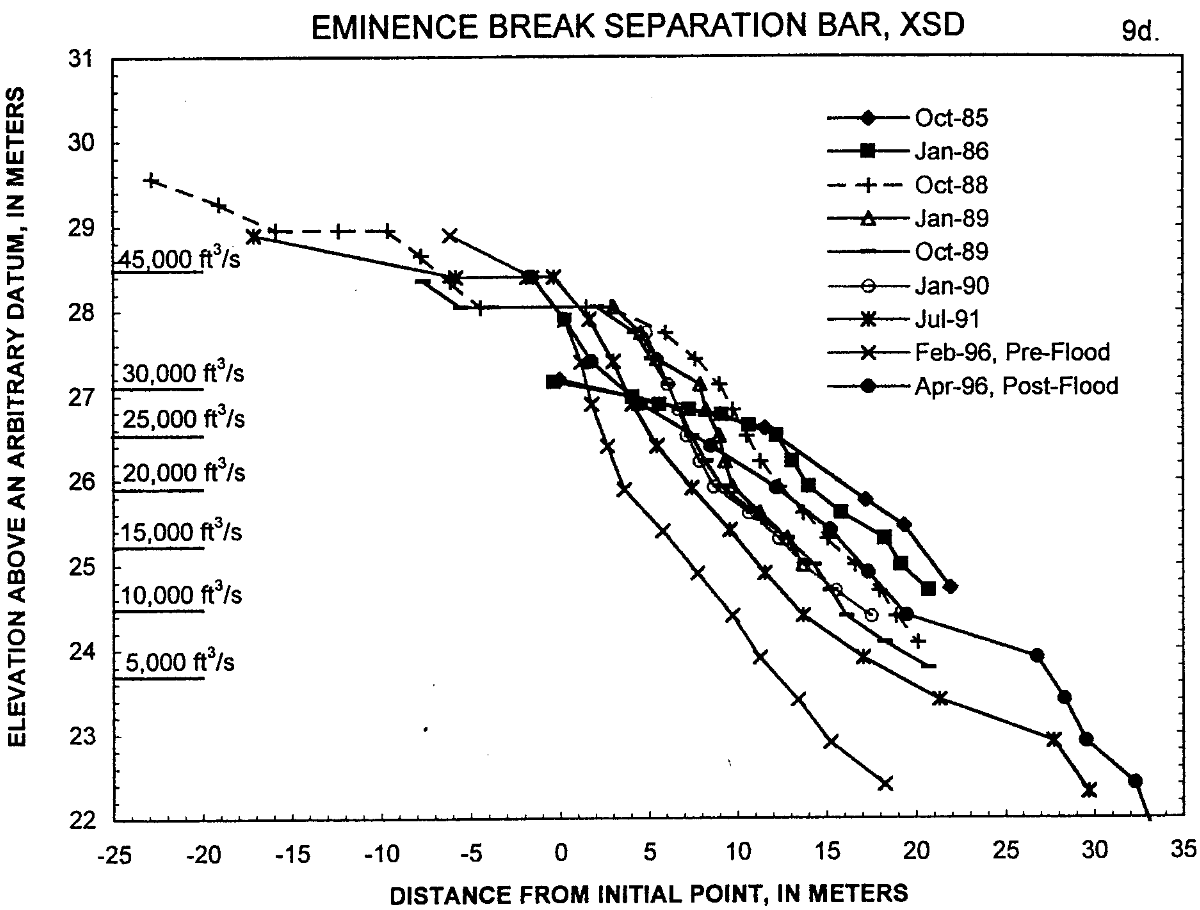
EMINENCE BREAK SEPARATION BAR, XSA

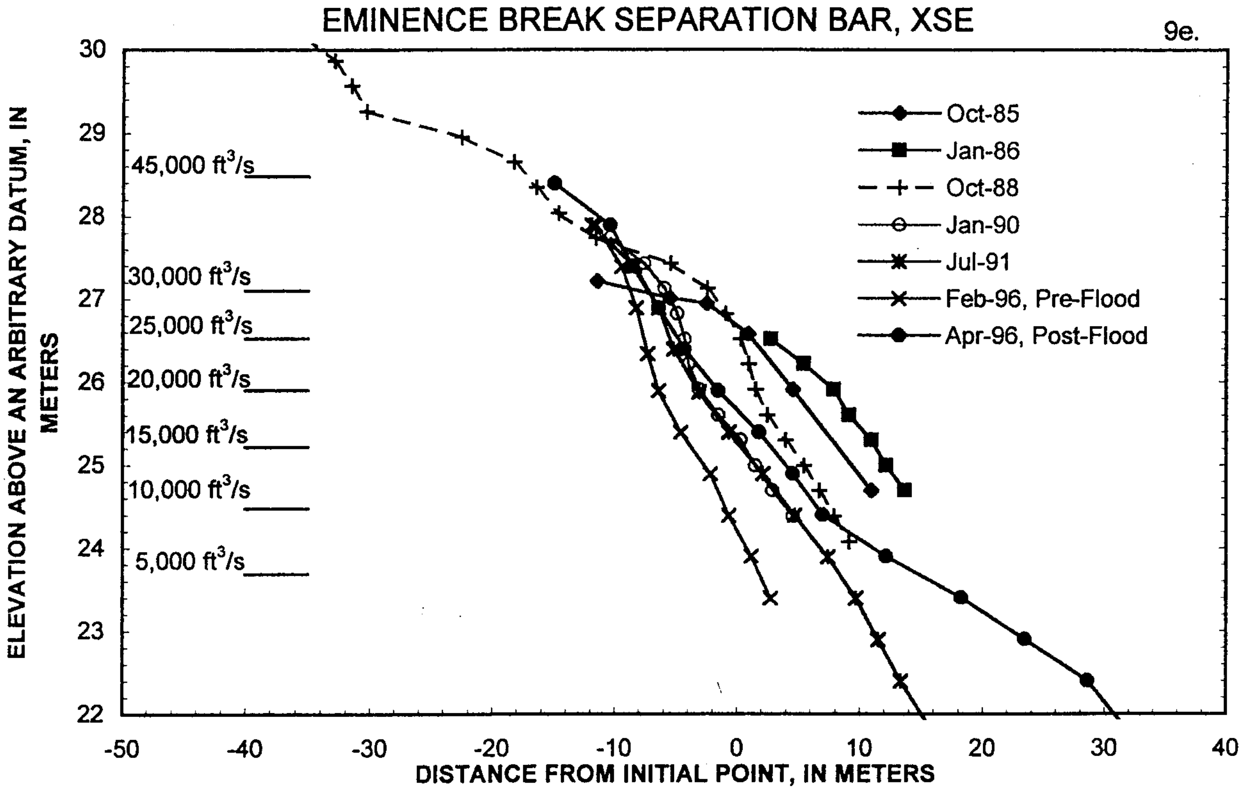


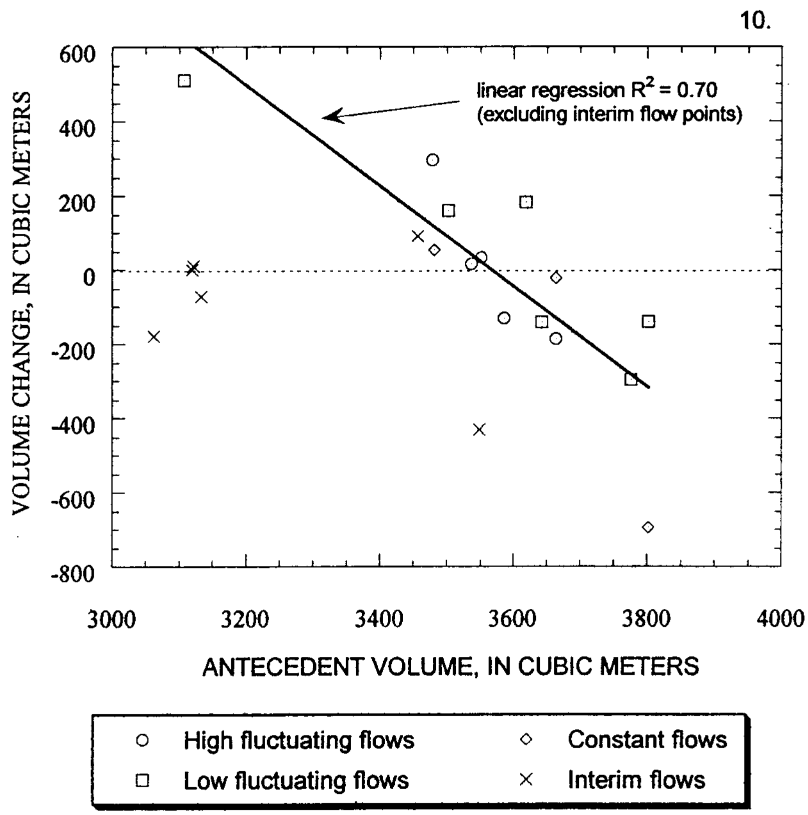

EMINENCE BREAK SEPARATION BAR, XSB
9b.
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
Oct-85
Jan-86
Oct-88
Jan-89
Jul-91
Feb-96, Pre-Flood
Apr-96, Post-Flood
DISTANCE ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM INITIAL POINT, IN METERS
30
29
28
27
26
25
24
23
-15
-5
5
15
25
35
45

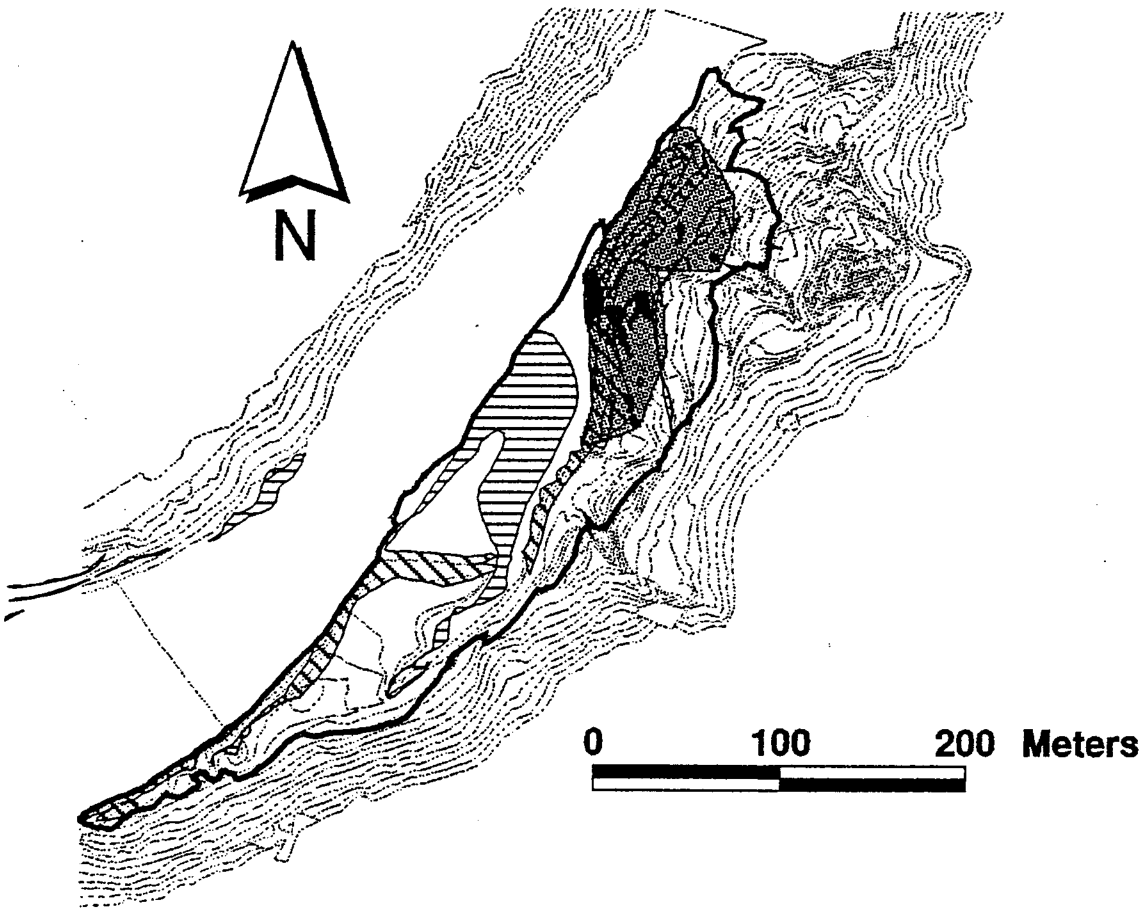


EMINENCE BREAK SEPARATION BAR, XSC
9c.
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
Oct-85
Jan-86
Oct-88
Jan-89
Jan-90
Jul-91
Feb-96, Pre-Flood
Apr-96, Post-Flood
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM INITIAL POINT, IN METERS
29
28
27
26
25
24
23
22
-10
-5
0
5
10
15
20
25
30
35

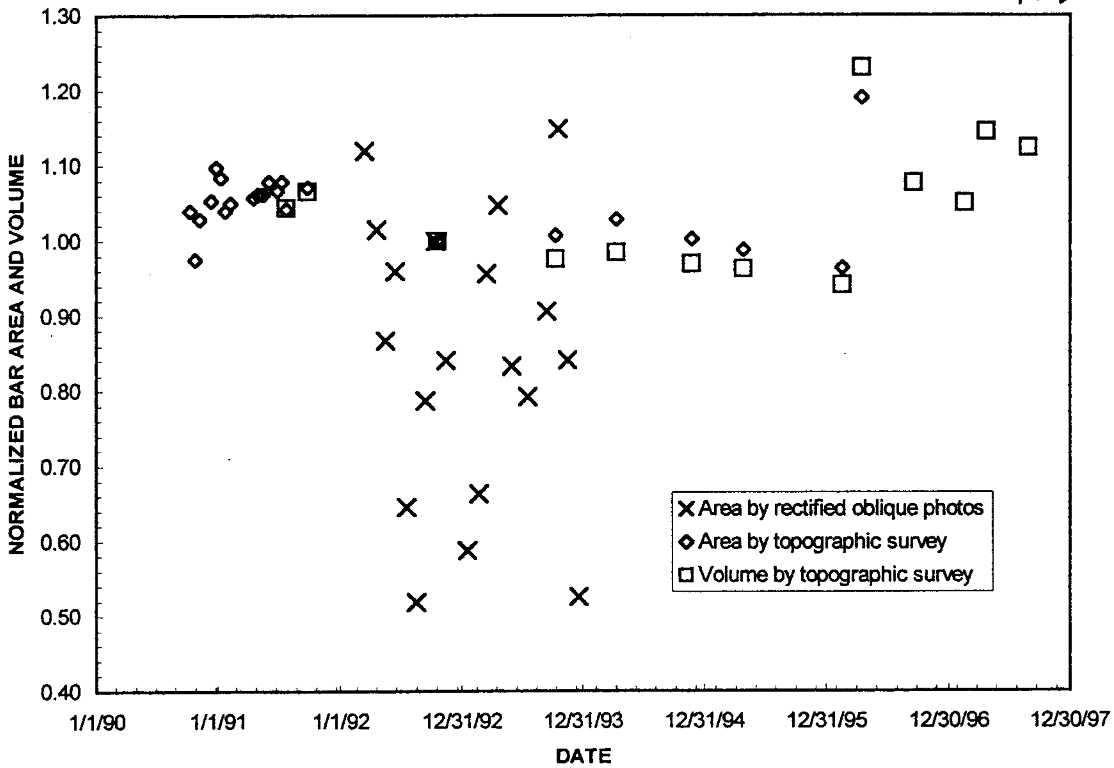

EMINENCE BREAK SEPARATION BAR, XSD
9d.
Oct-85
Jan-86
Oct-88
Jan-89
Oct-89
Jan-90
Jul-91
Feb-96, Pre-Flood
Apr-96, Post-Flood
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM INITIAL POINT, IN METERS
31
30
29
28
27
26
25
24
23
22
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35


EMINENCE BREAK SEPARATION BAR, XSE
9e.
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM INITIAL POINT, IN METERS
45,000 ft³/s
30,000 ft³/s
25,000 ft³/s
20,000 ft³/s
15,000 ft³/s
10,000 ft³/s
5,000 ft³/s
Oct-85
Jan-86
Oct-88
Jan-90
Jul-91
Feb-96, Pre-Flood
Apr-96, Post-Flood
30
29
28
27
26
25
24
23
22
-50
-40
-30
-20
-10
0
10
20
30
40


10.
linear regression R2 = 0.70
(excluding interim flow points)
VOLUME CHANGE, IN CUBIC METERS
600
400
200
0
-200
-400
-600
-800
3000
3200
3400
3600
3800
4000
ANTECEDENT VOLUME, IN CUBIC METERS
High fluctuating flows
Constant flows
Low fluctuating flows
Interim flows

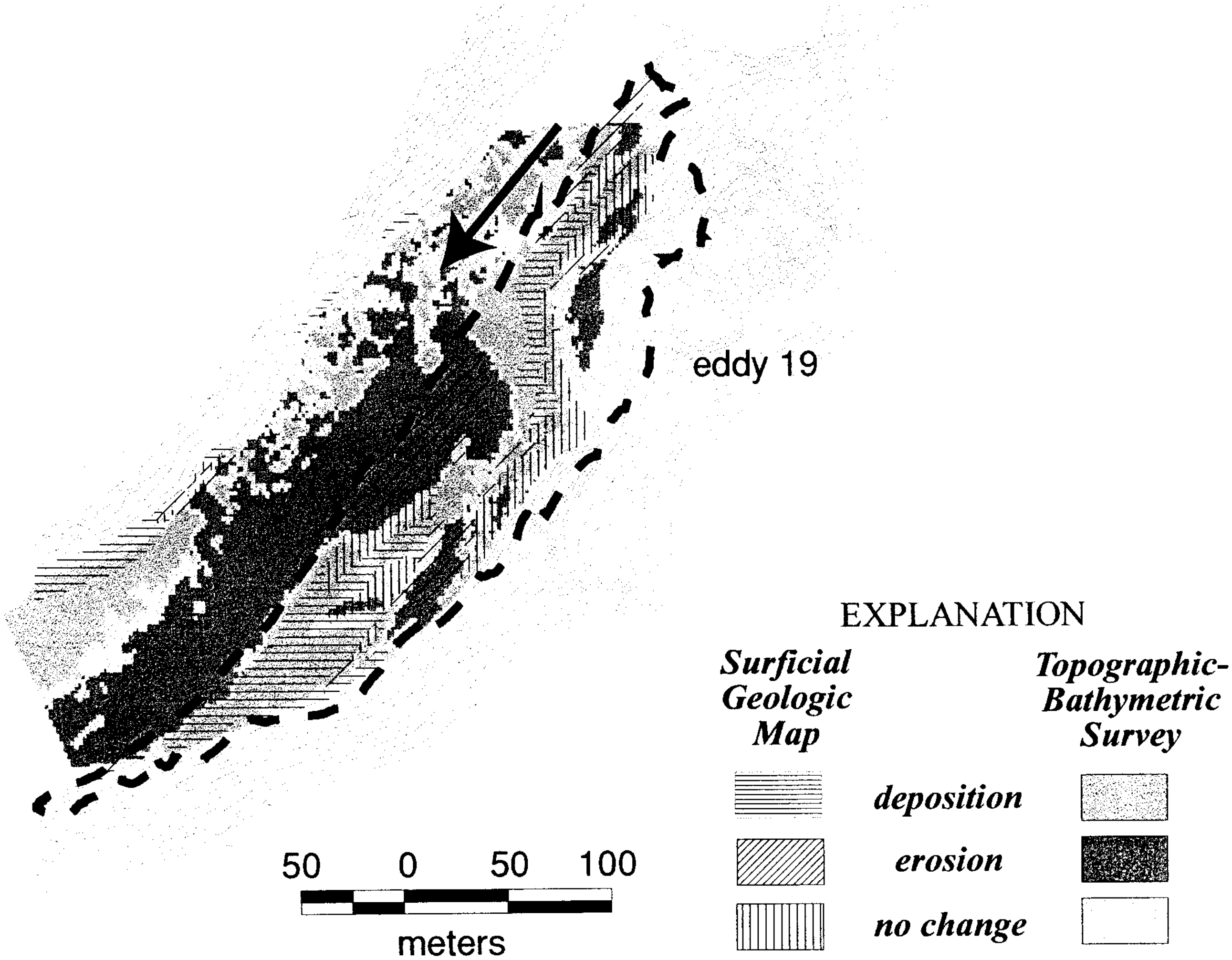

N
0
100
200 Meters

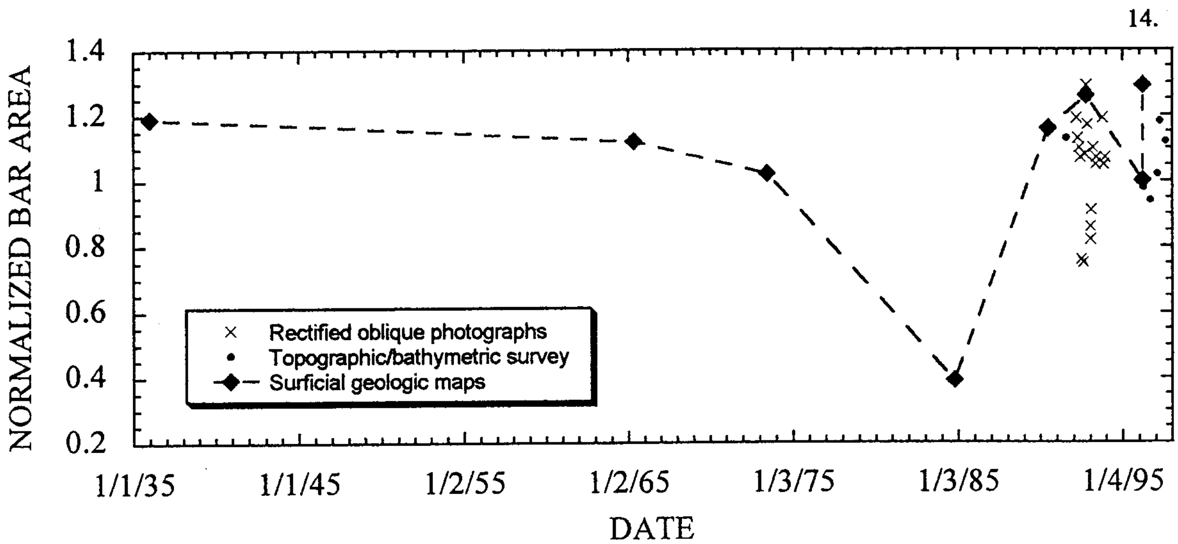
12.



NORMALIZED BAR AREA AND VOLUME
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
1/1/90
1/1/91
1/1/92
12/31/92
12/31/93
12/31/94
12/31/95
12/30/96
12/30/97
DATE
Area by rectified oblique photos
Area by topographic survey
Volume by topographic survey

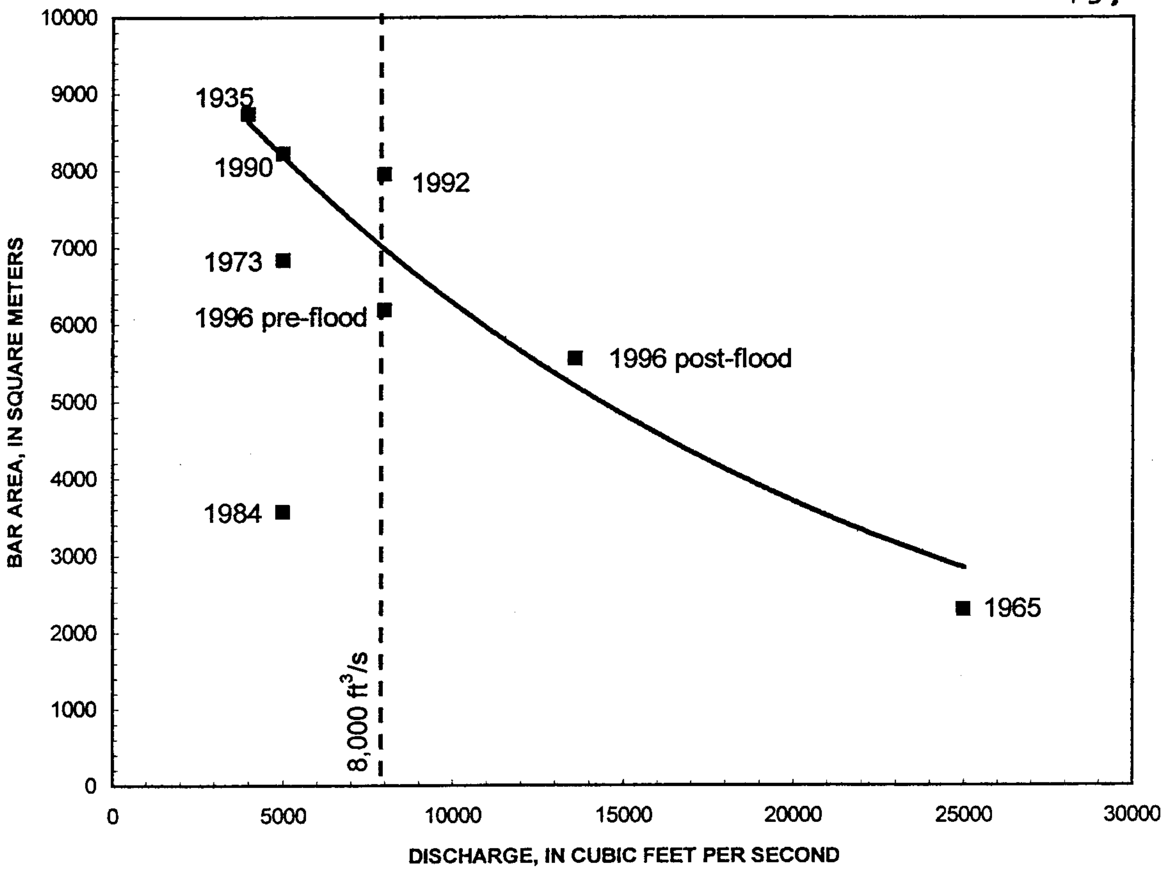
13.


eddy 19
EXPLANATION
Surficial Geologic Map
Topographic-Bathymetric Survey
deposition
erosion
no change
50 0 50 100
meters



14.
1.4
1.2
1
0.8
0.6
0.4
0.2
NORMALIZED BAR AREA
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE
Rectified oblique photographs
Topographic/bathymetric survey
Surficial geologic maps

15.



10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
BAR AREA, IN SQUARE METERS
1935
1990
1992
1973
1996 pre-flood
1996 post-flood
1984
1965
8,000 ft3/s
0
5000
10000
15000
20000
25000
30000
DISCHARGE, IN CUBIC FEET PER SECOND

B. Saddle Detailed Site Report

ABSTRACT

An extensive set of topographic and bathymetric measurements of the size of the reattachment bar downstream from Saddle Canyon demonstrates that post-dam floods have caused large-scale deposition at this site. The extent of deposition is probably greatest in years when the bar is small prior to flooding. The 1996 controlled flood did not restore the bar to its size that existed in 1984 and 1985, nor what had existed in 1935. The controlled flood did cause large-scale deposition near the reattachment point. High rates of erosion occur at this site immediately following recession from high flows.

INTRODUCTION

Although there is great interest in the history and variability of sand storage in eddies, there are few sites where there are sufficient data to evaluate these changes over a long period of time. One place where there are abundant data is Saddle Canyon, located 47 river miles downstream from Lees Ferry. At least 55 individual measurements or aerial photographs of these sand bars were made between 1935 and present, although data are sparse before 1984 and are abundant after 1990. This report analyzes these data.

SITE DESCRIPTION

A very large persistent eddy occurs downstream from Saddle Canyon debris fan on river right (Figure 1). This eddy is the largest in the Point Hansbrough reach studied by Schmidt and Leschin (1995); this reach is named after the prominent bend in the river that occurs 3 mi upstream from Saddle Canyon. We believe that this eddy, whose area of maximum deposition is approximately 41,700 m^2, is one of the largest in all of Grand Canyon. The eddy is part of the Saddle Canyon fan-eddy complex, and the debris fan is the largest in the Point Hansbrough reach. A separation and a reattachment bar occur in this persistent eddy. Although the topography of the separation bar was first surveyed by Howard (1975), the reattachment bar has been the focus of most research and monitoring efforts since 1985. We focus on changes in the reattachment bar in this report, because changes in this bar reflect large-scale changes in eddy sand storage.

The constriction formed by the Saddle Canyon debris fan is among the narrowest in Grand Canyon, but a rapid does not occur in the constriction. The ratio of the channel width at the constriction to the upstream channel width is 0.36 at 5,000 ft^3/s, which is much less than the mean constriction ratio of 0.49 that Schmidt and Graf (1990) measured at large debris fans throughout Grand Canyon. This ratio increases to 0.54 at 40,000 ft^3/s (Schmidt and Graf, 1990). Deposition of the downstream end of the persistent eddy occurred here in 1983, suggesting that an eddy existed at discharges at least as high as 90,000 ft^3/s; Schmidt and Leschin (1995) showed that the Saddle Canyon fan was not overtopped by the 1983 peak discharge of about 90,000 ft^3/s.

Excavations of the reattachment bar in October 1990 demonstrated that bedform migration directions of the deposits that form this bar occurred in recirculating currents (Rubin and others, 1994). Rubin and others (1994) stratigraphically distinguished 3 depositional units believed to correspond with 1983, 1984-86, and post-1986 depositional events. The 1983 deposit consisted of a coarsening-upward sequence with on-shore migrating climbing ripples of moderately-sorted fine sand (D_{50} = 0.19 mm) at the base, overlain by off-shore migrating well-sorted fine and medium sand (D_{50} = 0.23 to 0.28 mm). Pre-dam deposits, sampled by Schmidt and Graf (1990) are much finer and consisted of moderately to well-sorted, fine to very-fine sand (D_{50} = 0.074 to 0.13 mm).

AVAILABLE MONITORING DATA

The size and condition of the sand bars downstream from Saddle Canyon prior to 1985 can only be interpreted from historical aerial and oblique photographs. The quality of the aerial photographs and the discharge at which they were taken varies considerably. Leschin and Schmidt (1995; 1996) used these photographs and more recent photographs to map surficial geology of the Point Hansbrough reach. We measured the area of exposed sand in each year in which maps were made. The measured values depend on the discharge at the time of the photos and the actual bar size (Table 1).

Inventories of Grand Canyon campsites were conducted in 1973, 1983, 1991, 1994, and in 1996 before, after, and 6 months after the controlled flood. These inventories include a semi-quantitative evaluation of campsite size, based on estimated campsite capacity and, in some cases, include measurements of the total campable area. The separation bar was recorded as a large camp in each of those years, and no change in campable area occurred due to the controlled flood. The reattachment bar was first included in the campsite inventory in 1983, although air photos show that a large bar occurred here prior to this time.

The separation bar at Saddle Canyon has been an established campsite since at least the early 1970's. A single profile extending along the downstream slope of the fan through the campsite was surveyed in 1980 and 1985 by the US Bureau of Reclamation (Ferrari, 1985). Formal monitoring of the reattachment bar began with the establishment of a series of 6 topographic profiles in 1985 by Ferrari (1985). Between 1985 and 1990, various parties made either repeat surveys of the profiles or topographic maps of the bar; we reconstructed profiles from these maps (Table 1). Reattachment bar sedimentology was examined in trenches excavated in October 1990 and June 1996. Total sand volume of the reattachment bar was estimated by probing the bar to determine sand thickness in October 1990 (Rubin and others, 1990).

Throughout most of 1990 and 1991, combined topographic and bathymetric data were collected at twice monthly intervals to evaluate the effects of a series of "test flows" on sand bar dynamics (Beus and others, 1992). During this period, low-altitude aerial photographs were used to measure the area of exposed sand at 5,000 ft^3/s after each test flow, herein referred to as the "test-flow air photo study" (Table 1). Biannual topographic/bathymetric surveys are the only regular monitoring data collected since 1991 (Kaplinski and others, 1995; Hazel and others, 1999). However, during the 1996 controlled flood, these data were supplemented with daily bathymetric surveys (Andrews and others, unpubl. manuscript), pre- and post-flood surficial geologic maps (Leschin and Schmidt, 1996), and scour chains (Schmidt and others, 1996). Daily oblique photographs of the reattachment bar have been taken for several years (J.E. Hazel, personal communication) but were not available for our analysis.

HISTORY OF BAR CHANGE DETERMINED FROM AERIAL PHOTOGRAPHY: 1935 TO 1984

The earliest available aerial photographs, taken in 1935 while the river was flowing at 4,000 ft^3/s, show a large reattachment bar that nearly fills the eddy. The reattachment bar is slightly smaller in 1935 than the bar that was photographed in 1984 but the 1935 bar extends farther into the main channel (Figure 2). The separation bar is obscured by a dark shadow in the 1935 photographs. The May 14, 1965, aerial photographs, taken at 25,000 ft^3/s, show newly-deposited sand on the reattachment bar. This deposition must have occurred during the 45,000 ft^3/s bypass-tube test release of May 8, 1965. In both the 1935 and 1965 photographs, vegetation occurs only along a narrow margin of the sand bar near the base of the talus slope. By June 1973, vegetation had expanded towards the river at the downstream end of the reattachment bar and over most of the separation bar (Figure 3). Most of the reattachment bar platform in 1973 was bare sand, indicating that this surface was regularly inundated and reworked.

An oblique photograph taken in May 1984 (Figure 4) shows that a small area of the reattachment bar was emergent at about 45,000 ft^3/s, and we believe that this emergent sand had been deposited in 1983. Areas of sand higher than 45,000 ft^3/s were mapped as "flood sands of 1983 (fs deposits)" by Leschin and Schmidt (1995), and lower elevation areas were mapped as "high flow sands of 1984-86 (hf deposits)" (Figure 1). Aerial photographs were taken in October 1984 during a steady discharge of 5000 ft^3/s. The area of exposed sand at this time was greater than in any other year for which data are available at a similar discharge (Figure 2). The reattachment bar platform in 1984 was divided into an upper and a lower topographic surface by a prominent cutbank that likely formed during 45 days of steady 26,000 ft^3/s flows that preceded the 1984 photographs. The upper surface of this bar was very similar in area and shape to the bar surface exposed in the 1965 photographs (Figure 3). The lower surface had bedforms distinctive of deposition by recirculating flow. The upper topographic surface shows some eolian reworking of the 1983 and 1984 deposits. Vegetation on the hf and fs levels at the downstream end of the reattachment bar was as extensive in 1984 as in 1973, but was denser (Figure 3).

TOPOGRAPHIC SURVEYS 1985 – 1990

Topography of the reattachment bar was first surveyed in September 1985. The bar consisted of a main bar platform about 4 to 5 ft above the 22,000 ft^3/s stage. This topography had probably been sculpted by steady high flows of about 50,000 ft^3/s that occurred in May and June 1985. This high-elevation sand had probably been emplaced in 1983. The bar was next surveyed in January 1986. Between these surveys, a fluctuating-flow test occurred, during which maximum flows did not exceed 22,000 ft^3/s. Topographic profiles of the bar, constructed from the topographic maps, show that erosion occurred along the steep bar face downstream from the reattachment point (Figure 5a) but that the main bar platform did not change significantly between these surveys (Figure 5b). A small amount of deposition occurred on the most downstream end of the bar.

A detailed topographic map of the reattachment bar was next surveyed in January 1988. Between this date and the prior survey, there was a sustained release at 45,000 ft^3/s in May and June 1986 that peaked at 53,200 ft^3/s. High-volume fluctuating flows with daily maximums between 22,000 and 30,000 ft^3/s and minimums between 3,000 and 8,000 ft^3/s occurred after the 1986 high flows. Comparison of profiles constructed from the 1986 and 1988 topographic maps shows that erosion occurred over most of the reattachment bar platform (Figure 5b) and along the bar face on the downstream portion of the bar (Figure 5a). The large-scale erosion of the bar platform could have occurred during the 1986 high releases or by cutbank retreat during the high fluctuating flows of 1987. This uncertainty can only be evaluated if photographs taken between June 1986 and January 1988 are acquired. A small area of deposition, near profile CS-4 (Figure 5a), occurred near the reattachment point at an elevation that was inundated by the high 1986 flows.

Relatively little topographic change occurred during high fluctuating flows that occurred between January 1988 and October 1989. These surveys indicate some bank retreat and deposition at elevations below the 22,000 ft^3/s stage. A sparse array of survey points preclude detailed analyses of the 1989 topographic data. Profiles constructed from the October 1990 surveys show that a 1-m high eolian dune developed on the hf level between profiles CS-2 and CS-5 (Figure 5). Bank retreat occurred at elevations above about the 22,000 ft^3/s stage near the reattachment point (CS-3 and CS-4), and deposition occurred in this region at lower elevation between the 8,000 and 22,000 ft^3/s stage elevations.

BAR TOPOGRAPHY 1990 AND 1991: THE TEST FLOWS

Between June 1990 and August 1991, topographic and photographic data were collected with much greater frequency in order to evaluate the effects of a series of "test flows" on sand bar area and volume. The test flows included high-volume fluctuating flows (large daily range), low-volume fluctuating flows (low daily range), and steady flows (Beus and Avery, 1992). The "test-flow air photo" study (Cluer, 1992) compared the areas of sand bars digitized from low-altitude aerial photographs. Comparisons of sand bar area can only be made at comparable stages. This study determined that several short-term fluctuations in bar area at Saddle Canyon occurred, and that there was a net decrease in area during the 1-yr study period (Table 1) (Cluer, 1992).

Although sand bar surveys during these test flows did not establish a positive link between discharge regime and bar response, these data did demonstrate the importance of antecedent conditions in affecting bar response. These surveys also demonstrated that both high- and low-volume fluctuating flows can cause erosion and deposition. These surveys occurred twice-monthly and involved topographic and bathymetric surveys of 29 sand bars, including Saddle Canyon (Beus and others, 1992). Analysis of these results demonstrated that, on average for all 29 sites, sand bar volume change following any given test-flow regime was best correlated with antecedent conditions and total volume of sediment transported by each test flow (Beus and others, 1992). Bars typically eroded if they were large prior to the start of a test flow; these bars had deposition if they were small at the start of a test. The reattachment bar downstream from Saddle Canyon responded in a style consistent with this overall trend, but the change in volume of the Saddle Canyon reattachment bar was weakly negatively correlated ($R^2 = 0.32$) with the antecedent bar volume (Figure 6).

TOPOGRAPHIC SURVEYS AND SURFICIAL GEOLOGIC MAPS 1991 – 1996: THE INTERIM FLOWS

Sand bar change between 1991 and 1996 was monitored by twice-yearly topographic surveys and surficial geologic maps made from aerial photographs taken in 1991, 1992, and March 1996. The releases from Glen Canyon Dam during this time were limited to low-volume fluctuating flows with daily minimums averaging about 6,000 ft^3/s and daily maximums between 16,000 and 18,000 ft^3/s. Sustained high releases of about 18,000 ft^3/s occurred between June and October 1995. Normalized to the bar volume above the 5,000 ft^3/s stage measured in July 1991, the topographic data show a progressive decrease between 1991 and February 1996 (Figure 7). The rate of erosion was similar at high elevations above the 20,000 ft^3/s stage and for entire bar volume that is emergent at 5,000 ft^3/s. Measurements based on surficial geologic maps of the bar developed from aerial photographs showed a similar decrease in area of exposed sand, and the areas of erosion are consistent between the 2 methods (Figure 8). Erosion was concentrated in two areas: (1) on the hf and ff levels near the reattachment point, and (2) near the upstream end of the eddy (Figure 8). These results indicate that even with the magnitude of fluctuating flow reduced, bar erosion occurred and was progressive at Saddle Canyon.

1996 CONTROLLED FLOOD

The Saddle Canyon reattachment bar was as small as had ever been measured prior to the 1996 controlled flood, and it had only been that small in 1973. Bar volume was the lowest measured between 1991 and March 1996 (Figure 7). These antecedent conditions should have encouraged deposition at this site during the 1996 controlled flood. Topographic surveys conducted in February and April 1996 demonstrated that deposition occurred at the reattachment bar and that the volume of the bar increased at both low and high elevations (Figure 7). The surficial geologic maps made from aerial photographs taken immediately preceding and following the controlled flood also measured a large area of deposition that was consistent with the area of deposition measured by the topographic surveys (Figure 9). Near the reattachment point, the deposition restored the bar topography to a condition similar to that surveyed in 1985 (Figure 5a). The area of new deposition extended downstream approximately the length of the entire high-discharge recirculation zone (Figure 10). Upstream near the center of the eddy, however, the bar was much smaller following the controlled flood than in 1985 (Figure 5b). Net erosion occurred over most of the upstream portion of the eddy during the controlled flood (Figure 9). In fact, the elevation of the bar platform in this area was lower than at any other time since July 1991 (Figure 11).

Scour chains placed in the bar are consistent with the measurements made by topographic surveys and reveal the actual depths of scour and fill that resulted in the measured net change. All 4 of the chains that were inundated by the flood were located in areas where net erosion occurred, and 3 of these chains were located on or near profile CS-2 (Figure 5b). At 2 of these locations, the net scour included 9 cm of fill and at 1 location no fill occurred (Figure 5b). The erosion that occurred during the controlled flood was greater than the amount of erosion that occurred between 1990 and February 1996.

Daily bathymetric surveys also measured erosion and deposition during the controlled flood (Andrews and others, unpubl. manuscript). These data indicate that scour on the first day of the flood was 2.7 times greater than the net change for the event (Table 2). The volumes listed in Table 2 illustrate that the magnitude of scour and fill were not consistent from day to day, nor were they progressive, during the flood. These data cannot be accurately compared with other historical data, however, because the area surveyed by Andrews and others (unpubl. manuscript) differed from day to day. Despite these large changes in eddy volume on a daily time scale, the net scour for the pre- to post-flood period (Table 2) is consistent with the results of Hazel and others (1999) based on their February and April pre- and post-flood surveys.

COMPARISON

The surficial geologic map measurements of areas of erosion and deposition agree well with the topographic data where measurements overlap. Where both data sets are geo-referenced, measurement pairs can be compared spatially (Figure 8 and Figure 9), and there is good agreement. Thus, recent topographic measurements can be compared with measurements made from aerial photographs that depict pre-dam conditions (Fig 12) and from aerial photographs analyzed by Cluer (1992). Because of differences in measurement methods, actual areal measurements cannot be compared directly, however, but relative changes can be compared if each data set is normalized to a common date (Table 1).

The time series shown in Figure 12 was constructed by normalizing the 3 data sets -- topographic surveys, surficial geologic maps, and test-flow aerial photographs. The test-flow air photo data were normalized under the assumption that the area measured by that method on September 30, 1990, characterized the same bar that was topographically surveyed on September 29, 1990. These days were then used as the baseline for the normalization of those data (Table 1). The closest overlap between the surficial geologic maps and the topographic data occurred for the measurements of June 30 and July 14, 1990 (Table 1). The surficial geologic map data were then normalized to force the June 30 measurement to equal the normalized area determined by topographic survey on July 14. The final underlying assumption in this normalization is that each method adequately characterizes bar area independently, even though measurement areas are not equivalent.

The range between the maximum and minimum bar areas measured between 1990 and present is very similar to the range of extremes that occurs in the historical record (Figure 12). However, the time series also illustrates that the magnitude of erosion and deposition measured at twice-monthly intervals during the test-flow period is small relative to long-term trends in bar area and volume. These short-term fluctuations cause bar area to vary by about 26% of the average bar area, while the long-term range between maximum and minimum area is about 80% of the average area.

The values for bar area determined by surficial geologic map in Figure 12 exclude the 1965 data because of the large difference in discharge between this and other years. The years that are plotted include maps made from photographs taken at discharges of 4000, 5000, 8000, and 13,600 ft^3/s (Table 1). These data, therefore, are biased to show that bar area is smaller in years of higher discharge. This bias can be accounted for by plotting the exposed bar area against the discharge and comparing these to the area-discharge relationship for the bar determined from topographic survey data collected in

April 1996 (Figure 13). The difference between the bar area measured from photographs and the area-discharge relation is an estimate of the bar area in those years relative to the area following the controlled flood. This approach presents the most accurate possible portrayal of bar size from the older photographs and is the only means of interpreting the 1965 photographs. This shows that the area of sand exposed in the 1935, 1965, 1984, and 1990 was greater than the area of sand following the 1996 flood, and that only in the 1973 and the 1996 pre-flood photographs was the bar smaller (Figure 14).

CONCLUSIONS

The reattachment bar at Saddle Canyon is a persistent site of deposition by post-dam floods. The 1965 spillway test, the 1983 spillway flood, the 1984-86 bypass floods, and the 1996 controlled flood all resulted in deposition over at least parts of the reattachment bar. By far, the most deposition was measured following the 1983 and 1984 events, which included the largest post-dam flood and a sustained period of bypass releases. This deposition occurred at a time when the antecedent condition of the bar was degraded, based on the 1973 surficial geologic maps (Figure 14), and sediment storage in the channel was likely high after 18 yrs without flows greater than powerplant capacity. The 1996 controlled flood also caused substantial aggradation on the reattachment bar, but most deposition was localized to the vicinity of the reattachment point and the upstream portion of the eddy experienced erosion.

Thus, flooding in the post-dam era has restored the area of this bar emergent at low discharges to pre-dam sizes. There is insufficient data available with which to analyze the volume of the bar prior to completion of Glen Canyon Dam. Based on twice-monthly measurements made in 1990-91, there is a weak relationship between antecedent conditions and the amount of bar deposition wherein the magnitude of deposition is greater if the bar is initially small.

The volume of deposition near the reattachment point during the 1996 controlled flood restored this part of the bar to the volume that had existed there in fall of 1984 or fall of 1985 (Figure 5a). However, the controlled flood caused erosion in the center of the eddy; in contrast, the reattachment bar had been of high elevation in the center of the eddy in 1984. The topography of the center of the eddy during the pre-dam era, reflected by the 1935 air photos, also was high (Figure 5b). Thus, the controlled flood did not restore the reattachment bar to the size it had been in some earlier periods.

Erosion of high elevation sand has occurred at Saddle Canyon during periods that lack floods. Periods of erosion occurred between 1986 and 1988 and between 1990 and 1996. Erosion did not cease after interim operating rules were established after 1991. Erosion rates are probably highest immediately after recession from high flows, such as occurred during the high-volume fluctuating flows that occurred in fall and early winter of 1985-86 and after recession from high flows in 1986.

High discharge deposits formed by high flows in 1983 and 1996 coarsen upward consistent with observations made elsewhere in Grand Canyon by Rubin and others (1998).

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LIST OF FIGURES

Figure 9. Map showing areas of significant aggradation and degradation measured by topographic/bathymetric survey (between February 18 and April 19, 1996) and surficial geologic mapping (between March 24 and April 4, 1996) downstream from Saddle Canyon. Areas of erosion, deposition, and less than 0.3 m of change are shown by red, green, and blue, respectively. Areas shaded by diagonal lines are erosion measured by surficial geologic maps. The thick line shows the area of the persistent eddy. The location of the topographic profile shown in Figure 11 is indicated.

Figure 10. Map showing eddy current recirculation patterns at 45,000 ft^3/s and locations of the separation and reattachment points at 8,000 and 45,000 ft^3/s. The shaded area is the area over which deposition occurred during the 1996 controlled flood. This area of deposition is smaller than the area of significant aggradation (Figure 9) because areas of flood reworking and deposition did not necessarily vertically aggrade.

Figure 11. Cross section of upstream portion of eddy and main channel (Figure 9). Showing scour in the eddy to lowest elevation measured.

Figure 12. Time-series plot of normalized sand bar area from 1935 to present. See text for description of normalization procedure. Note shift in horizontal scale at 1990.

Figure 13. Plot showing the relationship between measured sand bar area and discharge. The diamonds are the bar area above the indicated discharge calculated from the post-1996 flood topographic data (Hazel and others, 1999). The line is a logarithmic best fit (R^2= 0.98). The squares show area of exposed sand above the indicated discharge measured from surficial geologic maps (Schmidt and Leschin, 1995).

Figure 14. Time-series plot of residuals of Figure 13. Positive residuals are years in which the bar area measured from surficial geologic maps was greater that the post-1996 flood bar area above the same discharge. Negative residuals are years in which the bar area was less than the post-1996 flood bar area.

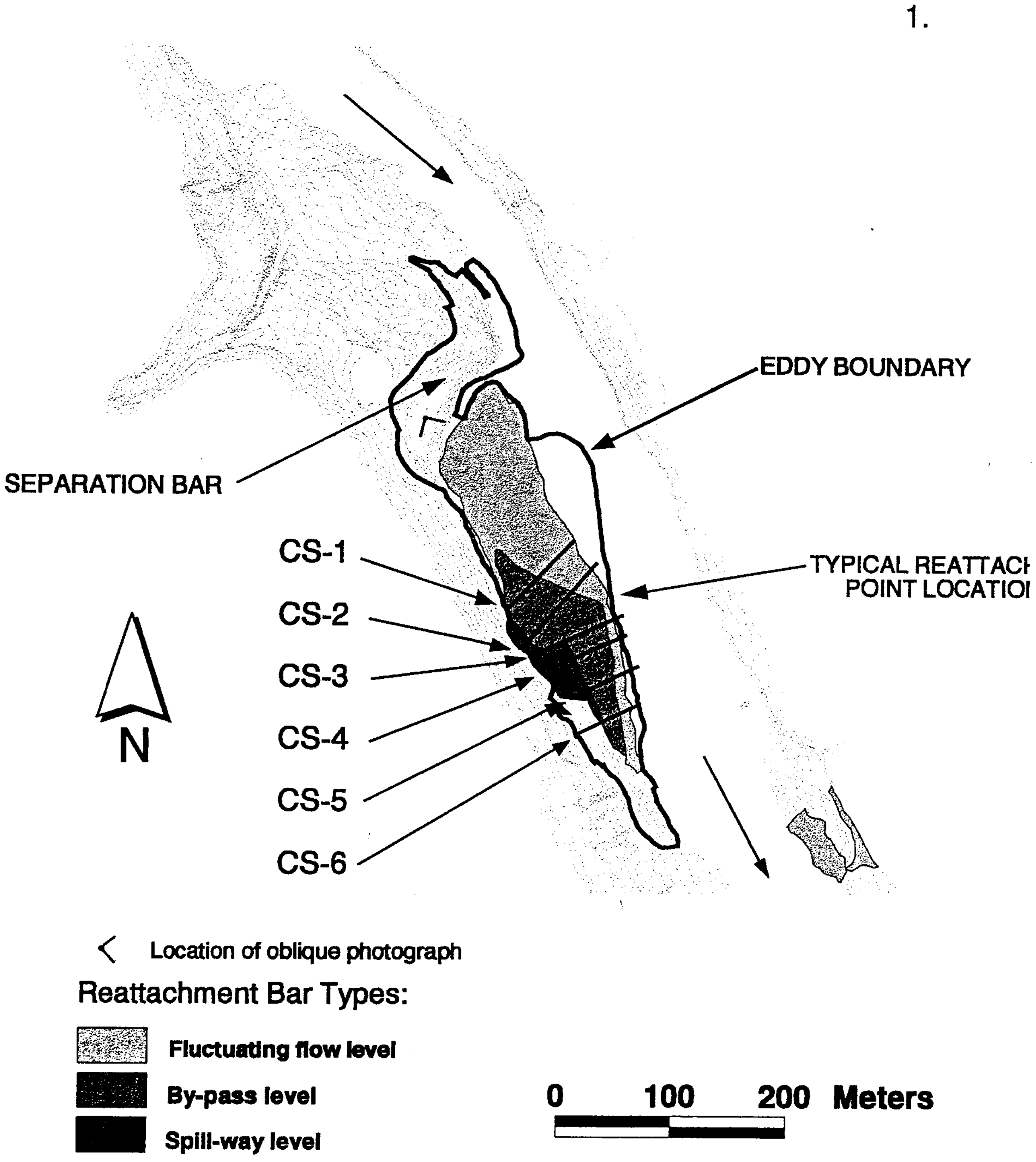
Table 1. Sand bar monitoring data available for Saddle Canyon (RM 47R).

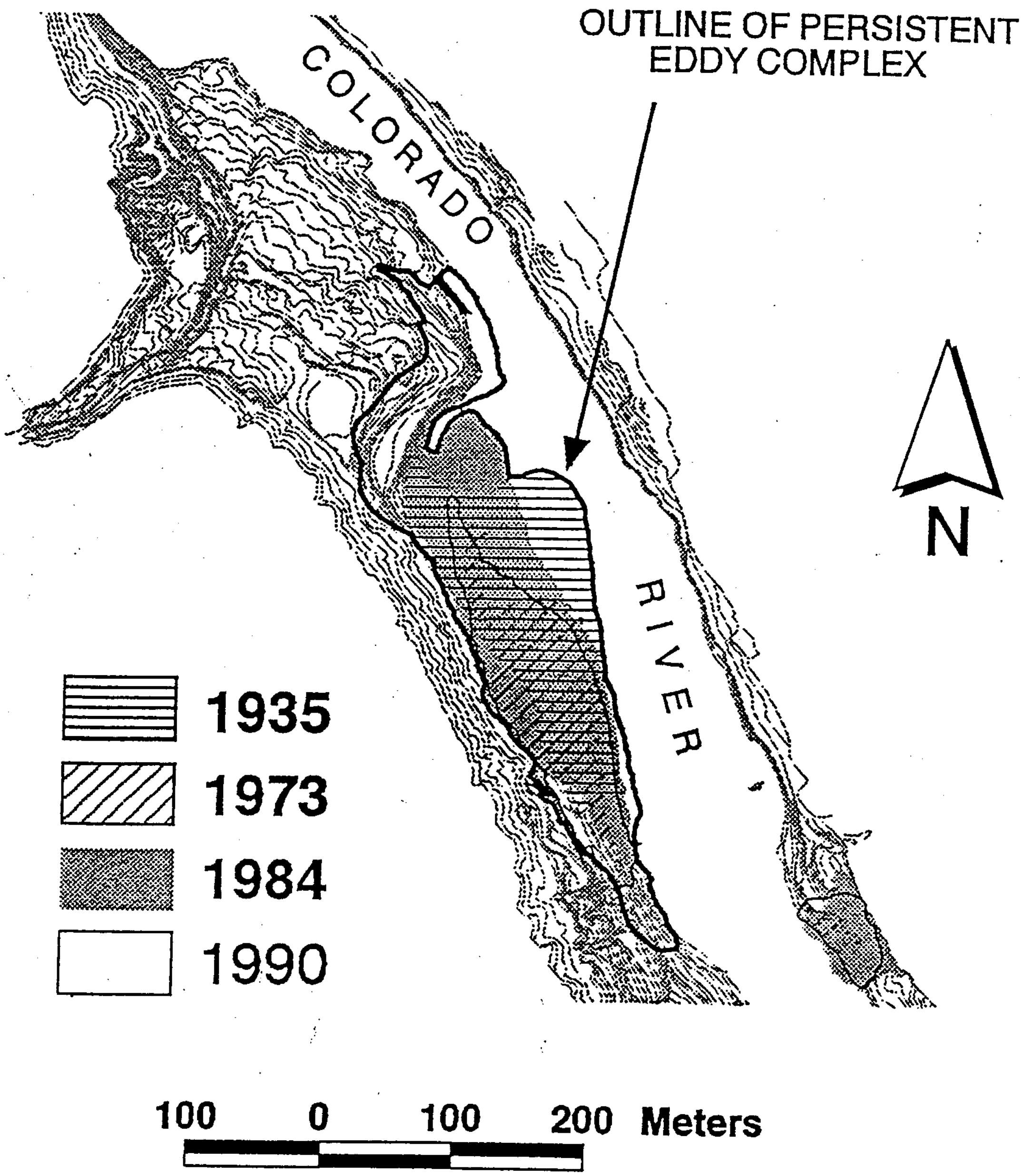
Date	Method	Reference	Area*, in m^2	Normalized area#	Discharge**, in ft^3/s
12/31/35	surficial geologic map	Leschin and Schmidt (1995)	20250	1.12	4000
05/14/65	surficial geologic map	Leschin and Schmidt (1995)	na	na	25000
06/16/73	surficial geologic map	Leschin and Schmidt (1995)	10750	0.59	5000
10/21/84	surficial geologic map	Leschin and Schmidt (1995)	20500	1.13	5000-8000
09/24/85	topographic survey	Ferrari (1985)	na	na	na
01/18/86	topographic survey	USBR	na	na	na
01/01/88	topographic survey	USBR	na	na	na
01/20/89	topographic survey	Middlebury College	na	na	na
01/01/90	topographic survey	Middlebury College	na	na	na
05/05/90	test-flow air photo	Cluer (1992)	15825	0.93	5000
06/30/90	surficial geologic map	Leschin and Schmidt (1995)	15250	0.84	5000
07/14/90	topographic/bathymetric survey	Beus and others (1992)	6575	0.84	na
07/28/90	topographic/bathymetric survey	Beus and others (1992)	6914	0.88	na
09/15/90	topographic/bathymetric survey	Beus and others (1992)	7555	0.97	na
09/29/90	topographic/bathymetric survey	Beus and others (1992)	7829	1.00	na
09/30/90	test-flow air photo	Cluer (1992)	17094	1.00	5000
10/13/90	topographic/bathymetric survey	Beus and others (1992)	7693	0.98	na
10/15/90	topographic survey	Schmidt	na	na	na
10/27/90	topographic/bathymetric survey	Beus and others (1992)	7728	0.99	na
11/10/90	topographic/bathymetric survey	Beus and others (1992)	7615	0.97	na
11/11/90	test-flow air photo	Cluer (1992)	17130	1.00	5000
12/15/90	topographic/bathymetric survey	Beus and others (1992)	7628	0.97	na
12/30/90	test-flow air photo	Cluer (1992)	16885	0.99	5000
01/12/91	test-flow air photo	Cluer (1992)	16544	0.97	5000
01/12/91	topographic/bathymetric survey	Beus and others (1992)	7298	0.93	na
01/26/91	test-flow air photo	Cluer (1992)	16000	0.94	5000
01/26/91	topographic/bathymetric survey	Beus and others (1992)	7216	0.92	na
02/09/91	test-flow air photo	Cluer (1992)	15869	0.93	5000
02/09/91	topographic/bathymetric survey	Beus and others (1992)	7083	0.90	na
04/20/91	test-flow air photo	Cluer (1992)	16117	0.94	5000
04/20/91	topographic/bathymetric survey	Beus and others (1992)	6796	0.87	na
05/18/91	topographic/bathymetric survey	Beus and others (1992)	6801	0.87	na
05/19/91	test-flow air photo	Cluer (1992)	15355	0.90	5000
06/02/91	test-flow air photo	Cluer (1992)	15516	0.91	5000
06/04/91	topographic/bathymetric survey	Beus and others (1992)	6643	0.85	na
06/29/91	topographic/bathymetric survey	Beus and others (1992)	6951	0.89	na
06/30/91	test-flow air photo	Cluer (1992)	13431	0.79	5000
07/13/91	topographic/bathymetric survey	Beus and others (1992)	7105	0.91	na
07/14/91	test-flow air photo	Cluer (1992)	14950	0.87	5000
07/27/91	test-flow air photo	Cluer (1992)	15405	0.90	5000
07/27/91	topographic/bathymetric survey	Beus and others (1992)	9125	0.92	na
10/11/92	surficial geologic map	Leschin and Schmidt (1995)	12000	0.66	8000
10/22/92	topographic/bathymetric survey	Kaplinski and Hazel (1995)	7812	0.79	na
10/11/93	topographic/bathymetric survey	Kaplinski and Hazel (1995)	7976	0.80	na
04/11/94	topographic/bathymetric survey	Kaplinski and Hazel (1995)	7085	0.71	na
11/23/94	topographic/bathymetric survey	Kaplinski and Hazel (1995)	6741	0.68	na
04/28/95	topographic/bathymetric survey	Kaplinski and Hazel (1995)	5797	0.58	na
02/18/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	7338	0.74	na
03/24/96	surficial geologic map	Leschin and Schmidt (1996)	9000	0.50	8000
04/04/96	surficial geologic map	Leschin and Schmidt (1996)	12000	0.66	13600
04/19/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	7587	0.76	na
09/16/96	topographic/bathymetric survey	Hazel and Kaplinski (1998)	5763	0.58	na
02/17/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)	6591	0.66	na
04/24/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)	8970	0.90	na
08/27/97	topographic/bathymetric survey	Hazel and Kaplinski (1998)	8915	0.90	na

* The values for area are those reported for each respective measurement method. The boundary in which area is measured is not consistent between methods and for the photographic methods, discharge varies between some measurements. Thus, these numbers are not directly comparable. For the topographic/bathymtric surveys, the area reported is the area above the 5000 ft^3/s stage.

\# Normalized bar area is the area for the given normalized to the area for a chosen reference measurement. The topographic/bathymetric surveys and the test-flow air photo study were normalized to September 29 and 30, 1990, respectively. The bar areas from the surficial geologic maps were normalized such that the area on June 30, 1990 equalled the area measured by topographic map on July 14, 1990, which assumes no change occurred in the interim.

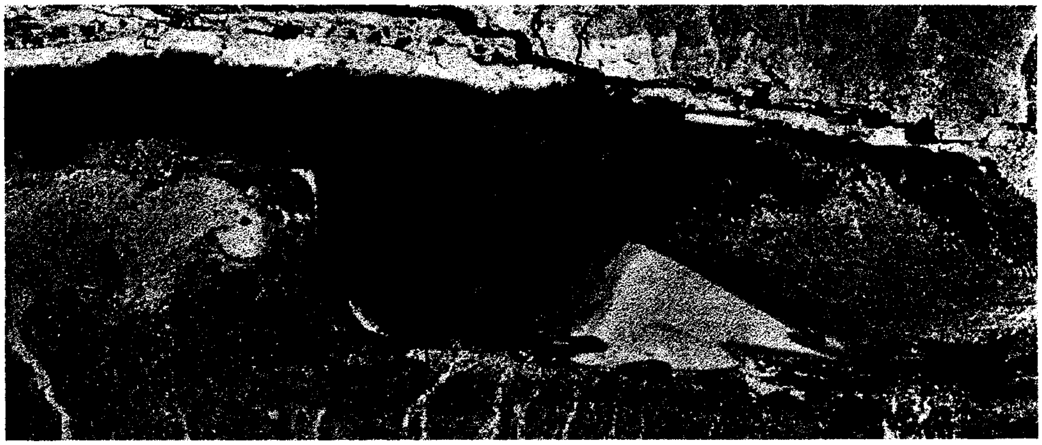
** Discharge is reported only for the methods for which bar area is a function of discharge.


1.
EDDY BOUNDARY
SEPARATION BAR
TYPICAL REATTACH
POINT LOCATIO
CS-1
CS-2
CS-3
CS-4
CS-5
CS-6
N
Location of oblique photograph
Reattachment Bar Types:
Fluctuating flow level
By-pass level
Spill-way level
0 100 200 Meters

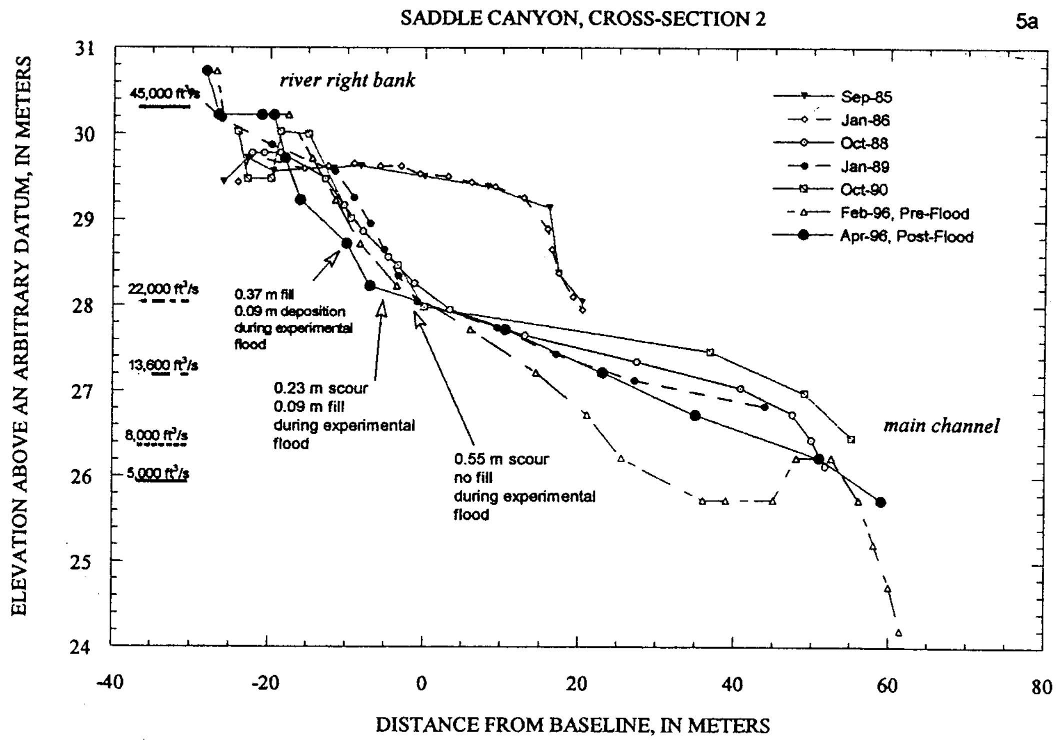

OUTLINE OF PERSISTENT EDDY COMPLEX
COLORADO
RIVER
N
1935
1973
1984
1990
100 0 100 200 Meters

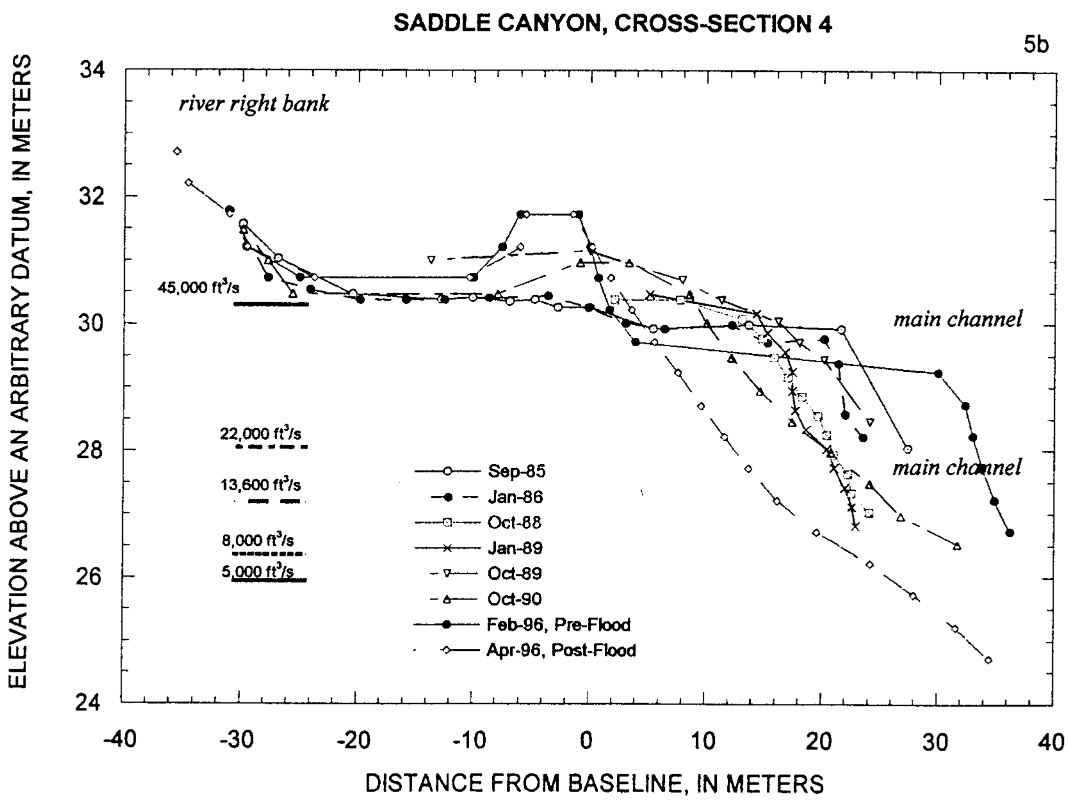
3a.

3b.

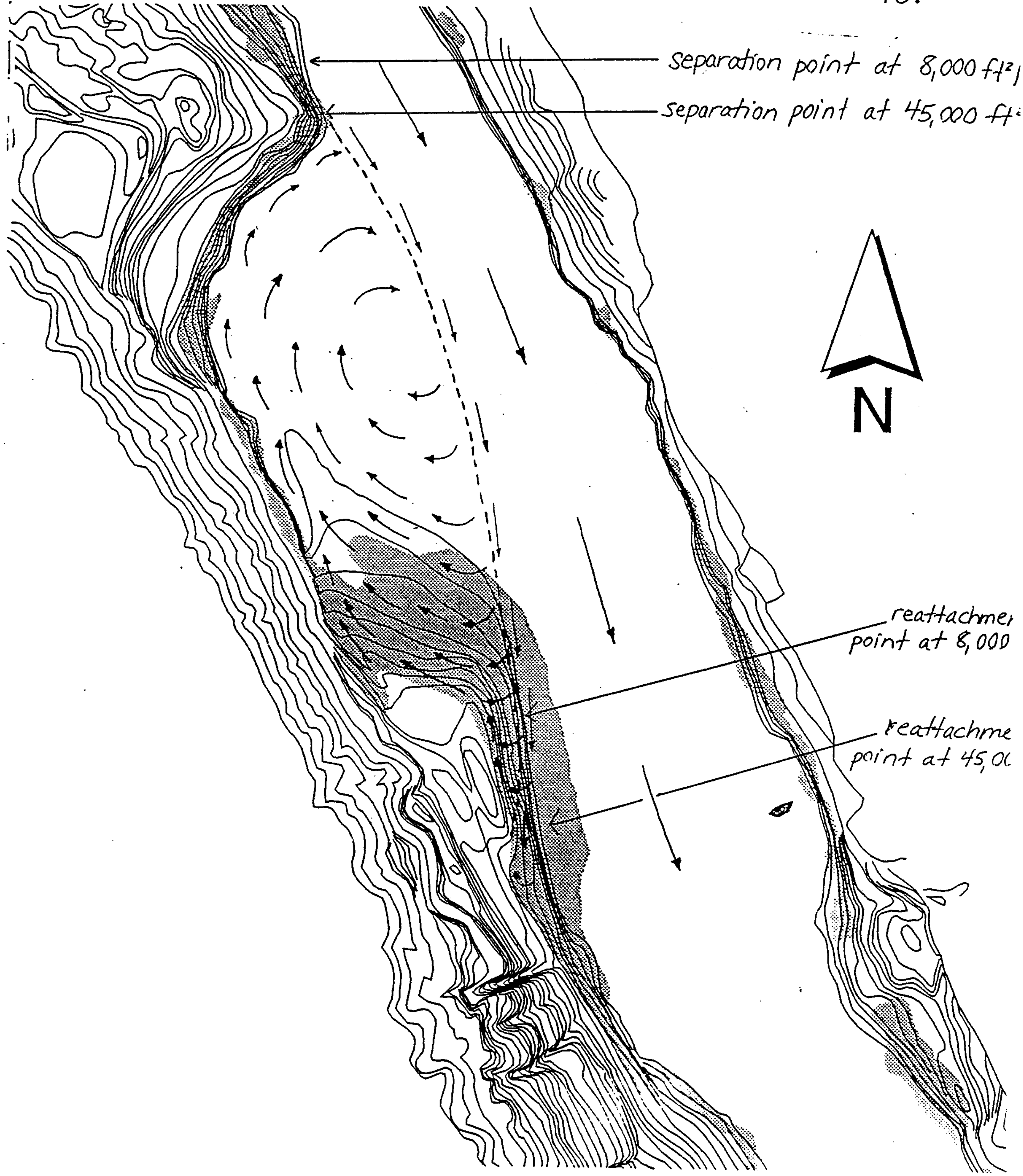


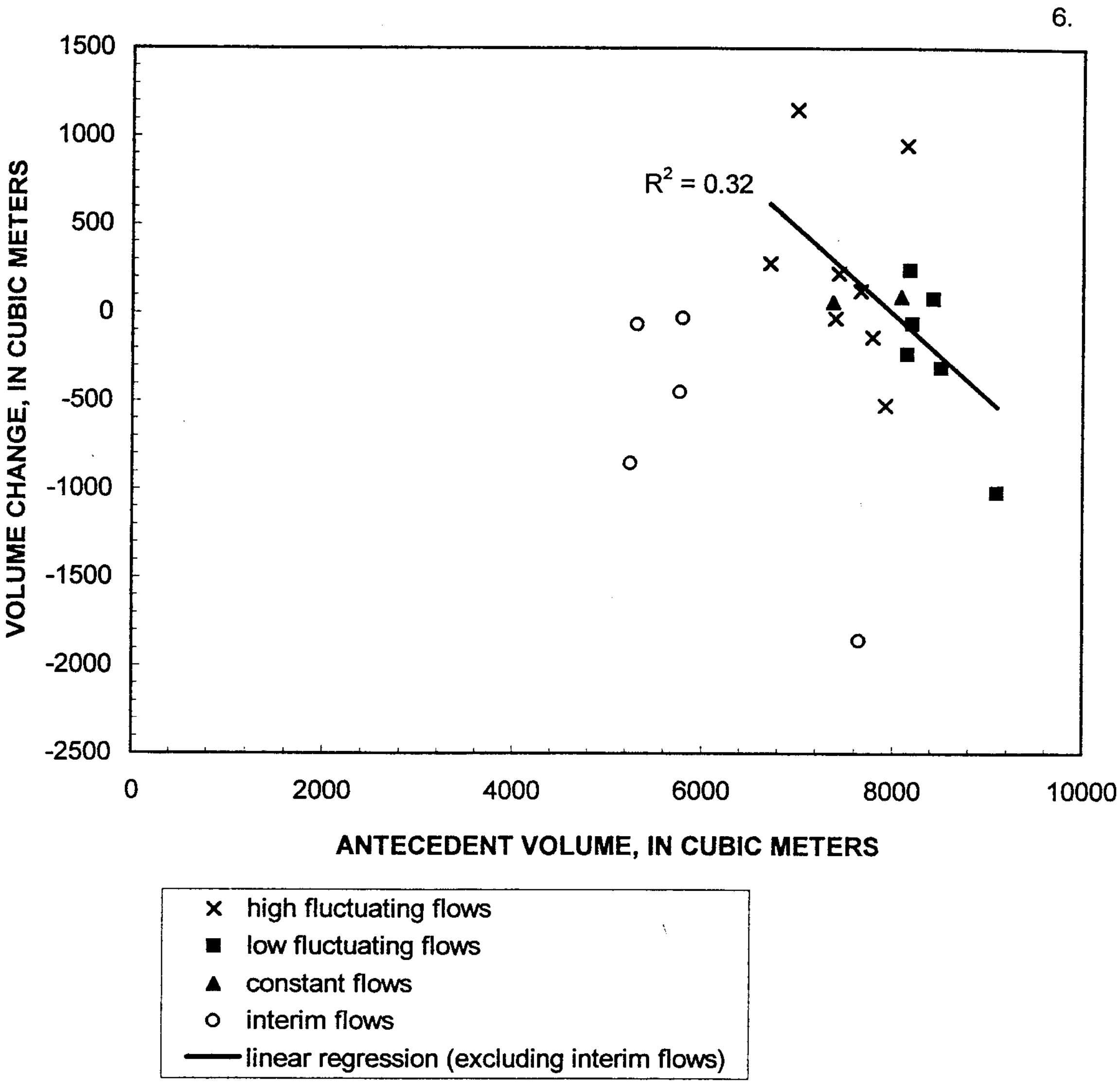
3c.


SADDLE CANYON, CROSS-SECTION 2
5a
river right bank
45,000 ft³/s
22,000 ft³/s
13,600 ft³/s
8,000 ft³/s
5,000 ft³/s
Sep-85
Jan-86
Oct-88
Jan-89
Oct-90
Feb-96, Pre-Flood
Apr-96, Post-Flood
0.37 m fill
0.09 m deposition
during experimental
flood
0.23 m scour
0.09 m fill
during experimental
flood
0.55 m scour
no fill
during experimental
flood
main channel
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BASELINE, IN METERS


SADDLE CANYON, CROSS-SECTION 4
5b
river right bank
45,000 ft³/s
22,000 ft³/s
13,600 ft³/s
8,000 ft³/s
5,000 ft³/s
main channel
main channel
Sep-85
Jan-86
Oct-88
Jan-89
Oct-89
Oct-90
Feb-96, Pre-Flood
Apr-96, Post-Flood
ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
DISTANCE FROM BASELINE, IN METERS

10.


separation point at 8,000 ft²/
separation point at 45,000 ft
N
reattachme
point at 8,000
reattachme
point at 45,0


6.
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
VOLUME CHANGE, IN CUBIC METERS
0
2000
4000
6000
8000
10000
ANTECEDENT VOLUME, IN CUBIC METERS
R² = 0.32
high fluctuating flows
low fluctuating flows
constant flows
interim flows
linear regression (excluding interim flows)

7.

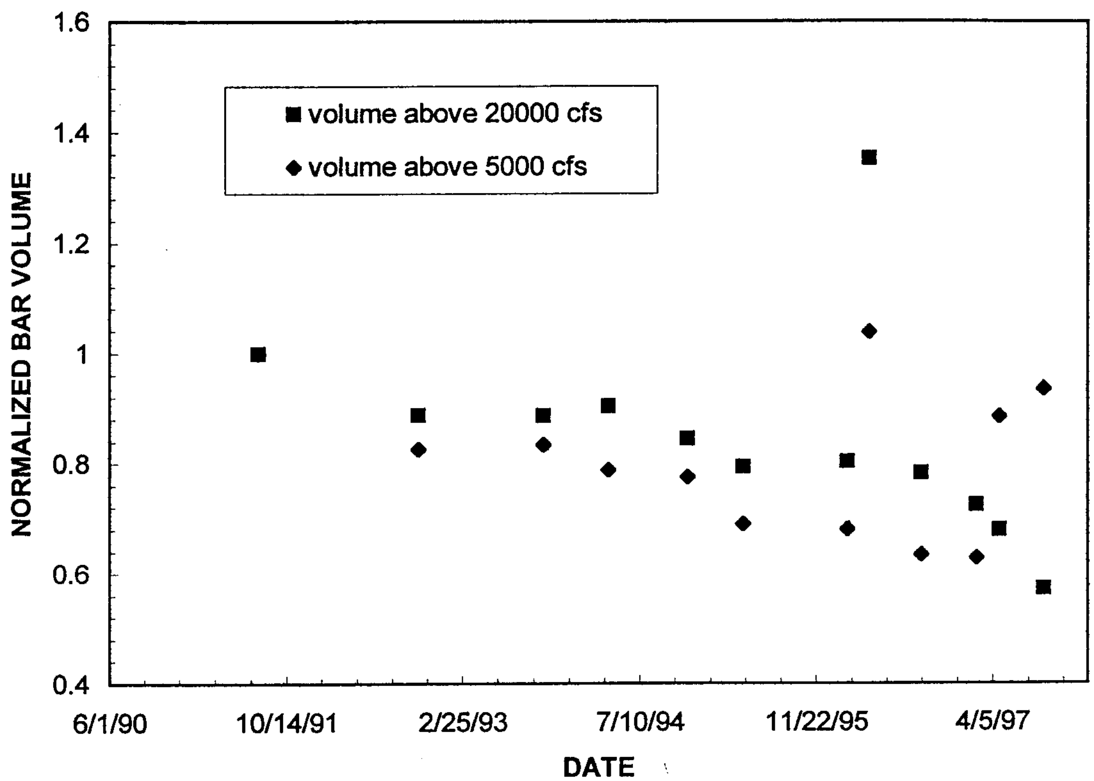
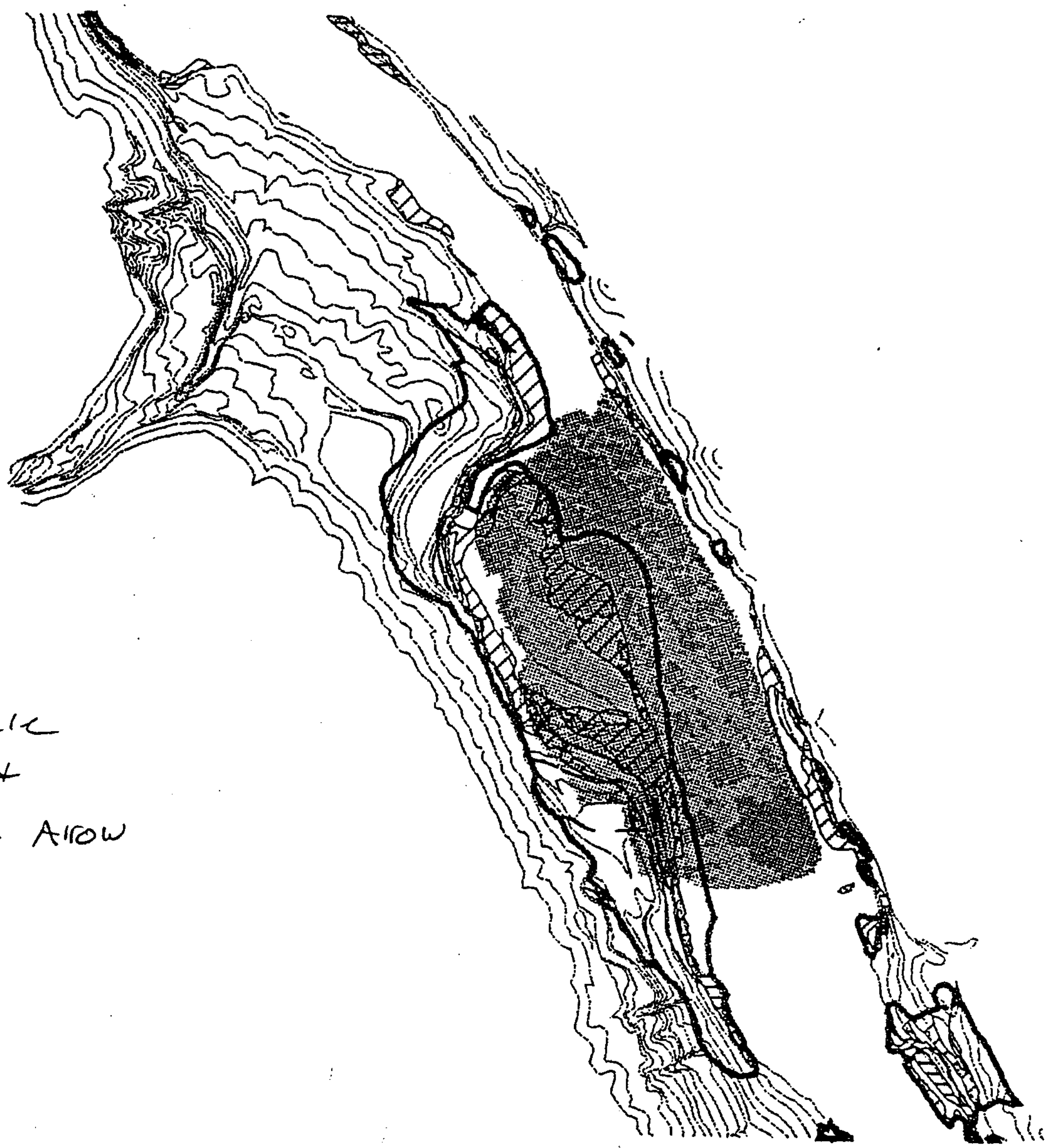
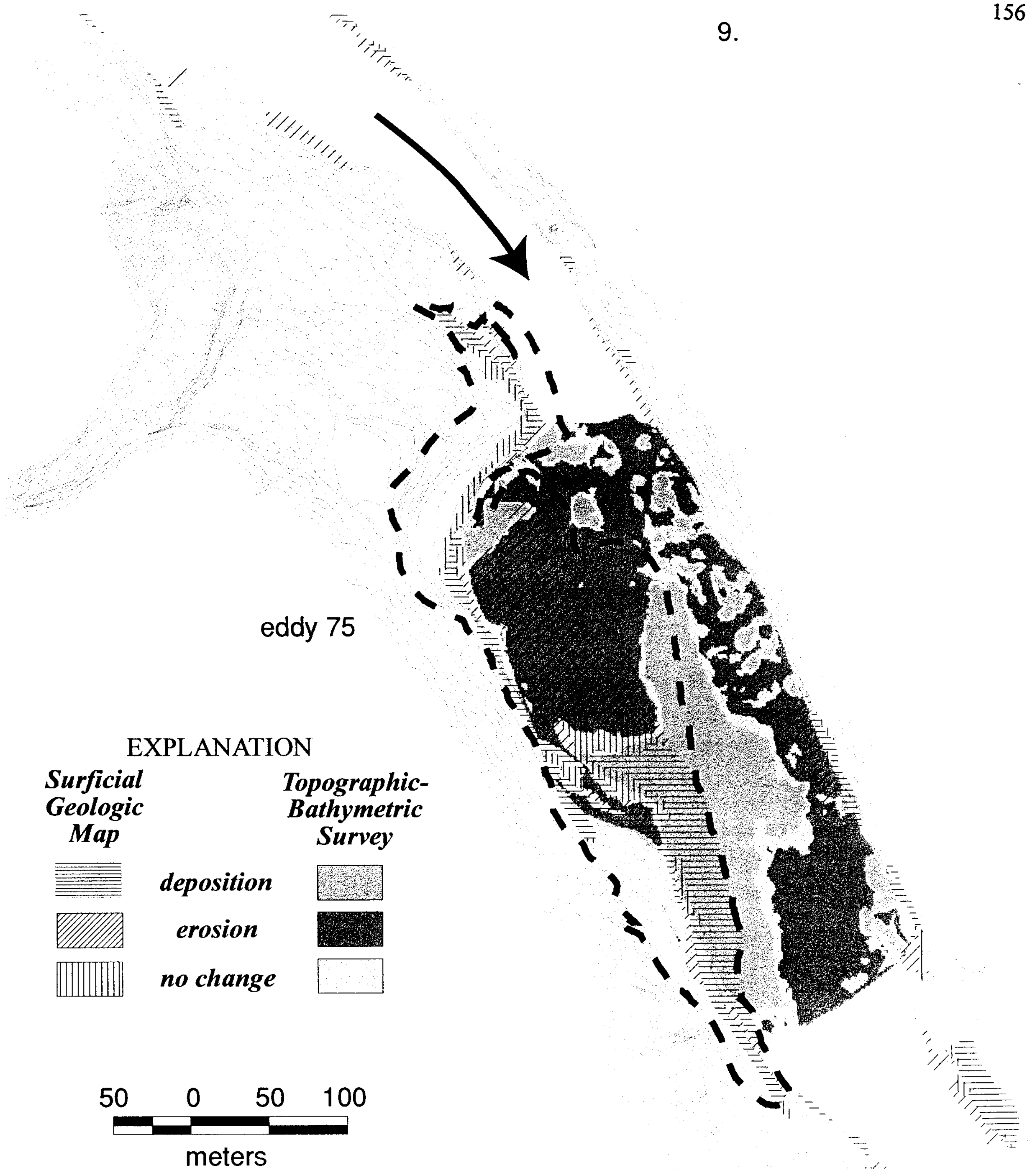

1.6
1.4
1.2
1
0.8
0.6
0.4
NORMALIZED BAR VOLUME
volume above 20000 cfs
volume above 5000 cfs
6/1/90
10/14/91
2/25/93
7/10/94
11/22/95
4/5/97
DATE

Fig III-8

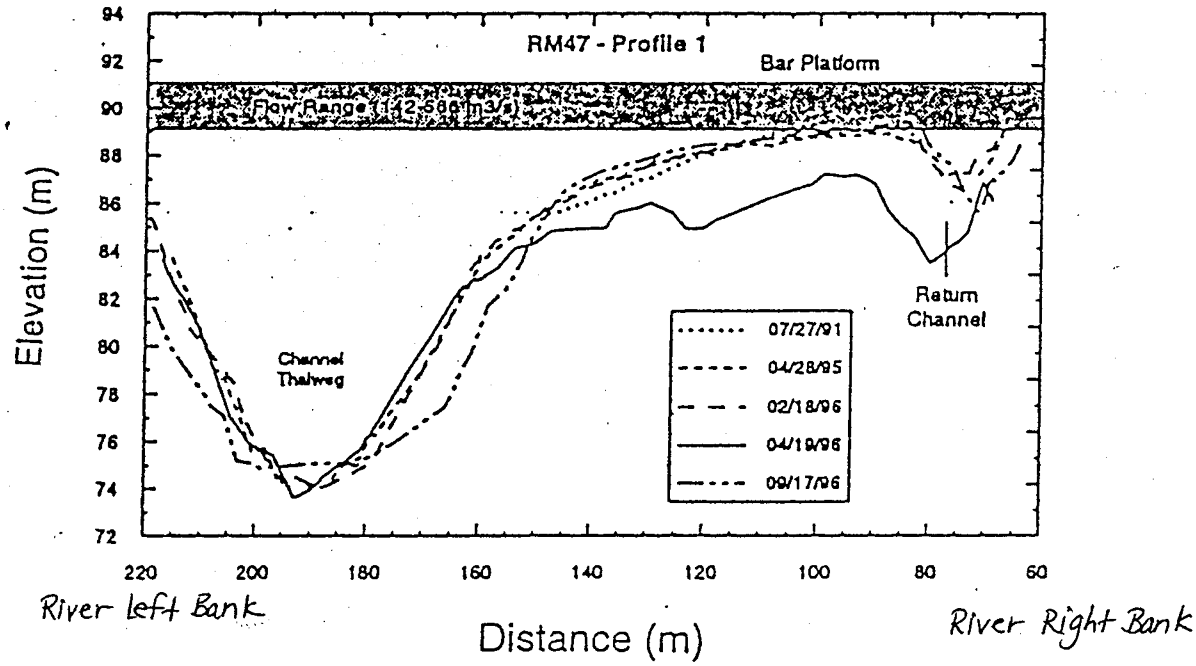


Scale
&
North Arrow

9.


eddy 75
EXPLANATION
Surficial Geologic Map
Topographic-Bathymetric Survey
deposition
erosion
no change
50 0 50 100
meters

11.


RM47 - Profile 1
Bar Platform
Flow Range (142-586 m3/s)
Channel Thalweg
Return Channel
07/27/91
04/28/95
02/18/96
04/19/96
09/17/96
Elevation (m)
94
92
90
88
86
84
82
80
78
76
74
72
220
200
180
160
140
120
100
80
60
Distance (m)
River left Bank
River Right Bank

C. Mile 61.8 Detailed Site Report

ABSTRACT

An eddy exists in the expansion at river mile 61.8 on the right side of the river (RM 61.8R) at spillway, by-pass, and powerplant discharges. The eddy is energetic at moderate and high discharges because the main flow is directed towards the canyon wall and restricts downstream migration of the reattachment point. The bar has been a site of high-elevation deposition at times that the antecedent conditions provide room for sand deposition. Thus, significant deposition occurred here in 1983, 1993, and 1996. Minimal deposition, and perhaps erosion occurred between 1984 and 1986. The eddy can be a site of low-elevation deposition or erosion during high flows. Fluctuating flows typically erode the streamward edges of high-elevation deposits, and cause low-elevation deposition. A monumented profile established by Howard (1975) and repeatedly surveyed through 1986 does not describe typical behavior of the bar but did document deposition of the 1983 and 1984 high flows. Daily changes depicted on 35-mm photography show that low-elevation parts of the bar can change significantly in response to fluctuating and high flows.

INTRODUCTION

The eddy bar at river mile 61.8 right (RM 61.8R) mantles the downstream part of a debris fan that is about 275 m downstream from the large island located at the mouth of the Little Colorado River (Figure 1). Gravel bars occur along both margins of the channel upstream from the fan, and the fan itself is of moderate size, covering an area of about 10,000 m^2. The maximum elevation of the fan, measured between base flow (approximately 5,000 ft^3/s) and the fan apex, is about 16 m. Parts of the fan are higher than the estimated water surface elevation of the 1983 spillway flood (Schmidt and Leschin, 1995, Figure 14b), and an eddy probably exists at all discharges that have occurred since completion of Glen Canyon Dam.

A debris fan that is opposite and downstream from this site directs river flow against bedrock ledges on the right bank, truncating the river-right eddy at all flows less than maximum by-pass tube capacity (45,000 ft^3/s). The reattachment point did not migrate downstream between March 25 and March 28, 1996, when discharge had increased from 8000 to 45000 ft^3/s (Figure 2). The separation point did migrate upstream, however, and the total area of recirculating flow increased by about 30 percent. The expanded portion of the recirculation zone is the typical site of sand deposition (Figure 2). Sedimentology of this bar has not been described in any published reports, although Schmidt and Andrews (unpubl. data) made reconnaissance observations in February 1993. At that time, the bar contained upstream-migrating bedforms across most of the bar surface and wave-dominated bedforms along the margins at water's edge. Comparison of these structures with flow-pattern maps made during the 1996 flood shows that a well-defined return-current channel does not develop at this site, and that separation and reattachment barforms merge. Thus, it is appropriate to classify this site as an undifferentiated eddy bar.

AVAILABLE MONITORING DATA

Howard (1975) established one monitoring profile at this site on July 10, 1975 (Figure 1). The profile is located along the upstream margin of the deposit near the debris fan. This profile was resurveyed by Beus et al. (1984, 1985, 1986, 1987) in 1983, 1984, 1985, 1986, and 1987. The profile was also surveyed by Schmidt and Graf (1990) in 1986. Kyle (1992) summarized the history of topographic change along this profile. The topography of the site was photogrammetrically measured in June 1990 with a contour interval of 0.5 m and is shown on Map 3 of the GCES GIS Site 5 maps. Surficial geologic maps of this site were completed by Leschin and Schmidt (1995) from air photos taken in 1935, 1965, 1984, 1990, 1992, and 1993. The area was also mapped before and after the 1996 beach/habitat-building flow. Cluer et al. (1994) analyzed daily photos of this site taken in 1992 and 1993 with a 35-mm camera located on river left. This site has been included in river campsite inventories beginning in 1971 analyzed by Kearsley and Warren (1993), Kearsley (1995) and for the experimental flood by Kearsley (1997). These workers have variously referred to this site as "below LCR confluence", "below LCR island", "mile 61.6", and "mile 61.7". These data are summarized in Table 1.

TOPOGRAPHIC CHANGES

The earliest data depicting this site are from aerial photographs taken in December 1935, and a large bar is exposed at the very low discharge of about 3,800 ft^3/s. The bar mantles the downstream part of the fan and extends further downstream than in any other photo except the May 1993 photo, which shows the deposition from the January 1993 Little Colorado River flood.

Only a portion of the bar is visible in the 1965 photographs because the discharge was between 25,000 to 27,000 ft^3/s at the time of the aerial photography. The clean and wet sand interpreted from this photo strongly suggests that this sand had been deposited by flows that had reached 44,800 ft^3/s during the prior month. High-elevation sand deposits perched on the debris fan occur in both 1935 and 1965. The discharge difference between 1935 and 1965 precludes analysis of changes of low elevation parts of the bar.

There is no 1973 air photo coverage for this site, and Howard's 1975 profile does not describe the condition of the main part of the bar. Nevertheless, Howard's measurements can be compared with other measurements along the same profile, and this comparison shows that the elevation of the bar in 1975 was neither the highest nor lowest that was measured during the period 1975 to 1987 (Figure 3).

The spillway flood of 1983 deposited more sand at high elevation than did any other flood that has occurred since completion of Glen Canyon Dam, based on Beus' August 1, 1983, repeat survey of the profile. However, much of this sand was eroded from the upstream part of the bar during the by-pass flood of 1984 (Figure 3), based on the profile survey of August 4, 1984. The post-1984 flood topography of the bar along the profile was similar to the topography surveyed in 1975. The October 1984 photographs show that the area of open sand in 1984 was similar to that exposed in 1935 at a similar discharge. The 1984 bar did not extend as far downstream as the 1935 bar but extended slightly farther into the river channel. Interpretation of the 1984 photographs shows deposits at two distinct levels above the stage of maximum powerplant capacity that correspond to the spillway and by-pass releases of 1983 and 1984. However, the elevation of about 50 percent of the bar area was less than the stage of maximum powerplant capacity. The photographic and profile data indicate that the 1984 by-pass flood eroded, but did not entirely remove, sand that had been deposited by the 1983 flood.

Comparison between the distribution of sand exposed in the 1984 and 1990 photographs shows that net deposition occurred at fluctuating flow and bypass elevations above a stage of about 5,000 ft^3/s. Profile surveys of May 1985 and August 1986 show no change on the upstream end of the bar. Most of the deposition interpreted from the 1990 photographs occurred on the downstream portion of the separation bar and at fluctuating-flow stage. Some of the deposition occurred at by-pass flow elevations and therefore was likely the result of the 1985 or 1986 high flows. The bypass-level deposition is shown in Figure 4 as the strip of deposition along the shoreward side of the area of 1984 to 1990 deposition. Analysis of the 1990 and 1992 aerial photographs shows additional deposition at fluctuating-flow elevations.

The January and February 1993 flood (Figure 2) in the Little Colorado River (LCR) caused erosion or deposition to occur at most of the eddy bars downstream from LCR confluence. The surficial geologic map made from the May 1993 photography shows the extent of the bar to be greater than in any other year mapped including 1935. In contrast to the 1984 flood, most of the deposition occurred at middle and low elevations, although some of the deposition occurred at elevations that were mapped as distinct Little Colorado River flood deposits. The peak discharge of the flood was about 30,000 ft^3/s on the Colorado River. Thus the LCR flood deposits are lower than the by-pass deposits and equivalent to the highest elevation fluctuating-flow deposits

Comparison of the surficial geologic maps made of the Mile 61.8 eddy bar before and after the 1996 experimental flood show high elevation deposition and low elevation erosion. The areas of erosion exceeded the areas of deposition by about 5 percent of the eddy complex area. Thus the area of high-elevation deposition was less than the area of low-elevation erosion.

Short-Term Changes As Detected By Daily Time-Lapse Photography

This sand bar was monitored by a remote 35-mm camera that took photographs daily from October 1992 to June 1993 (Cluer et al., 1994). These photographs documented erosional and depositional events that occurred during fluctuating flows and the LCR flood. Rectified images made from photographs taken at similar discharges show that bar area varied between 80 and 120 percent of the initial area in June 1993. These changes occurred on the low-elevation portion of the bar affected by fluctuating flows.

Status Of Backwater Habitat

Backwater habitat is rare at this site due to lack of a well-defined return-current channel.

Status Of The Campsite

No significant changes in the campable area at this site were measured prior to the 1996 experimental flood. The site was qualitatively assessed as a medium campsite in 1983 and a small campsite in 1991. The campable area was measured as about 900 m^2 in 1991 and 1000 m^2 in 1996 pre-flood. Immediately after the test flow, the campable area decreased by 80 percent due to erosion of the downstream portion of the bar. This is consistent with the measurements made from the surficial geologic maps. The campsite analysis did not measure deposition that may have occurred on the upstream and higher elevation portions of the bar. No significant changes in campable area were observed in the 6-mth period following the test flow.

GENERALIZED RESPONSE TO FLOODS

The behavior of the Mile 61.8 R eddy bar is different between low-elevation and high-elevation areas of the bar and also different between upstream and downstream parts of the bar. The high elevation and upstream portion of the bar aggraded in response to the 1983 and 1984 floods, the 1993 Little Colorado River flood, and the 1996 experimental flood. This aggradation was measured by the single profile for the 1983 and 1984 flood and by the GIS analysis of surficial geologic maps for all of the floods. The low elevation and downstream part of the bar, however, aggraded during some floods and eroded during other floods. The 1983, 1984 floods and the 1993 flood resulted in deposition at low elevations while the 1996 flood resulted in erosion at low elevations. The data analyzed by Cleur et al. (1994) show that the low elevation parts of the bar are subject to catastrophic slumping that may explain the variable response of the low-elevation areas documented by the interpretation of the surficial geologic maps.

The measurements of sand bar size made by repeat surveys of the profile, surficial geologic mapping from aerial photographs, and rectification of oblique photographs were normalized to a common datum for comparison. The profile surveys were normalized to the measurement made August 4, 1984 and the area of sand measured from surficial geologic maps was normalized to the area measured October 21, 1984. The area of exposed sand was measured by surficial geologic maps made from October 11, 1992 aerial photographs and by rectified images made from October 12, 1992 oblique photographs. The oblique photograph data was thus normalized to the other data assuming the area of exposed sand on these days was the same. Discharge differences and photograph scale precludes use of the 1935 and 1965 photographs for areal measurements. Visual comparison indicates that the area of sand, with discharge differences considered, is not significantly different from that in the October 1984 aerial photograph. These compiled data are shown in a time series plot in Figure 5. Short-term variability measured by oblique photographs is large but decade-scale trends are also shown. These trends are largely determined by large floods such as occurred in 1983, 84, 93, and 96 that cause erosion or deposition.

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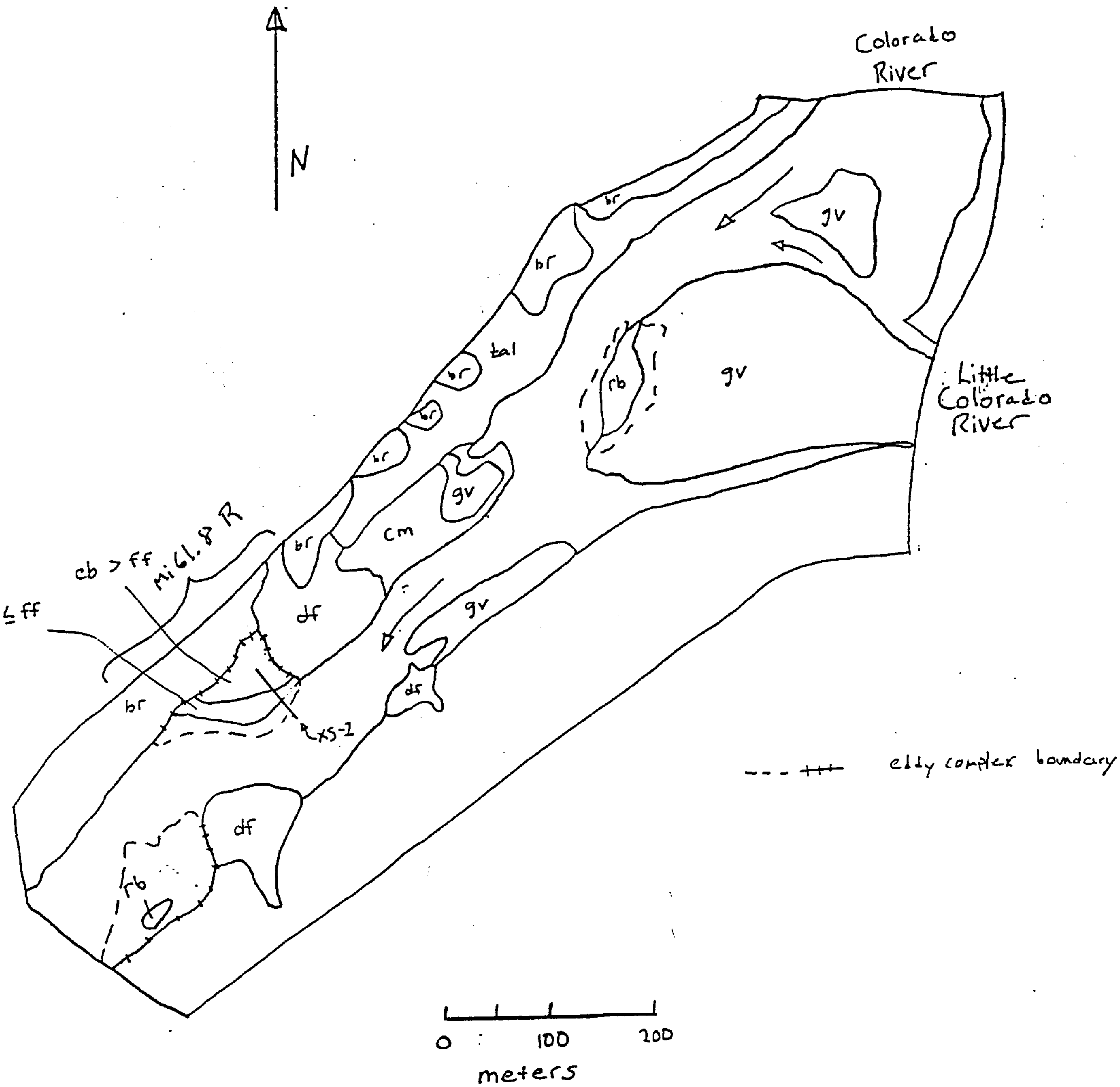
Schmidt, J. C. and Leschin, M.F., 1995, Geomorphology of post-Glen Canyon dam fine-grained alluvial deposits of the Colorado River in the Point Hansbrough and Little Colorado River confluence study reaches in Grand Canyon National Park, Arizona: Final Report to U.S. Bureau of Reclamation, Glen Canyon Environmental Studies, Flagstaff, AZ, 93 p.

LIST OF FIGURES

Table 1. Summary of measurements of topographic change of RM 61.8R.

DATE	Measurement*	Area**	Normalized Area	Note
1935	map	n	1	large exposed bar
1965	map	n	1	only high sand visible due to high discharge
7/10/75	profile	62	1.0	initial measurement
8/1/83	profile	81	1.2	deposition occurred above 20000 cfs stage
8/4/84	profile	65	1.0	erosion occurred at 28 to 35000 cfs stages
10/21/84	map	3250	1.0	similar extent of sand as in 1935
5/12/85	profile	61	0.9	erosion occurred at 28 to 35000 cfs stages
8/4/85	profile	61	0.9	no change
8/1/86	profile	60	0.9	deposition occurred at 14 to 35000 cfs stages
6/30/90	map	4250	1.3	deposition occurred at most levels mapped
10/11/92	map	4750	1.5	deposition occurred at low elevations and erosion at high elevations
10/12/92	photo	3753	1.5	initial measurement
11/9/92	photo	3441	1.3	erosion occurred at fluctuating flow levels
12/12/92	photo	3443	1.3	no change
1/17/93	photo	4006	1.6	deposition due to LCR flood at low elevations downstream, some erosion upstream
3/14/93	photo	3055	1.2	erosion at low elevations downstream, deposition upstream
4/18/93	photo	4628	1.8	deposition at low fluctuating flow elevations
5/30/93	map	5250	1.6	deposition due to LCR flood at middle and low elevations, larger bar than in 1935
6/7/93	photo	3418	1.3	erosion at low fluctuating flow elevations
3/24/96	map	4387	1.3	erosion at middle and low elevations
4/4/96	map	3241	1.0	erosion at low elevations, deposition at high elevations

Figure 1


N
Colorado
River
Little
Colorado
River
gv
rb
br
tal
cm
df
mi 61.8 R
cb > ff
b ≤ ff
xs-1
eddy complex boundary
0
100
200
meters

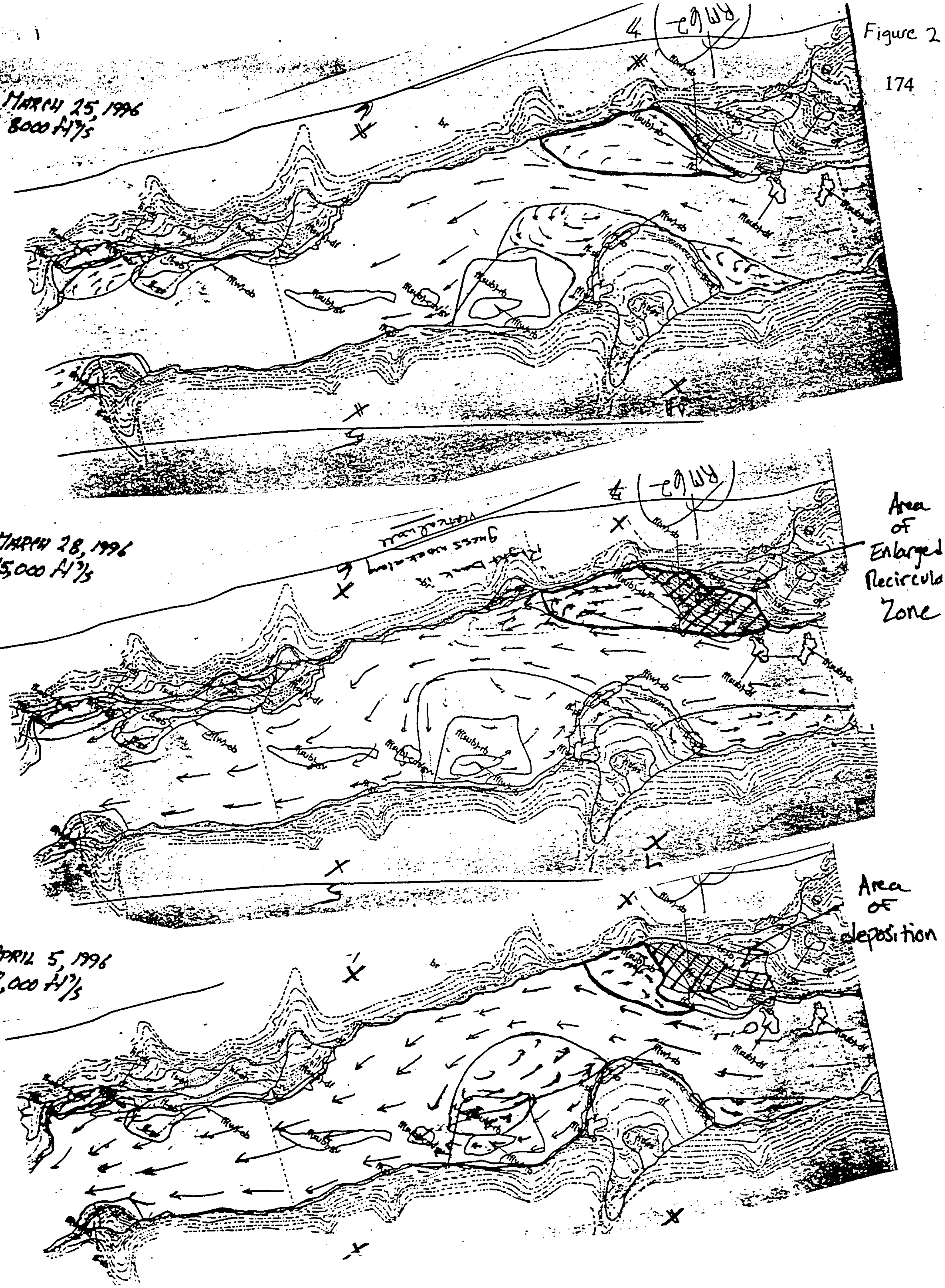
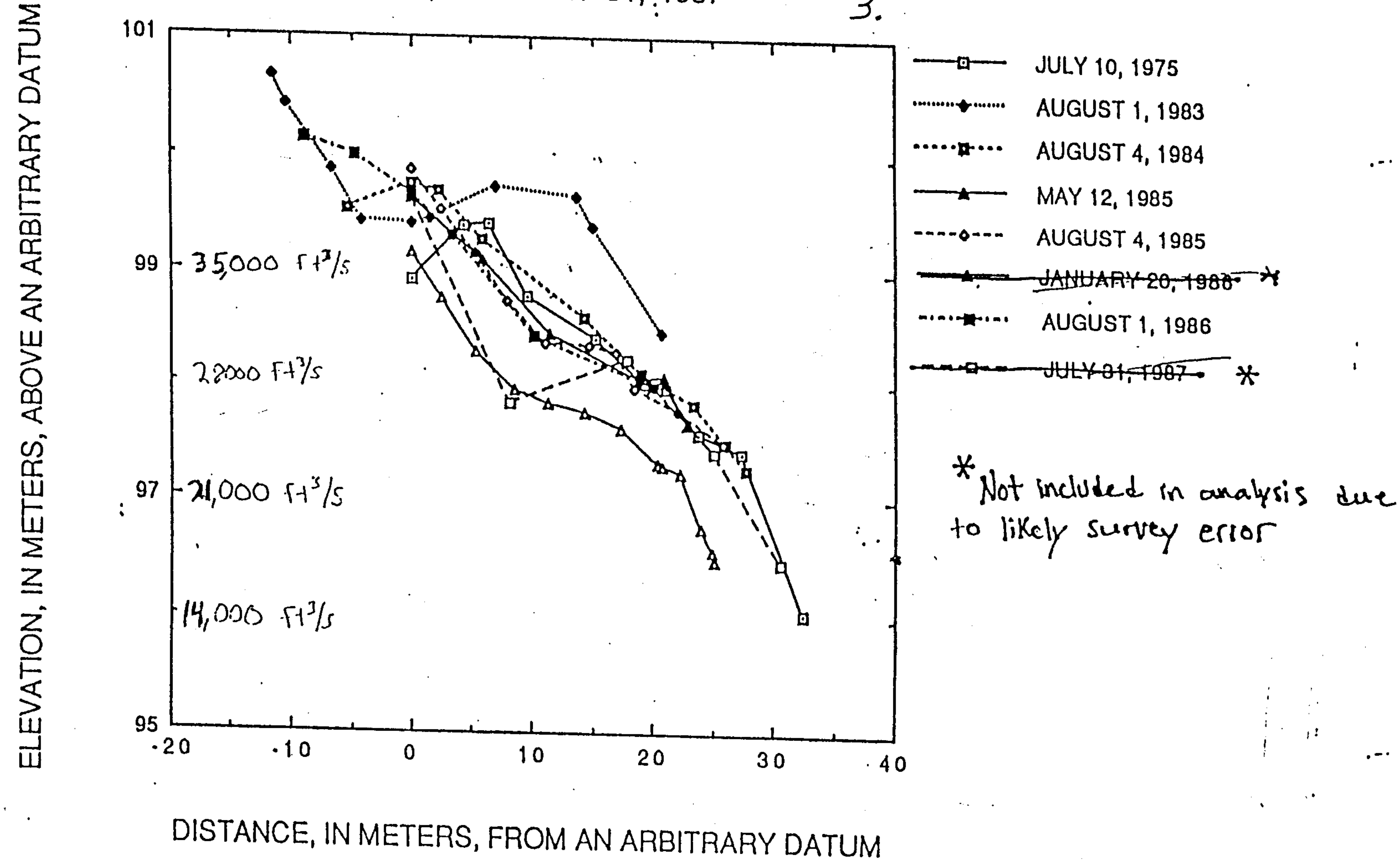

A. MARCH 25, 1996
8000 ft³/s
B. MARCH 28, 1996
45,000 ft³/s
Area of Enlarged Recircula Zone
C. APRIL 5, 1996
8,000 ft³/s
Area of deposition

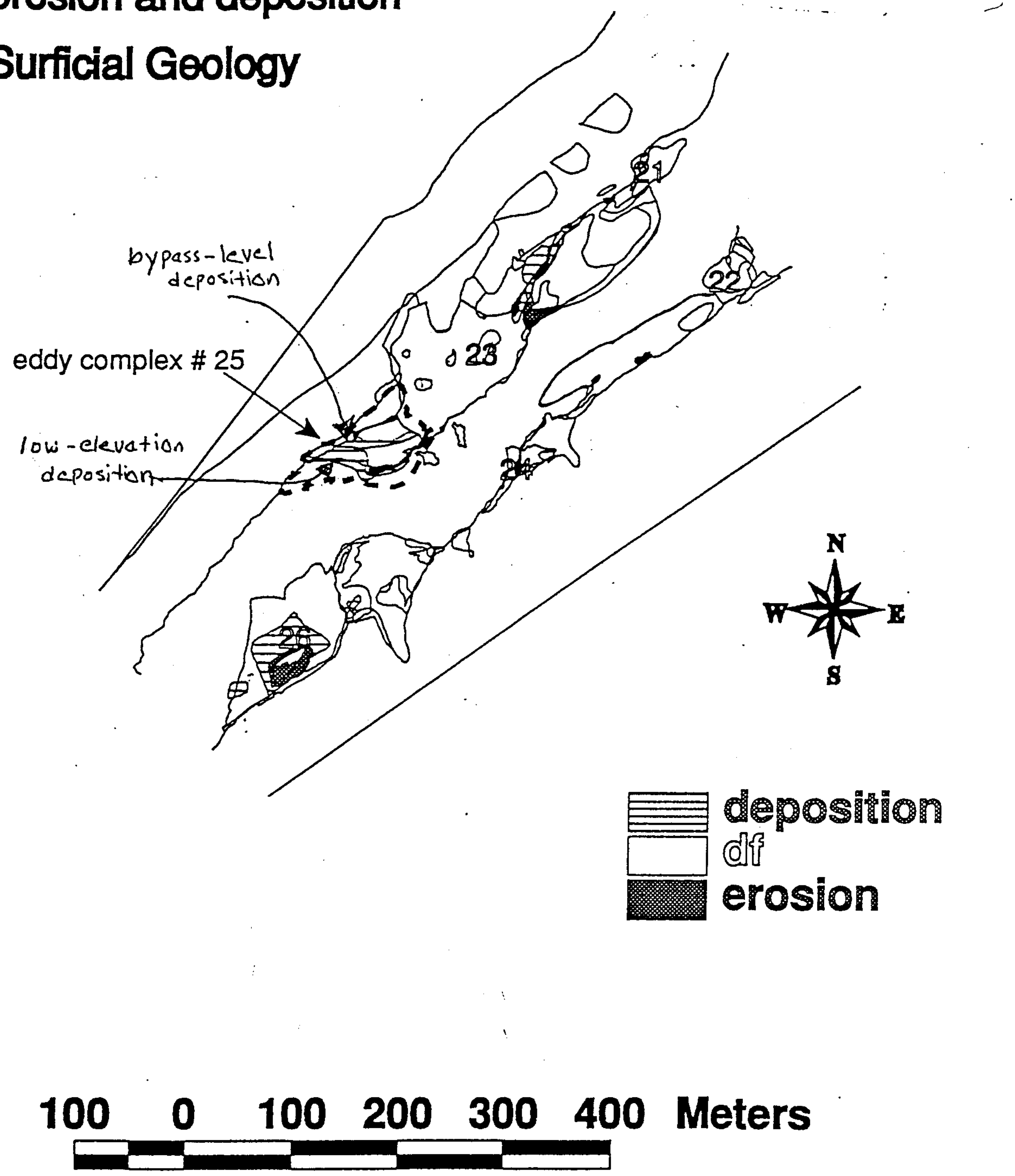
Figure 2

BELOW THE CONFLUENCE OF THE LITTLE COLORADO RIVER, PROFILE 1
JULY 10, 1975-JULY 31, 1987



Mile 61.8 Right
1984-90 erosion and deposition
1990 Surficial Geology

Figure 4.



1:6,000

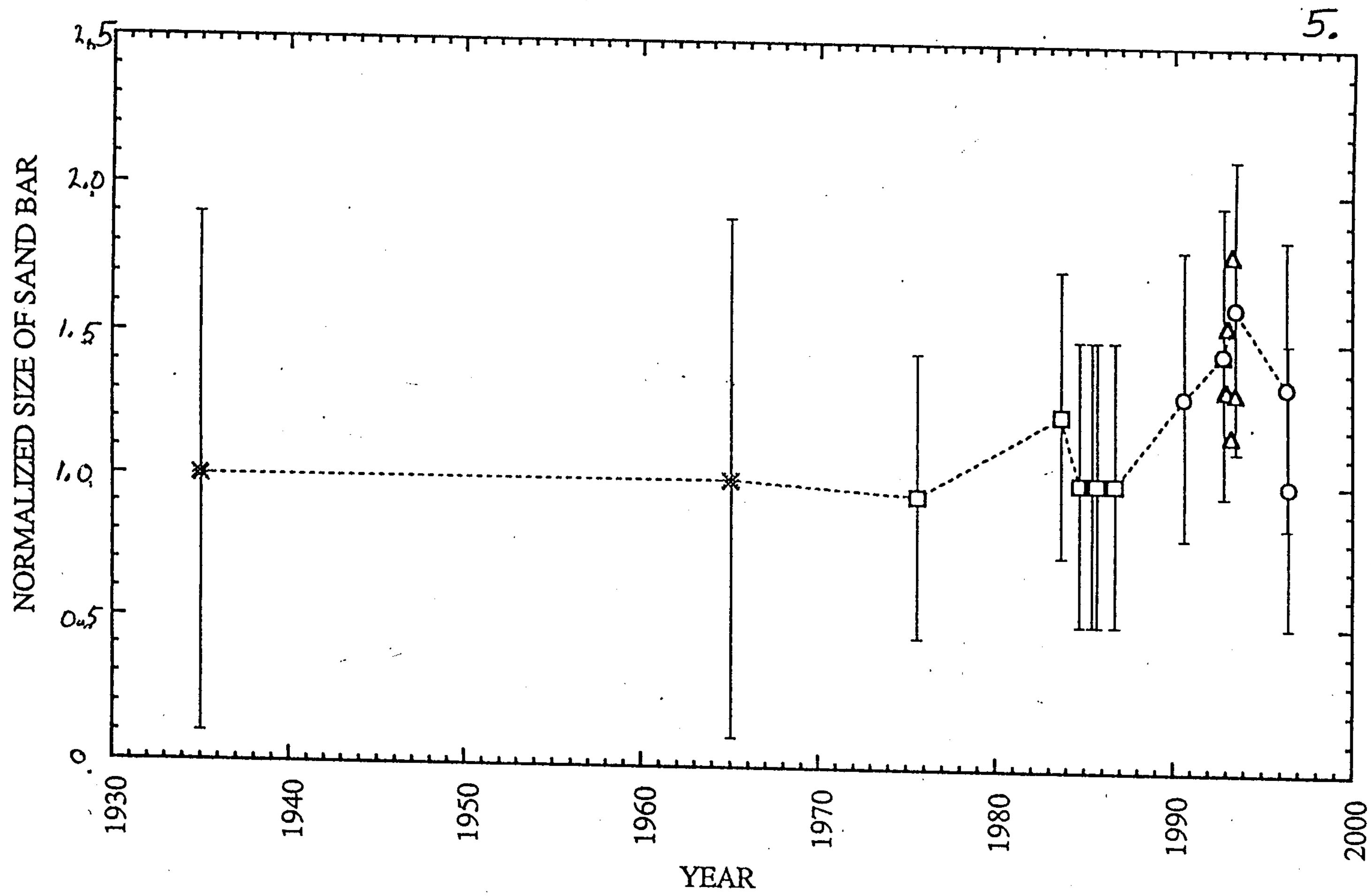


Figure 5. Normalized size of eddy bar at Mile 61.8 R. Size is represented by cross-sectional area of surveyed profile normalized to the August 1984 area for the points shown by boxes and by area of exposed sand normalized to the area exposed in October 1984 for the points shown by circles. The size of the sand bar in 1935 and 1965, shown by asterisk's, was visually estimated by comparison between these photographs and the 1984 photographs. The triangles are measurements of bar area made by remote camera normalized to the other measurements. The variability shown by these data is the basis for the error bars shown for the measurements made since 1975. Larger error bars are used for the 1935 and 1965 measurements because the pre-dam variability was likely greater than it is post-dam.

D. Crash Detailed Site Report

ABSTRACT

The volume and area of sand stored within the eddy complex located upstream from an unnamed tributary informally known as Crash Canyon has been regularly monitored since 1993. Analysis of older photography provides a record of erosion and deposition at this site beginning in 1935. These data demonstrate that sand bar area and volume have varied by an order of magnitude, the eddy has the potential to accumulate large volumes of sand when tributary floods charge the mainstem with sediment, and post-flood erosion rates can be very large. The largest volume of sand ever measured at this site was in 1993, demonstrating that erosion at this site caused by the existence of Glen Canyon Dam is not irreversible.

INTRODUCTION

Summary Characteristics of Site

1. An eddy exists here at all discharges less than about 100,000 ft^3/s. The upstream-controlling debris fan is not overtopped at discharges as large as those that occurred in 1983.

2. The separation bar at the upstream fan and high-elevation portions of the reattachment bar on the downstream fan are persistent sites of deposition at all discharges that exceed powerplant capacity.

3. The reattachment bar that forms within the primary eddy has been a persistent deposition site when mainstem suspended sediment concentrations are high. A large bar formed here in 1993 and in 1995 when tributary floods in the Little Colorado River raised the discharge and suspended sediment load of the Colorado River.

4. High rates of erosion can occur here. Erosion rates of up to 2500 m^3/day were measured when a large reattachment bar that had formed during winter 1993 was exposed to high-volume fluctuating flows between 12,000 and 18,000 ft^3/s between July and October 1993. Erosion rates of about 100 m^3/day were measured here when the same deposit was exposed to low-volume fluctuating flows between 8000 and 13,000 ft^3/s.

5. Sand bar area and volume exposed at 5000 ft^3/s has varied by an order of magnitude, and short-term erosion and deposition rates can be very high. The largest measured area and volume were 10,000 m^2 and 22,000 m^3, respectively, in spring 1993. The smallest area and volume ever measured was 1000 m^2 and 2000 m^3, respectively, on April 22, 1996. The highly variable nature of sediment storage at this site makes it inappropriate as a long-term indicator of sediment storage conditions in Grand Canyon.

6. The area of surveyed topography and bathymetry measured by Northern Arizona University is much larger than the area measured by air photo analysis. The two methods yield similar results where the survey areas overlap.

Site Description

The debris fan located at the mouth of an unnamed tributary at RM 62.5-R forms a large eddy that extends downstream to another large debris fan at RM 62.6-R. The downstream debris fan is located at the mouth of an unnamed tributary informally called Crash Canyon (Figure 1). This eddy has been variously referred to as Crash Canyon Eddy, Dead Chub Eddy, and Mile-62 Eddy. The debris fans at both ends of this eddy are of about average size for the reach. The area of the upstream fan is about 7500 m^2, and the area of the Crash Canyon fan is about 11,000 m^2. The elevation of the apex of the upstream fan is about 17 m above the stage at 5000 ft^3/s, and the estimated 1983 peak-flow water surface did not overtop this fan (Schmidt and Rubin, 1995). Therefore, an eddy has existed here at all flows that have occurred since dam closure.

Flow Patterns and Sedimentology

Maps of the eddy at discharges between 8000 and 45,000 ft^3/s that were made between March 25 and 28, 1996, and the distribution of eddy-deposited sediment, demonstrate that the eddy fence does not significantly change location over a wide range of discharges. However, the eddy lengthens at higher flows (Figure 2). The area of the eddy at 45,000 ft^3/s was about 27 percent larger than was the area at 8000 ft^3/s. Lengthening occurred by migration of the separation point onto the upstream debris fan and downstream migration of the reattachment point onto the Crash Canyon fan.

Deposition in this eddy complex occurs at both high and low elevations (Figure 3). High-elevation sand deposition occurs during floods greater than Glen Canyon Dam powerplant capacity, and low-elevation sand deposition occurs during flows less than powerplant capacity, usually when mainstem sediment concentrations are elevated due to tributary flooding. A high-elevation separation bar formed here in 1983, but there is no evidence of a 1983 spillway-elevation reattachment bar. High-elevation deposition occurred on the separation bar and downstream-most portion of the reattachment bar during by-pass discharges in 1984-86 and in 1996. A very large low-elevation reattachment bar was formed here in no more than 5 days by a mainstem flow of 31,000 ft^3/s in winter 1993 when mainstem suspended sediment concentrations were about 0.37 percent volumetric concentration (Wiele and others, 1996). In most years, the crest of the reattachment bar is lower in elevation than the crest of the separation bar. The only area of high-elevation reattachment bar that persists from year to year is a small area on the surface of the upstream side of the Crash Canyon fan.

Comparison of flow pattern maps and maps of sand deposits show that the separation bar forms in an area of unorganized low-velocity flow, upstream from the primary cell that fills most of the eddy. The morphology of the reattachment bar at those times when it fills most of the eddy is typical of reattachment bars throughout Grand Canyon. Sedimentology of the bar demonstrates that it forms within the primary eddy. Rubin and others (1994) described a sequence in which dunes graded upward into ripples that was exposed in a long, high cutbank in spring 1993 (Figure 4). Bedform-migration directions were typically onshore and upstream in the lower part of the exposure and were onshore in the upper part of the exposure. Kaplinski and others (1994) showed that the reattachment bar had aggraded to near the estimated 1993 high water surface.

Changes in Debris Fans

Debris flows that altered debris-fan morphologies occurred in both tributaries on or about September 24, 1990. Historical photographs demonstrate that these were the first fan-modifying debris flows to occur in either tributary since 1890 (Melis and others, 1995). The debris flow at RM 62.5-R delivered large boulders and fine sediment to the fan that increased the severity of the rapid, resulted in a more pronounced backwater upstream from the debris fan, and deposited 1 to 3 cm of red mud on the separation bar. The Crash Canyon debris flow deposited sediment on the separation bar downstream from Crash Canyon, but did not have a noticeable effect on the RM 62.6-R eddy complex (Melis and others, 1995).

from this flood were mapped from aerial photographs taken in May 1993. The area of newly deposited sand shown in the 1993 air photo is similar to the area of sand exposed in 1935 (Figure 3). The volume of sand in the eddy was probably larger in 1993 than in 1935 or any other year of measurements because the 1993 photograph was taken at a higher discharge, yet shows a higher proportion of exposed dry sand. By October 1993, the low-elevation sand bar deposited by the LCR flood had eroded to an area similar to or smaller than the area of the bar in October 1992 (Table 1). Thus, very large changes in sediment storage can occur here in short time periods. The volume of eroded sand was about 65,000 m^3, as measured by topographic surveys conducted in April and October 1993. Observations of the site made in June 1993 indicate that only about 5 percent of the volume eroded between April and June during low-volume fluctuating flows (8,000 to 13,000 ft^3/s per day). Most of the erosion occurred between July and October 1993, after a July 1 transition to high-volume fluctuating flows (12,000 to 18,000 ft^3/s per day). These volume changes correspond to estimated erosion rates of about 100 m^3/day and 2500 m^3/day for the periods of low- and high-volume fluctuating flows, respectively (Kaplinski and others, 1995).

Additional topographic surveys show that the sand bar volume and area above baseflow discharge (approximately 5,000 ft^3/s) continued to decrease through November 1994. Between November 1994 and April 30, 1995 deposition was measured by topographic survey (Table 1). This deposition is likely related to winter floods from the LCR that peaked at 5700 and 6600 ft^3/s on February 19 and March 9, respectively (Figure 5). The sand deposited by the 1995 LCR flood was significantly eroded by August 1, 1995, and repeat topographic surveys and mapping from air photos both indicate that the reattachment bar remained small in area and volume through March 24, 1996 (Figure 7).

The 1996 beach/habitat-building flood deposited sand on the separation bar and portions of the downstream end of the reattachment bar on the Crash Canyon fan. However, there was net erosion in the eddy and channel. Two scour chains placed on the downstream end of the reattachment bar (Figure 8) recorded no scour at this location and between 1.1 and 1.2 m of fill.

Agreement of Measurement Methods

The areas of erosion and deposition measured by repeat air-photo mapping and repeat topographic surveys are generally in agreement where the areas of measurement overlap. The areas of erosion and deposition measured by each method between April/May 1993 and February/March 1996 and between February/March 1996 and April 1996 are overlain in Figure 7 and Figure 8, respectively. Large areas of erosion measured by the topographic survey are unmeasured areas on the surficial geologic maps, and some of the areas of deposition on the separation bar shown on the surficial geologic map are outside the boundary of the topographic measurements. Both maps indicate erosion of most of the low-elevation reattachment bar between 1993 and 1996 and deposition on the downstream end of the reattachment bar during the 1996 flood. Only the topographic measurements show erosion as the net change in the eddy complex because the surficial geologic maps do not measure changes in the eddy and channel.

Generalized Response to Floods

Significant deposition on the low-elevation platform of the reattachment bar occurred only as a result of sediment-contributing floods from the Little Colorado River.

The most deposition occurred during the largest of these events, which was in January/February 1993. The February and March 1995 LCR floods were smaller than the 1993 flood and resulted in a smaller amount of deposition. Deposition on the separation bar occurred during mainstem floods greater than power-plant capacity in 1983 and 1996.

Status of Backwater Habitat

This site has the potential for a large backwater habitat area to exist in the eddy return current channel when a large reattachment bar is present. However, only during low discharge, as in 1935, or immediately following a large aggradational event, as in 1993, was a large reattachment bar exposed. Thus, this eddy complex is likely to contain viable backwater habitat only at low discharges (less than about 8000 ft^3/s) and requires frequent bar-building events to maintain the reattachment bar.

Status of the Campsite

The campsite at Crash Canyon was recorded as a medium-sized campsite in 1973 and 1983 and a large campsite in 1991 (Kearsley and Warren, 1993). Although the surficial geologic maps and pre- and post-experimental flood oblique photos show deposition at the Crash Canyon campsite (Figure 9), no change in campsite area was recorded in the campsite inventory (Kearsley and Quartaroli, 1997).

Time Series of Sand Bar Change

All measurements of sand bar area made by surficial geologic mapping and repeat topographic surveys (Table 1) were normalized to overlapping dates of measurement. The measurements of bar area made by surficial geologic mapping were first corrected for differences in discharge at the time of aerial photography. This correction was made by developing a relationship between bar area and discharge using the bar topography measured following the 1996 experimental flood (Figure 10). This curve was then moved up or down on the graph to intersect each plotted measurement of bar area. Then for each measurement, the bar area at 8,000 ft^3/s was determined as the intersection of the curve and a vertical line passing through 8,000 ft^3/s. These discharge-adjusted measurements of bar area were normalized to the area measured in 1984 by dividing the area measured on a given date by the area measured in 1984. The area measured by topographic survey was normalized to the same datum by assuming the area surveyed in April 1993 is the same area that was measured from air photos in May 1993. The time series (Figure 11) suggests that the size of the bar has been more variable and generally smaller post-dam than it was pre-dam, but this conclusion is very tentative. Very little pre-dam data are available, and the variability during that period was likely much greater than is shown. This variability is a reflection of the short-lived nature of the reattachment bar. Deposition occurs rapidly during sediment-charged tributary floods. A large low-elevation reattachment bar may fill 50 percent or more of the eddy complex area. However, because this is a low-elevation deposit, it is subject to reworking and erosion by mainstem flows such as occurred in the summer of 1993 after deposition by the Little Colorado River flood in January of that year. Different portions of the eddy complex behave differently during any depositional or erosional event. While the net change of the eddy was erosion during the 1996 experimental flood, portions of the separation bar and downstream end of the reattachment bar aggraded significantly. Thus, this site is probably not appropriate as a long-term monitoring site because of the short-term variability in bar size.

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LIST OF FIGURES

Table 1. Summary of available monitoring data for RM 62.6-R.

Date	Method of Measurement	Area[1] (m^2)	Normalized Area[2]	Volume (m^3)	Normalized Volume[3]
12/31/35	surficial geologic map	15194	7.05		
5/14/65	surficial geologic map	1069	0.50		
6/16/73	surficial geologic map	1669	0.78		
10/21/84	surficial geologic map	2154	1.00		
6/30/90	surficial geologic map	1518	0.70		
10/11/92	surficial geologic map	1314	0.61		
5/30/93	surficial geologic map	7041	3.27		
3/24/96	surficial geologic map	930	0.43		
4/4/96	surficial geologic map	2295	1.07		
4/5/93	topographic survey	10258	3.27	21511	4.00
10/13/93	topographic survey	2556	0.81	2323	0.43
4/13/94	topographic survey	1127	0.36	1745	0.32
11/24/94	topographic survey	1135	0.36	1843	0.34
4/30/95	topographic survey	4913	1.57	4909	0.91
8/1/95	topographic survey	1121	0.36	1817	0.34
2/21/96	topographic survey	1188	0.38	1936	0.36
4/22/96	topographic survey	1038	0.33	1912	0.36
9/19/96	topographic survey	1072	0.34	1890	0.35
1973	campsite inventory				
1983	campsite inventory				
1991	campsite inventory				
1/20/1890	photo (2314a, 2314b)[4]				
10/?/37	photo (2024)				
2/5/91	photo (2314a, 2314b)				
8/5/91	photo (2022, 2023)				
8/6/92	photo (2256, 2024, 2025)				
3/1/94	photo (2022, 2256, 2024)				
2/23/95	photo (2022, 2023, 2256)				

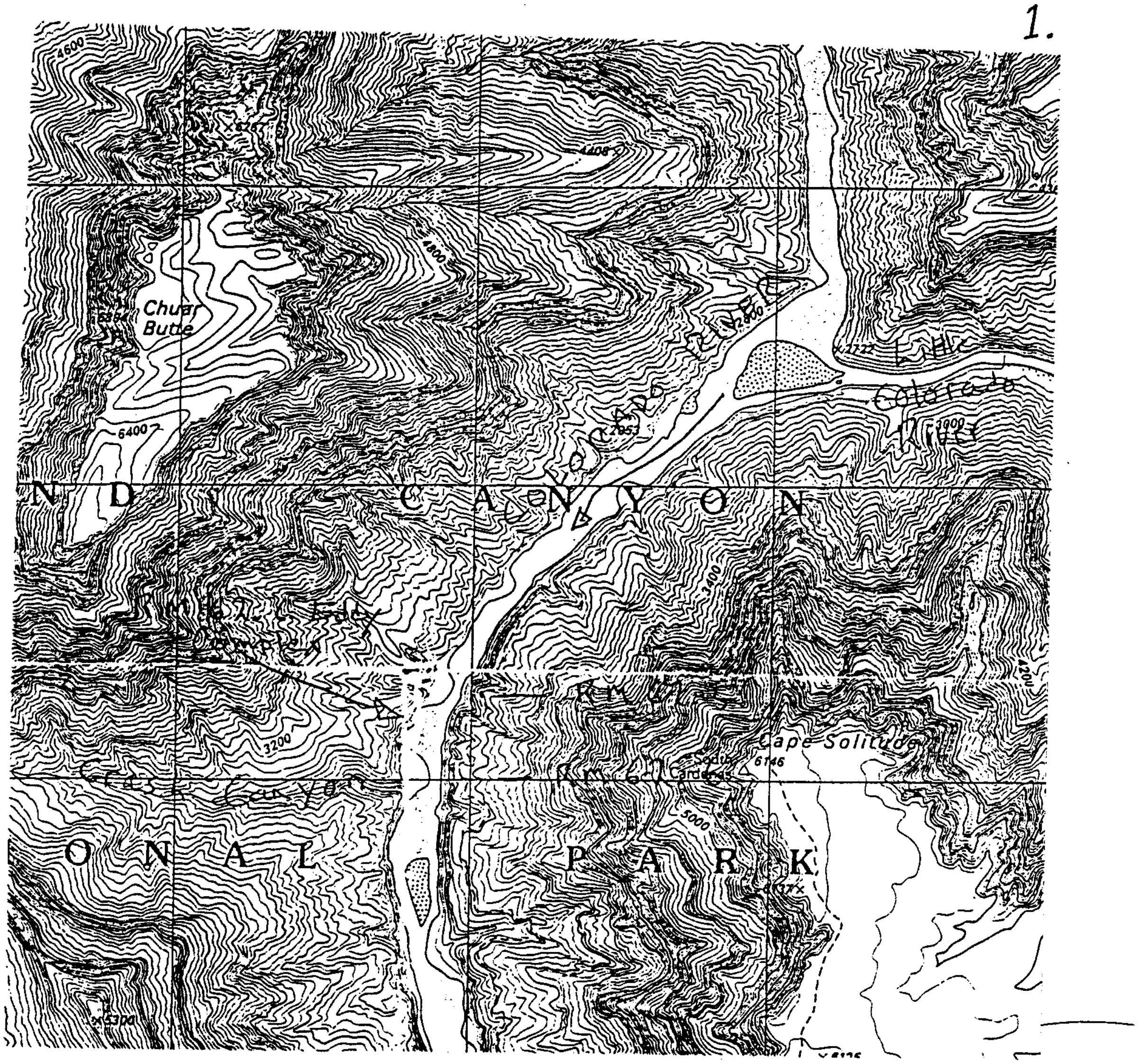
[1] Total area of sand within eddy complex measured from surficial geologic maps and corrected for differences in discharge at time of photography.

[2] Measurements from surficial geologic maps are normalized to October 21, 1984. Measurements from topographic surveys are normalized such that the area measured on the April 5, 1993 topographic survey equals the area measured by the May 30, 1993 surficial geologic map.

[3] Volume measurements from topographic surveys are normalized for comparison with area measurements.

[4] Numbers refer to established photograph locations (Melis and others, 1995).

1.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6400
N D C A N Y O N
Little Colorado River
3200
Cape Solitude
6146
5000
O N A L P A R K

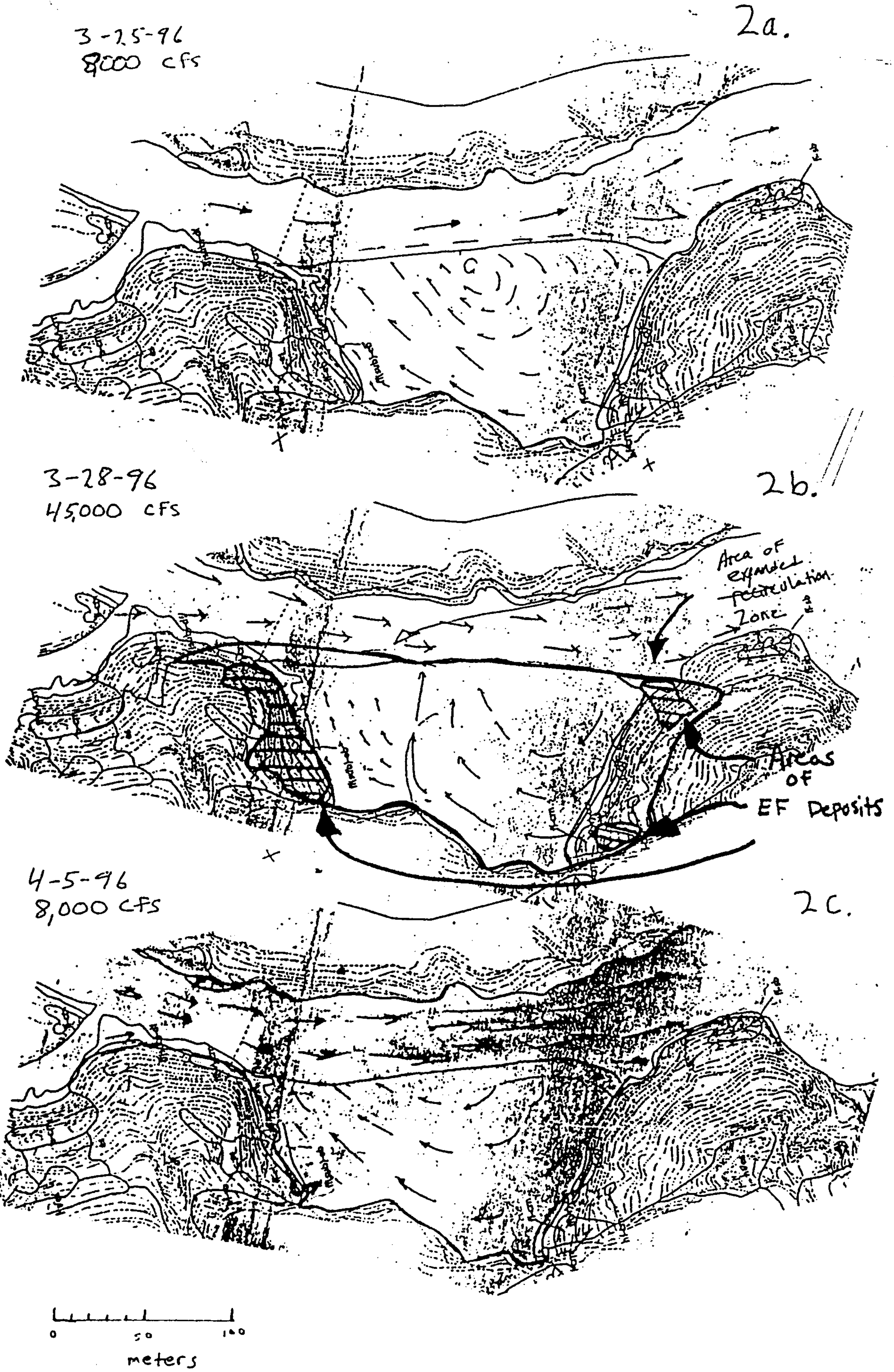
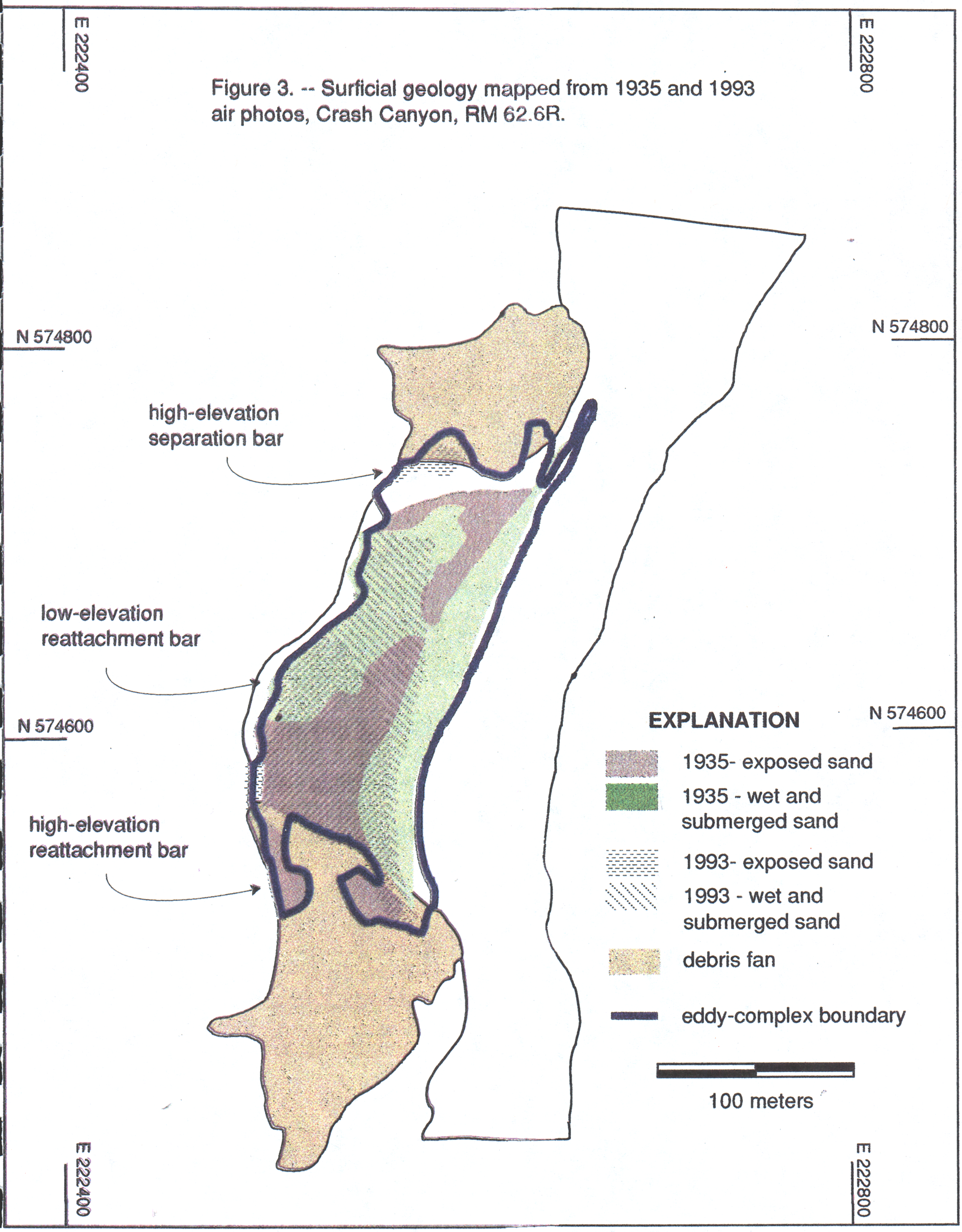
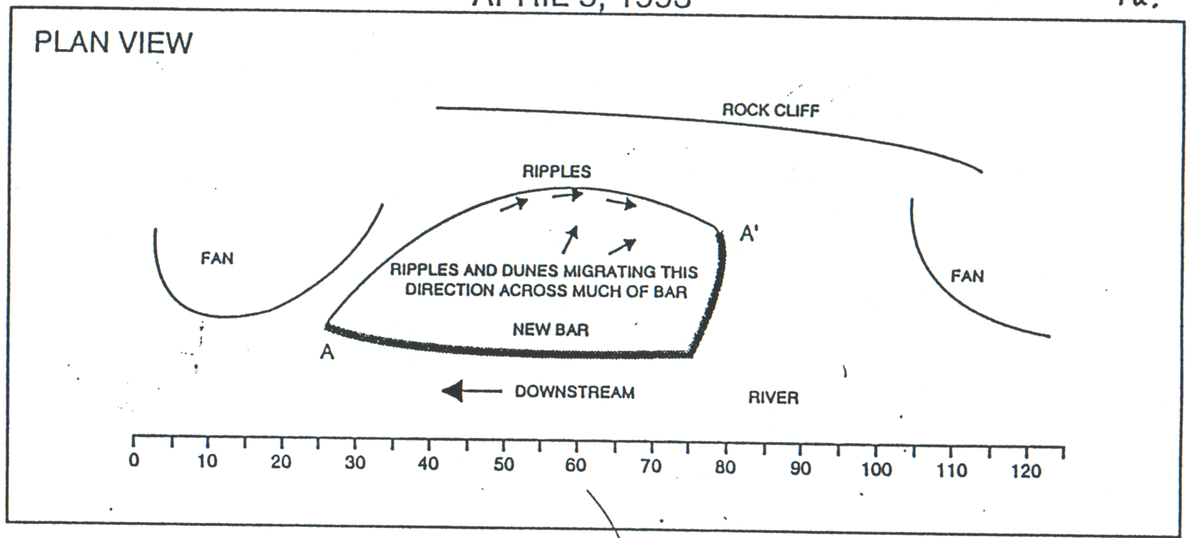

3-25-96
8000 cfs
2a.
3-28-96
45,000 CFS
2b.
Area of expanded recirculation zone
Areas of EF Deposits
4-5-96
8,000 CFS
2c.
0 50 100
meters

Figure 3. -- Surficial geology mapped from 1935 and 1993 air photos, Crash Canyon, RM 62.6R.

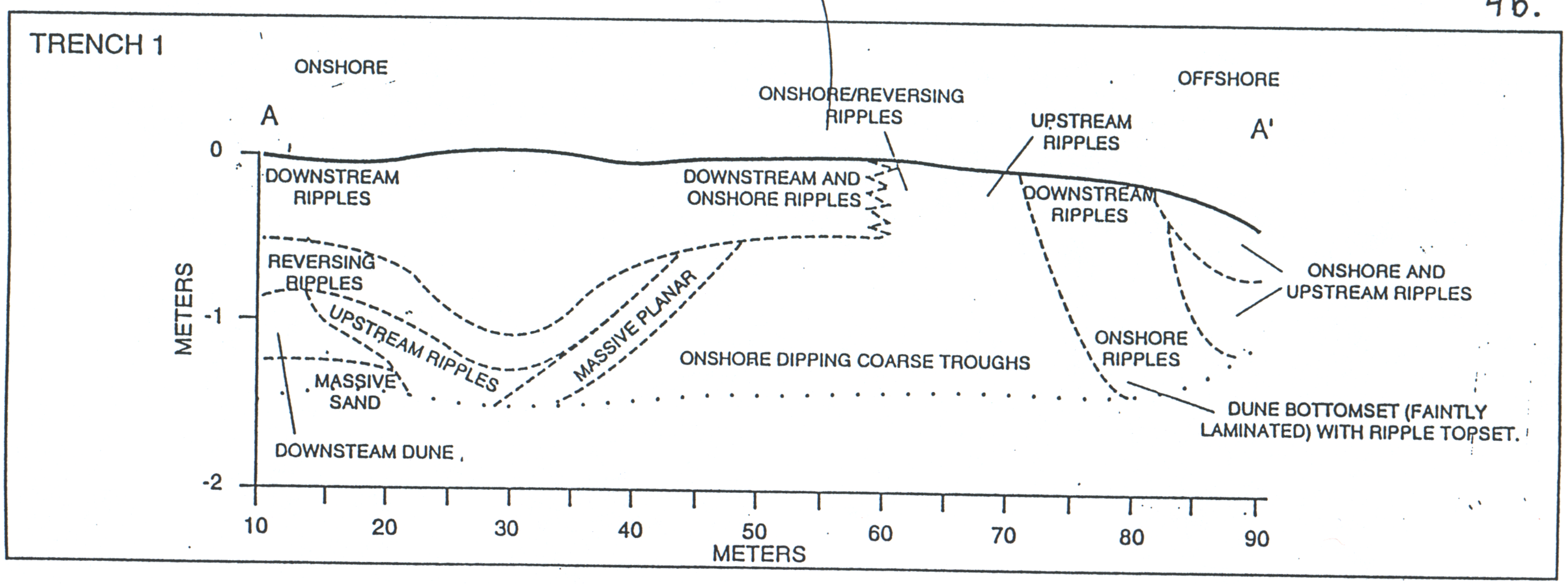


MILE 62.6 RIGHT
PLAN VIEW &
TRENCH 1
APRIL 5, 1993

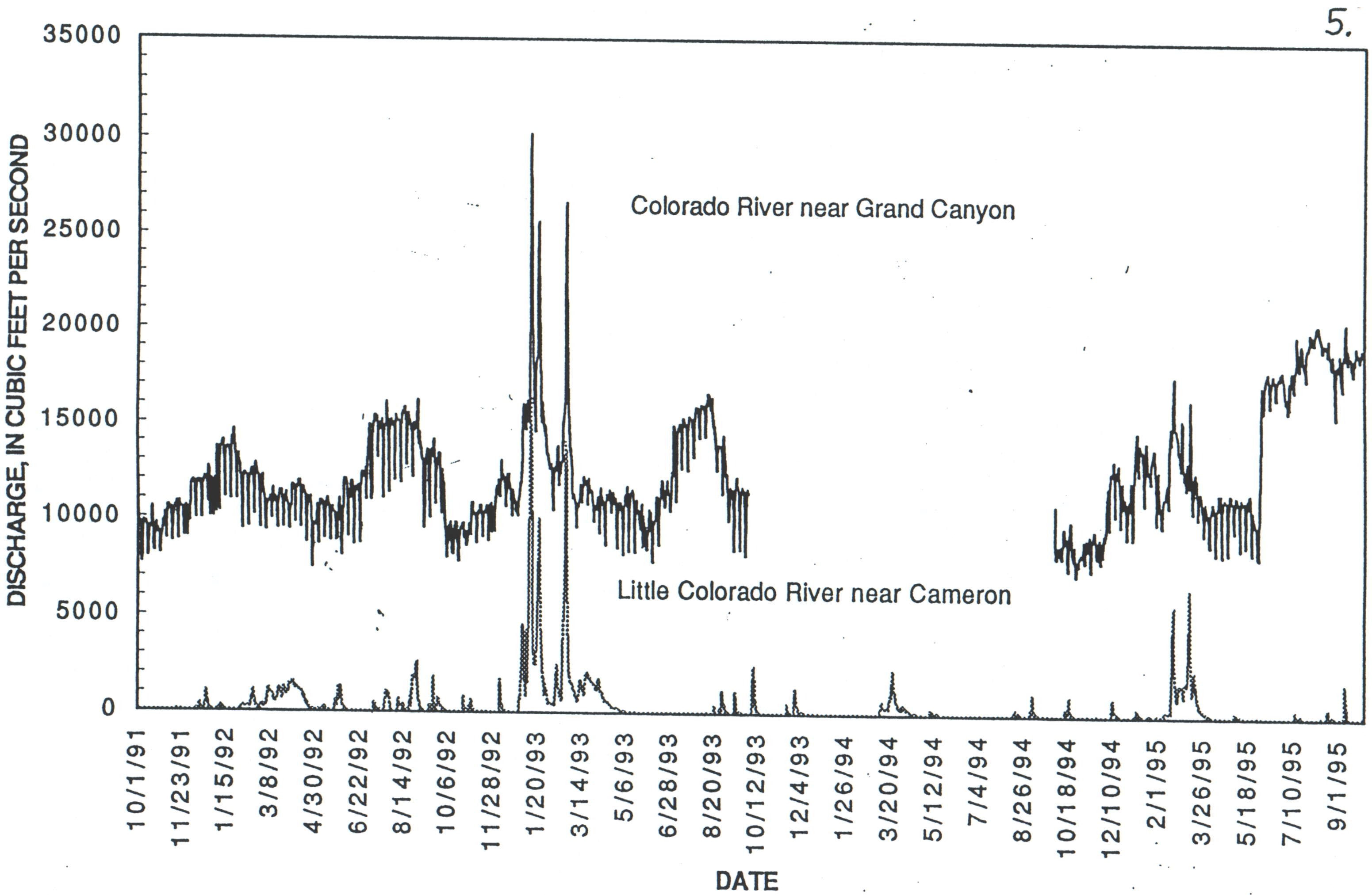
4a.



4b.



Mean Daily Discharge for Little Colorado River near Cameron, Arizona and Colorado River near Grand Canyon, Arizona



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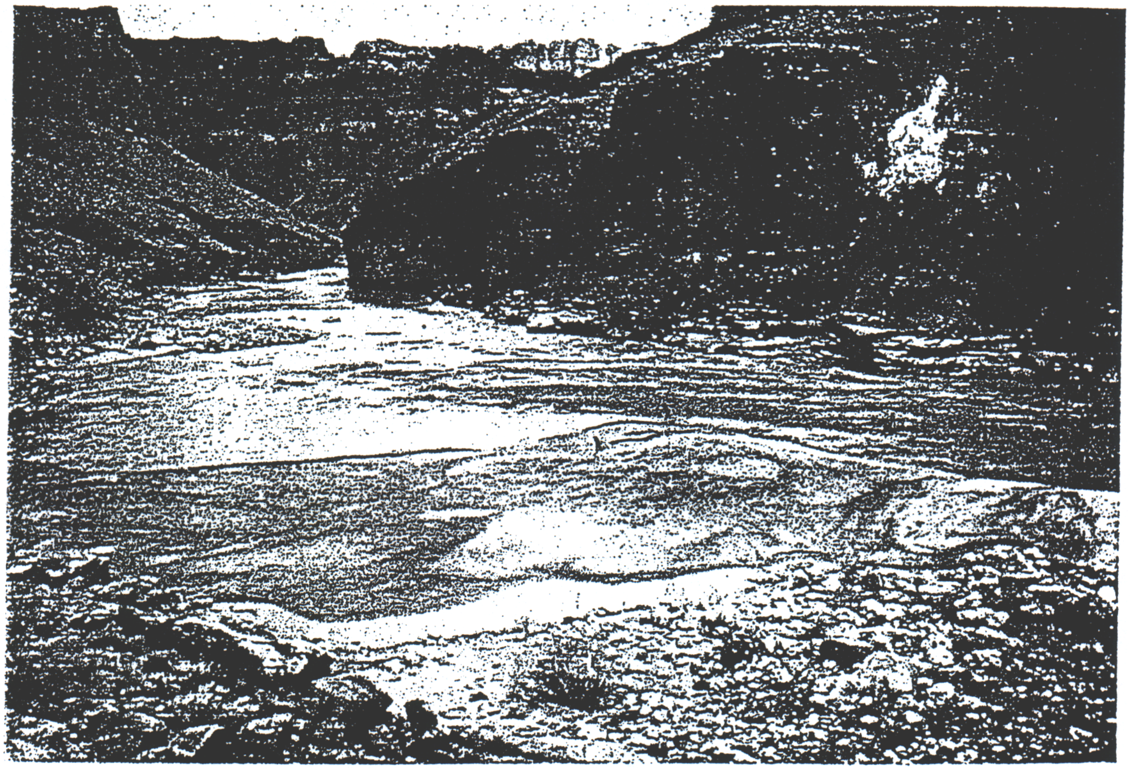


Figure 7. -- Overlay of erosion and deposition measured by topographic survey and surficial geologic map. Topography was measured April 5, 1993 and February 21,1996. Surficial geologic maps were made from air photos taken May 30, 1993 and March 24, 1996.

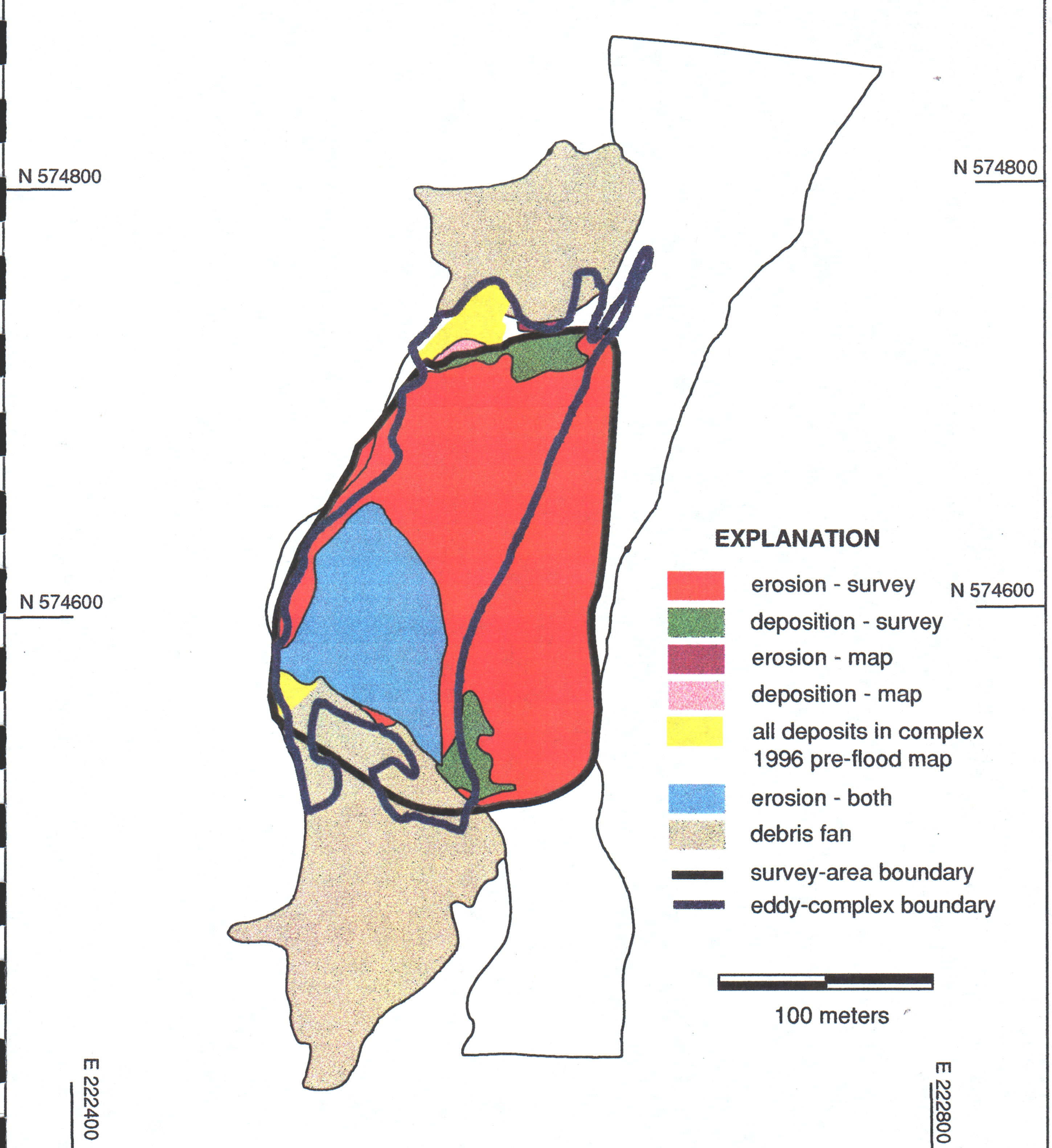
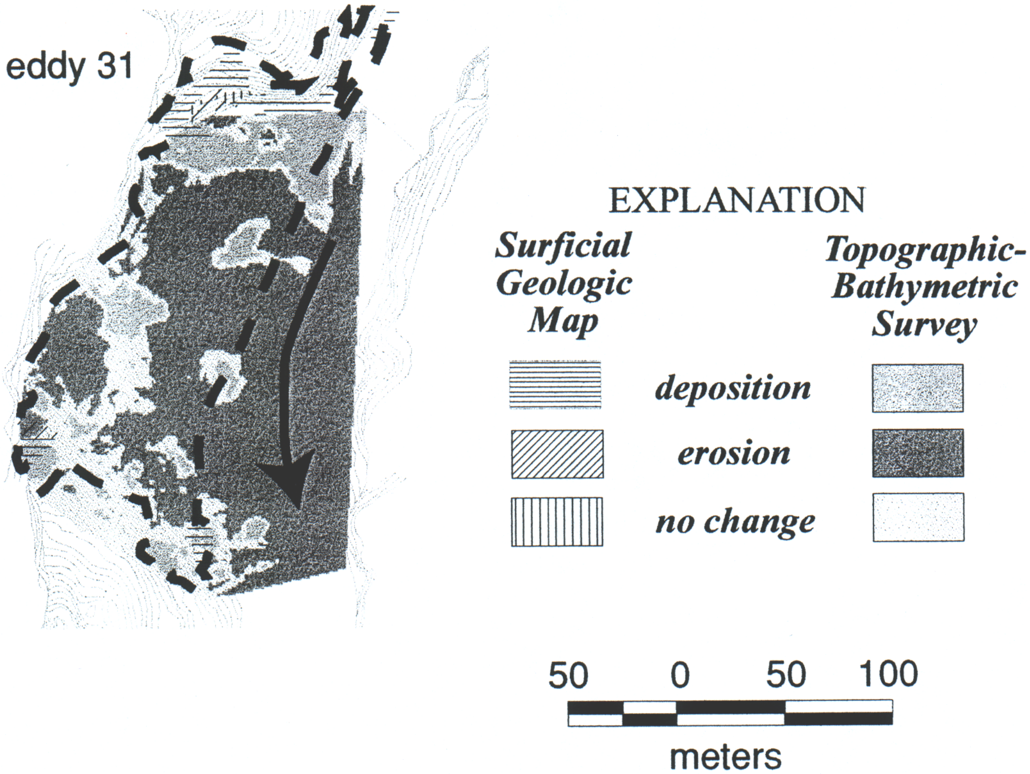
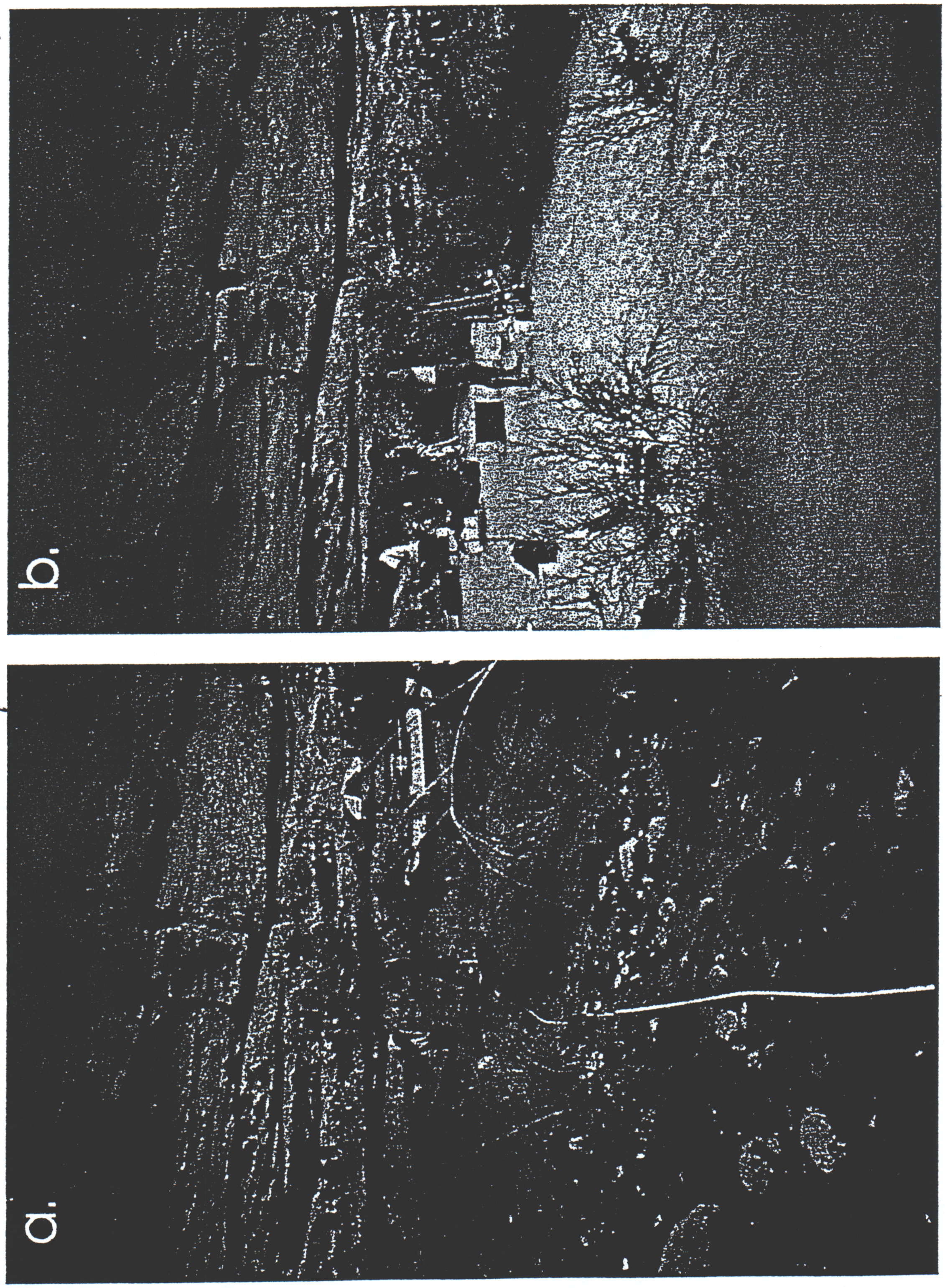
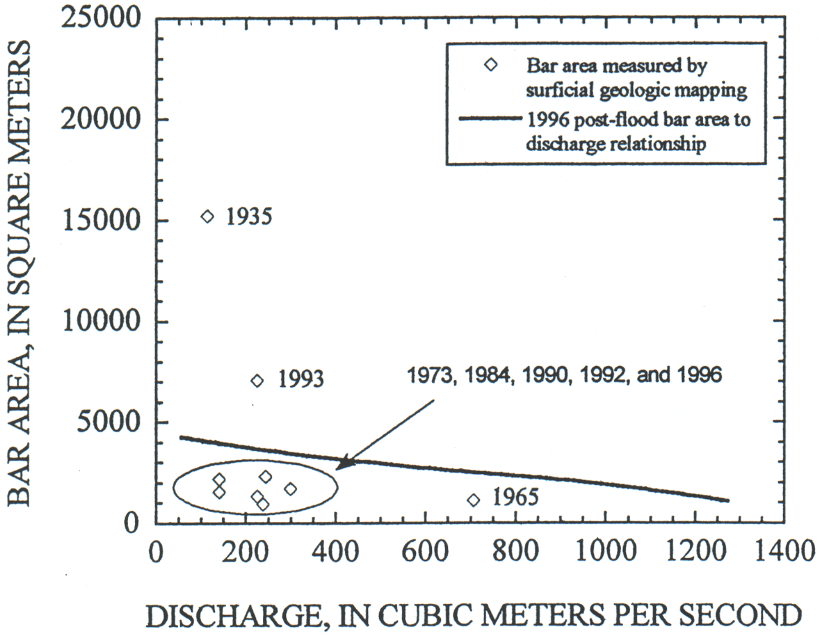


Figure 8.


eddy 31
EXPLANATION
Surficial Geologic Map
Topographic-Bathymetric Survey
deposition
erosion
no change
50
0
50
100
meters

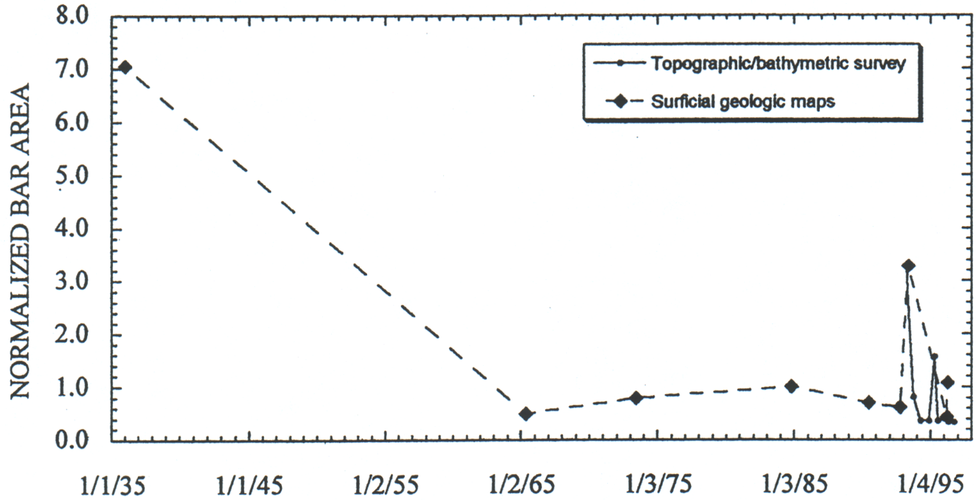

b.
a.

10.



25000
20000
15000
10000
5000
0
BAR AREA, IN SQUARE METERS
0
200
400
600
800
1000
1200
1400
DISCHARGE, IN CUBIC METERS PER SECOND
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1935
1993
1965
1973, 1984, 1990, 1992, and 1996

11.



8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
NORMALIZED BAR AREA
Topographic/bathymetric survey
Surficial geologic maps
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95

E. Palisades Detailed Site Report

ABSTRACT

The Palisades site includes a separation bar and a reattachment bar that form in the eddy that is on the left bank downstream from Lava Canyon Rapid. Oblique and aerial photographs from 1890, 1935, and 1963 show that the extent of high-elevation open sand was much greater in the pre-dam era. Most of the deposits that were open high-elevation sand are now vegetated terrace-like deposits. The area of the reattachment bar exposed at low discharges following post-dam floods is similar to the area of the reattachment bar exposed at similar low discharges in pre-dam photographs. Deposition of high-elevation sand during post-dam floods occurs primarily on the separation bar. Most of the reattachment bar is low-elevation sand, within the range of powerplant operations. High-elevation sand deposited at the reattachment bar is quickly eroded. Waves enhance the rate of erosion at this site. During the 1996 BHBF, scour occurred in the channel adjacent to the eddy and deposition occurred in the eddy.

INTRODUCTION

Site Description

Debris fans at the mouths of Palisades Creek and Lava Creek constrict the Colorado River, forming Lava Canyon Rapid at RM 65.5. The sand bars downstream from this rapid on the left bank have been called the Palisades (Yeatts, 1996), or Tanner Mine (Howard, 1975) study site (Fig. 1). The site is located in the upstream part of the 'Furnace Flats' geomorphic subreach (Schmidt and Graf, 1990), which is characterized by a relatively steep slope and a wide, gravel-bed channel that occurrs in an open valley formed in the erodible sandstones, shales, and siltstones of the Dox Fomation. The eddy that extends downstream from the Palisades Creek fan on the left bank is long and narrow and typically contains both a separation bar and a reattachment bar. Downstream from the rapid, the course of the river is straight and the eddy is not confined by the presence of downstream gravel bars or debris fans.

It is widely recognized that eddy-deposited sand bars are persistent landforms, because the debris fans that cause eddies are persistent features (Schmdt and others, 1995). The Palisades Creek and Lava Canyon fans are localities where both the long-term presence of debris-flow deposits and modern debris flow activity have been thoroughly documented. Hereford and others (1995) mapped surficial geology in the vicinity of Palisades Creek and differentiated three different fan-forming debris-flow deposits based on relative topographic position and surface-weathering characteristics (Fig 1). Based on stratigraphic correlations with dated alluvial deposits, these fan surfaces were deposited in at least three episodes between 770 B.C. and A.D. 1890 (Hereford and others, 1995). Modern debris flow activity in this area has been documented by Webb and others (1989) who concluded that channelized debris flows occur in Lava Canyon every 20 to 30 years based on radiocarbon dates of organic material collected from debris-flow levee deposits. Melis and others (1995) documented several channelized debris flows at Palisades Creek in the last century using historical photography. Hereford (1993) argued that channelized debris flows are distinct from fan-forming debris flows in that they are confined to an incised channel and do not add material to the fan surface although they may add material to the fan margin and the river channel affecting the characteristics of the rapid.

The long-term persistence of alluvial depositional sites downstream from the debris fan at Palisades Creek was also documented by Hereford (1993). Fine-grained sediments record more than 1000 yrs of deposition downstream from the Palisades Creek fan, although many of the older deposits have been reworked by wind. The oldest alluvial deposits are the pre-historic striped alluvium and alluvium of Pueblo-II age, which are at least 1500 and 800 yrs old, respectively (Hereford, 1993). Historic pre-dam deposits mapped by Hereford (1993) include the upper mesquite terrace, which is interpreted to have been deposited prior to 1880 by floods whose peak flow may have been between 300,000-500,000 ft^3/s; the lower mesquite terrace, which is interpreted to have been deposited by floods that occurred in the late 1800s and early 1900s whose peak flow was between 100,000-300,000 ft^3/s; and the pre-dam alluvium, which is lower than the mesquite terraces, higher than any post-dam flood deposits, and vegetated by saltcedar rather than mesquite. Hereford (1993) noted a lack of depositional record for the period between dam closure (1963) and the largest post-dam flood (1983) due either to lack of deposition or erasure of those deposits by the 1983 flood. Schmidt and Leschin (1995) developed map units consistent with Hereford's (1993) map units for post-dam deposits.

Additional post-dam geomorphic modifications described by Hereford (1993) include incision and extension of arroyos between 1973 and 1984, based on analyses of aerial photographs. Existing arroyos were rejunivated and extended, and some new arroyos were formed. This erosion of pre-dam alluvial deposits contributed to destruction of archeologic sites. Although high rainfall and runoff that occurred between 1978 and 1984 were the immediate causes of erosion, Hereford (1993) concluded that the process was exacerbated by reduced baselevel due to reduced height of Colorado River alluvial deposits. In the pre-dam era, arroyo cutting was probably interupted by large floods that deposited high-elevation sand bars and filled in arroyos, thus raising their baselevel (Hereford, 1993).

AVAILABLE MONITORING DATA

Campsite inventories made in 1973, 1983, 1991, and 1996 have monitored the carrying capacity of the primary campsite, which is the high-elevation portion of the separation bar (Fig. 2a). Formal monitoring was initiated at this site by Howard (1975) who established two profiles across the separation bar (Fig. 1). These profiles were reoccupied 5 times between 1980 and 1986 (Table 1). These data were summarized by Kyle (1992). Topographic maps of the reattachment bar were surveyed in January and October 1991 (J.C. Schmidt, personal communication). A small area of the downstream end of the separation bar was included in detailed surveys made in 1996 before and after the BHBF to measure erosion and deposition in the vicinity of archeological sites (Yeatts, 1996).

Schmidt and Leschin (1995) and Leschin and Schmidt (1996) mapped the exposed area of the separation and reattachment bars from aerial photographs taken between 1935 and 1996 (Table 1). Historical oblique photographs taken as early as 1891 also illustrate the pre-dam condition of this site (Melis and others, 1995).

The detailed bathymetry of the reach was mapped by Graf and others (1995a). Graf and others (1995b) also established 5 monumented channel cross sections, 3 of which cross parts of the reattachement bar (Fig. 1). Nine repeat measurements were made at these cross sections between 1993 and 1996 (Graf and others, 1995b; Graf and others, 1997; Konieczki and others, 1997).

SEDIMENT STORAGE CHANGES

The earliest data that depict either of the sand bars downstream from Palisades Creek are photographs from the 1891 Stanton expedition (Table 1). These photographs show that a greater thickness of sand covered the bar in 1871 than in 1991 when the photograph locations were reoccupied. The extent of sand in the 1891 photograph was mapped by identification of stable features recognizable both in the field and on the photographs. Schmidt (written communication) developed map of the 1891 sandbar which is compared to the extent of the sandbar following the 1984 bypass releases (Fig. 2a), following the 1993 LCR flood (Fig. 2b), and following the 1996 BHBF (Fig. 2c). Following each of these post-dam floods, the low-elevation bar was as large or nearly as large as in 1891. However, only the 1983 flood caused any deposition on the higher-elevation portions of the bar (Fig. 2a). The extent of the sandbar that was subaerially exposed in the 1935 aerial photographs is also very similar to that shown in the 1891 photograph (Fig 3). The low-elevation bar fills the eddy to a similar degree, and there is a large area of unvegetated high-elevation sand. The area mapped as 'clean sand' from the 1935 photographs corresponds to the area mapped as 'low sand' from the 1891 photographs and the area mapped as 'upper sand' from the 1935 photographs approximately corresponds to the area mapped from the 1891 photographs as 'open sand with scattered boulders.' The 1935 aerial photographs do not provide sufficient detail to determine the elevation of the sand relative to present conditions. An oblique photograph taken from Cape Solitude in 1963 also shows a sand bar very similar to the bar shown in the 1891 and 1935 photographs. The area of upper-elevation sand is mostly unvegetated with the exception of one line of trees that separates the high-elevation sand from the lower bar. The 1965 aerial photographs do not show low-elevation sand due to high discharge, but do show the same line of trees on the edge of the high-elevation sand. Between 1965 and 1984 vegetation spread across the high-elevation sand. Deflation of this surface increased exposure of boulders on the sand bar indicating that the thickness of sand decreased.

The surveyed profiles (Howard, 1975; Beus and others, 1986) summarized by Kyle (1992) show net erosion between 1974 and 1986 (Fig. 4). This progressive erosion was interupted at profile 1, the upstream profile (Fig. 1), by deposition that occurred during the 1983 spillway flood (Fig. 5). The different response of the two profiles, which are located about 27 m apart, is likely related to their position within the recirculation zone. At discharges of about 1200 m^3s^{-1}, profile 1 is located at the downstream end of a secondary eddy and profile 2 is at the upsream end of the primary eddy (Kyle, 1992). Thus profile 1 is more likely to be in a flow stagnation area and profile 2 is more likely to be in the path of the higher velocity eddy return current. Both profiles are located in an area where exposed cobbles and boulders may result in some armoring.

This site was not incorporated into the NAU sand-bar monitoring program (Kaplinski and others, 1995) but surveys were conducted over a limited area before and after the 1996 BHBF to monitor effects of that event on archeological sites (Yeatts, 1996). Because these surveys were designed to monitor changes in the vicinity of ephemeral washes, they only partially include the sand bar in the eddy. Less than 20 cm of erosion or deposition occurred over most of the surveyed area (Fig. 6). Up to 50 cm of deposition occurred over the survey area that measured the downstream end of the separation bar and 20-30 cm of deposition occurred over other small patches (Yeatts, 1997). Erosion occurred on the offshore edge of the survey area nearest the eddy center (Fig. 6).

Channel sediment-storage change is monitored in the vicinity of Palisades Creek by measurements made at 5 monumented cross sections (Graf and others 1995; 1997; Konieczki and others 1997). The cross sections that cross the reattachment bar (LE1,LE2, and LE3[Fig. 1]) show the high elevation bar that existed after the January 1993 Little Colorado River flood (Fig. 7). By February 1994, this bar had degraded about 2 m. Similar 'planing' of reattachment-bar surfaces was described by Bauer and Schmidt (199_) who attributed the phenomon to wave action. The varibility of the thalweg depth is minimal at all but cross-section LE2. This cross section was in a scoured condition in

Februay 1993 but had refilled by April 1993 (Graf and others, 1995). The channel was relatively stable between April 1993 and February 1996, during which time some sand was scoured from the vicinity of the thalweg. The largest change measured at this site occurred during the 1996 BHBF when 2-3 m of scour occurred across about one-third of the channel (Fig. 8).

Agreement of Measurement Methods

The locations of the bar profiles measured by Howard (1975) and Beus and others (1986) are not georeferenced. The approximate location of the profiles based on a location map provided by Kyle (1992) is indicated in Figure 2a. The areas covered by 1983 flood sand (fs) and 1984 high-flow sand (hf) as mapped by Leschin and Schmidt (1995) are also shown in Figure 2a. The profiles agree with the maps because they show deposition (above the 35,000 ft^3/s stage). However, the profiles do not extend away from the river far enough to show the full extent of the deposits. The profiles show erosion at the margins of the high-elevation sand between 1983 and 1986 (Fig. 4). The maps, on the other hand, indicate that most of the area of hf and fs deposits were still present in 1993 (Fig. 2b). Thus the separate measurements are not inconsistent, but neither method alone describes the changes completely.

The results generally agree where the survey data collected for the BHBF overlap with the surficial geologic maps of BHBF deposits (Schmidt and Leschin, 1996). The area of deposition shown by the survey coincides with the larger area of deposition on the separation bar and the strip of erosion shown by the survey is partially adjacent to the area of erosion shown in the map (Fig. 6). Although overlap is minimal, the results appear consistent.

The surveyed channel profiles also agree with the surficial geologic maps made from air photos. Channel cross section LE2 crosses the middle of the reattachment bar, which was mapped as an area of significant deposition of EF deposits (Fig. 2c). Cross section LE2 (Fig. 7) also shows deposition at the bar, although the thickness of the new deposit at the bar crest was not measured.

The subtle differences between depositional units are often difficult to distinguish from aerial photographs. The consistency of deposit identification can be evaluated by comparison between the surficial geologic maps of Schmidt and Leschin (1995) and the surficial geologic maps of Hereford (1993). Hereford's (1993) maps were prepared with a more detailed base map and include much more detail for the pre-dam alluvial deposits and tributary deposits, which were not the focus of the maps of Schmidt and Leschin (1995). Both maps, however, describe multiple levels of post-dam deposition; 1983 flood sand (fs), 1984 high-flow sand (hf), and fluctuating-flow level sand (ff). Overlay of the two maps for the area downstream from Palisades Creek shows consistency in the identification of the level of the hf and fs deposits (Fig. 1). The area mapped as fs by Hereford (1993) is smaller than the area Leschin and Schmidt (1995) mapped as fs. Hereford (1993) excluded areas that were mixed sand and gravel that Schmidt and Leschin (1995) included in the fs unit. Hereford (1993) also excluded coppice dunes on the fs deposit that Leschin and Schmidt (1995) mapped simpley as fs. In short, the identification of deposit levels seems consistent and most descrepencies arise from the more detailed mapping by Hereford (1993).

CONCLUSIONS

The persistence of the eddy-deposited sand bars downstream from the Palisades Creek fan is established by the rich record of historical oblique and aerial photographs that is available. These photographs demonstrate (1) that the low-elevation portions of the separation and reattachment bar have been as large in area during the post-dam era as they were during the pre-dam area, (2) that these parts of the bar are probably lower in elevation now than in the pre-dam era, and (3) that upper-elevation portions of the bar now covered by vegetation were bare sand in 1963 and earlier. Post-dam monitoring has shown that deposition during spillway and bypass releases can increase the area of the bar to approximately pre-dam size. The height of the post-dam flood deposits relative to pre-dam deposits is not known. Most of the higher elevation parts of the bar that were bare sand in 1890, 1935, and 1963 are now vegetated sand that were not inundated by bypass flows and only partially inundated by the 1983 spillway releases. Thus the most significant impact operation of Glen Canyon Dam has at this site is lack of deposition during periods that lack floods and lack of high-elevation deposition due to low peak flow magnitude.

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FIGURE CAPTIONS

Figure 1. Map showing Palisades Creek debris fan and vicinity. Alluvial deposits are those mapped by (a) Schmidt and Leschin (1995) from 1984 aerial photographs and (b) by Hereford (1993). The deposits labeled 'hf' and 'fs' are high-elevation sand, deposited by bypass and spillway releases, respectively. Deposits labeled 'ff' are deposited with the range of powerplant operations (see Hereford [1993] for a complete description of map units). Locations of sand-bar profiles established by Howard (1975) and cross sections established by Graf and others (1995b) are also indicated. Bathymetry is by Graf and others (1995a).

Figure 2. The sand bar downstream from Palisades Creek as mapped from 1890 Stanton photograph and as mapped from aerial photographs taken in (a) 1984, (b) 1993, and (c) 1996 post-BHBF. Spillway deposits (fs) are mapped in light red; bypass deposits (hf) are mapped in red; powerplant (ff) deposits are mapped in green; 1993 Little Colorado River flood deposits (lc) are mapped in orange; 1996 BHBF (ef) deposits are mapped in yellow; and tributary debris fans (df) are mapped in gray. The areas mapped as upper-elevation and low-elevation open sand from the 1890 photograph are indicated.

Figure 3. The sand bar downstream from Palisades Creek as mapped from 1890 Stanton photograph and as mapped from 1935 aerial photographs. Low-elevation bare sand is mapped in yellow and high-elevation open sand is mapped in red. The areas mapped as upper-elevation and low-elevation open sand from the 1890 photograph are indicated.

Figure 4. Thickness of sand averaged across sand bar profiles between 1974 and 1986. Values are normalized to the 1974 values.

Figure 5. Survey of profile 1 between 1974 and 1986 showing deposition by 1983 flood and progressive erosion between 1983 and 1986. The stage-discharge relationship is shown on the right axis.

Figure 6. Comparison between erosion and deposition as measured by repeat mapping from aerial photographs (Leschin and Schmidt, 1996) and by repeat topographic surveys (Yeatts, 1997). Horizontal and diagonal shading are areas of deposition and erosion, respectively, as measured by aerial photographs. Green, red, and blue are areas of deposition, erosion, and no significant change (< 20 cm change) as measured by repeat survey.

Figure 7. Repeat measurements of channel cross-section LE 1 between 1993 and 1994 (Graf and others, 1995b). Deposition by the January 1993 Little Colorado River flood on the river left sand bar is shown.

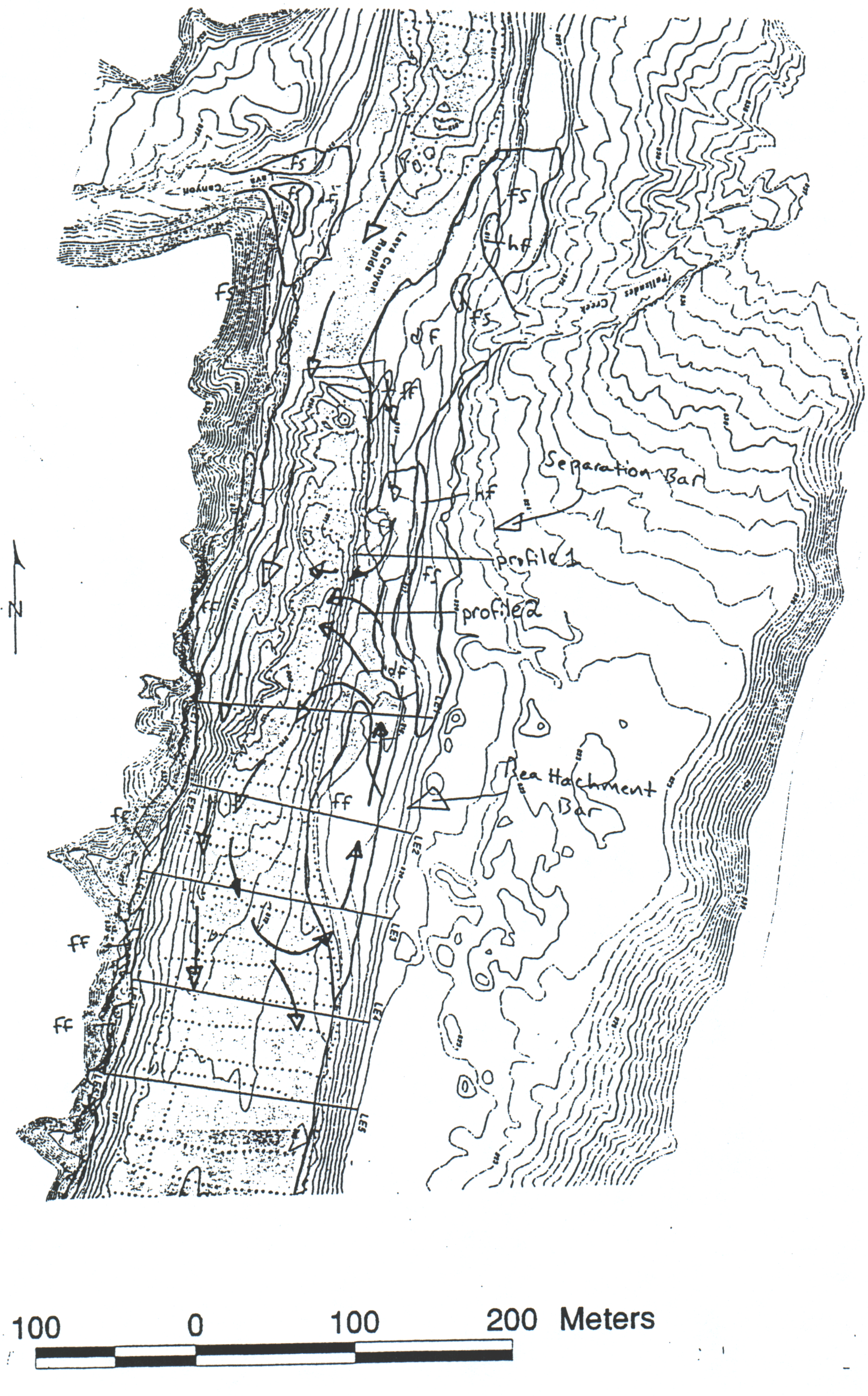
Figure 8. Channel cross-section LE 2 before and after the 1996 BHBF (Konieczki and others, 1997). Shows scour in thalweg and deposition on river left sand bar.

Table 1. Monitoring data available for separation and reattachment bars downstream from Palisades Creek debris fan (RM 65.5 L).

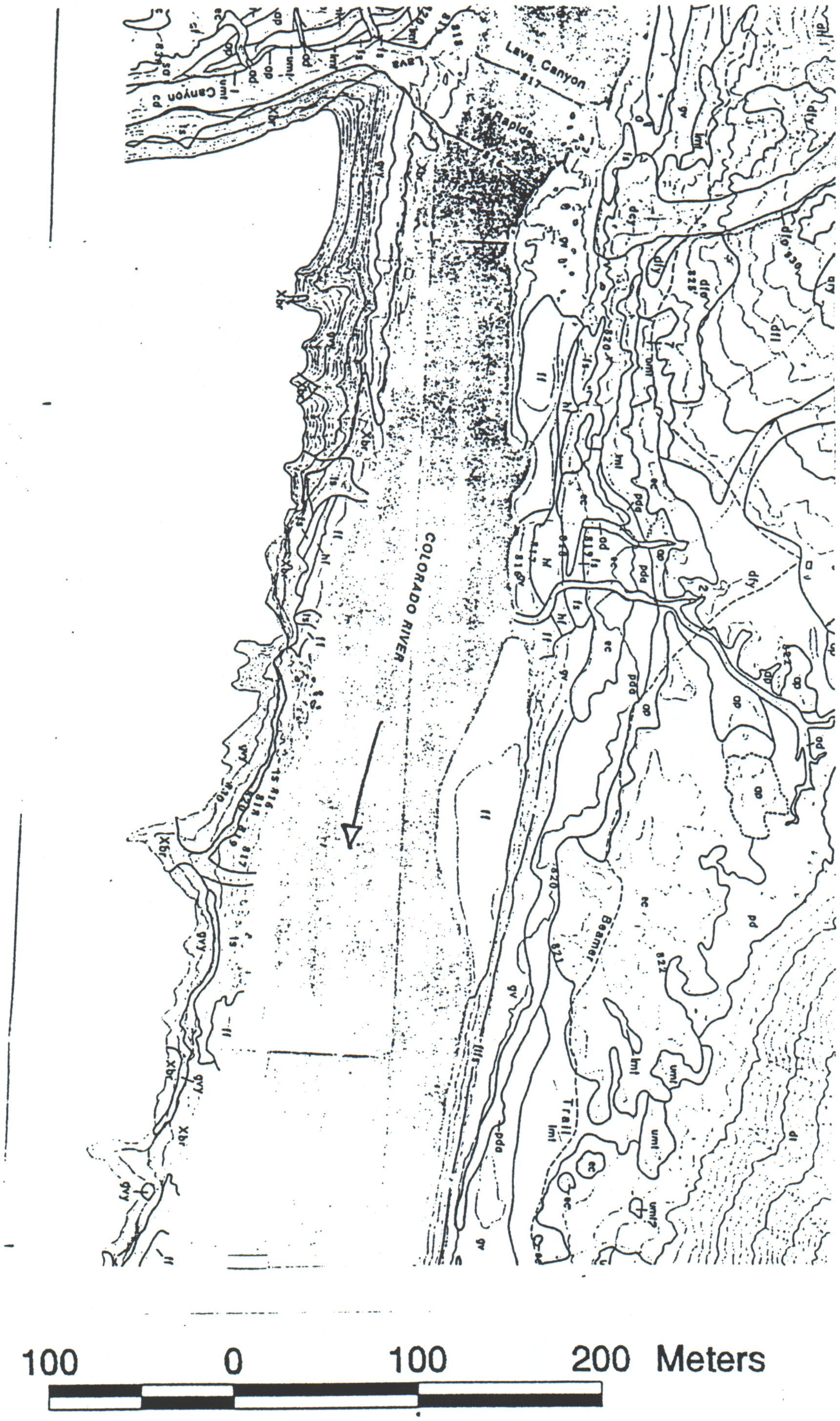
Date	Type of Data
8/25/1872	Hillers photo 858 (Stake 1080)
1/22/1890	Stanton photo 387 (Stake1436)
1/22/1890	Stanton photo 388 (Stake 1437)
8/14/23	LaRue photo 406 (Stake 1092)
8/14/23	LaRue photo 407 (Stake 1707a)
8/14/23	LaRue photo 408 (Stake 1570)
8/14/23	LaRue photo 409 (Stake 1707b)
12/31/35	surficial geologic map
10/?/37	Sharp photo (Stake 2358)
7/19/41	Heald 3:06:09 (Stake 2733)
7/19/42	Wilson photo 4:07:11 (Stake 2734)
6/25/59	Reilly photo L44-26 (Stake 2026)
7/13/63	Blaisdell photo (Stake 4283)
5/14/65	surficial geologic map
9/9/68	Hillers photo 858 (Stake 1080)
6/29/72	Hillers photo 858 (Stake 1080)
1973	Weeden I-90 (Stake 2344)
1973	Weeden I-91 (Stake 2345)
1973	Campsite inventory
6/16/73	surficial geologic map
6/20/74	Bar profile Survey (2)
7/26/74	LaRue photo 407 (Stake 1707a)
6/22/80	Bar profile Survey (2)
10/11/82	Hillers photo 858 (Stake 1080)
1983	Campsite inventory
8/1/83	Bar profile Survey (2)
10/22/83	Hillers photo 858 (Stake 1080)
10/22/83	LaRue photo 406 (Stake 1092)
8/4/84	Bar profile Survey (2)
10/21/84	surficial geologic map
8/4/85	Bar profile Survey (2)
8/1/86	Bar profile Survey (2)
1/23/90	Hillers photo 858 (Stake 1080)
1/24/90	Stanton photo 387 (Stake1436)
1/24/90	Stanton photo 388 (Stake 1437)
1/26/90	Melis (Stake 1431)
1/27/90	sand bar topographic survey
6/30/90	surficial geologic map
10/22/90	sand bar topographic survey
11/22/90	LaRue photo 407 (Stake 1707a)
1991	Campsite inventory
2/6/91	LaRue photo 408 (Stake 1570)
8/6/91	Reilly photo L44-26 (Stake 2026)
8/6/91	Weeden I-90 (Stake 2344)
8/6/91	Weeden I-91 (Stake 2345)
8/7/91	Sharp photo (Stake 2358)
10/10/91	LaRue photo 407 (Stake 1707a)

Date	Type of Data
10/10/91	LaRue photo 409 (Stake 1707b)
10/11/92	surficial geologic map
2/1/93	channel cross sections
2/25/93	Wilson photo 4:07:11 (Stake 2734)
2/25/93	Heald 3:06:09 (Stake 2733)
4/24/93	channel cross sections
5/30/93	surficial geologic map
9/17/93	channel cross sections
2/2/94	channel cross sections
5/3/94	channel cross sections
9/17/94	channel cross sections
4/26/95	channel cross sections
2/27/96	channel cross sections
3/24/96	surficial geologic map
1996	Campsite inventory
4/4/96	surficial geologic map
4/20/96	channel cross sections

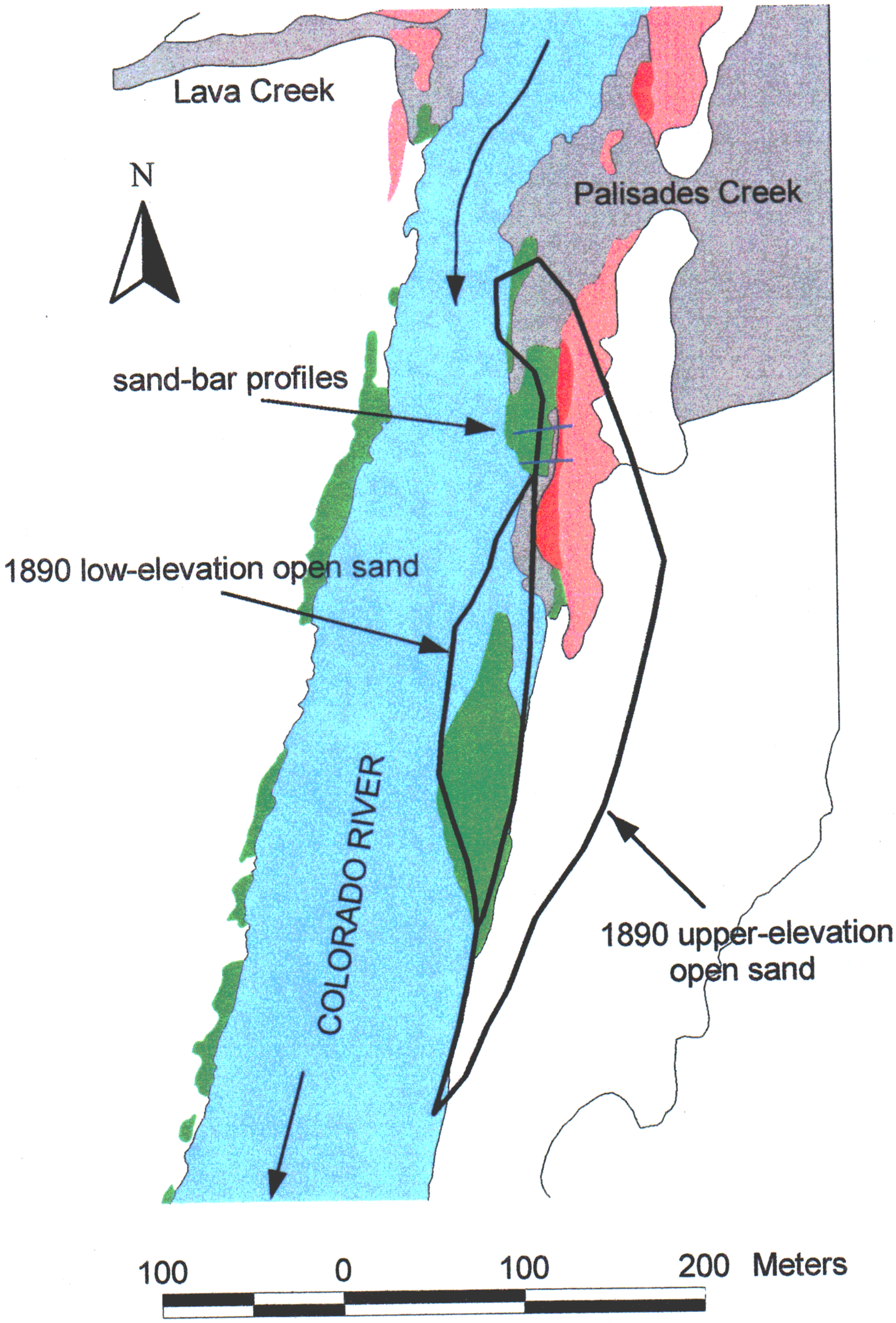
1a.

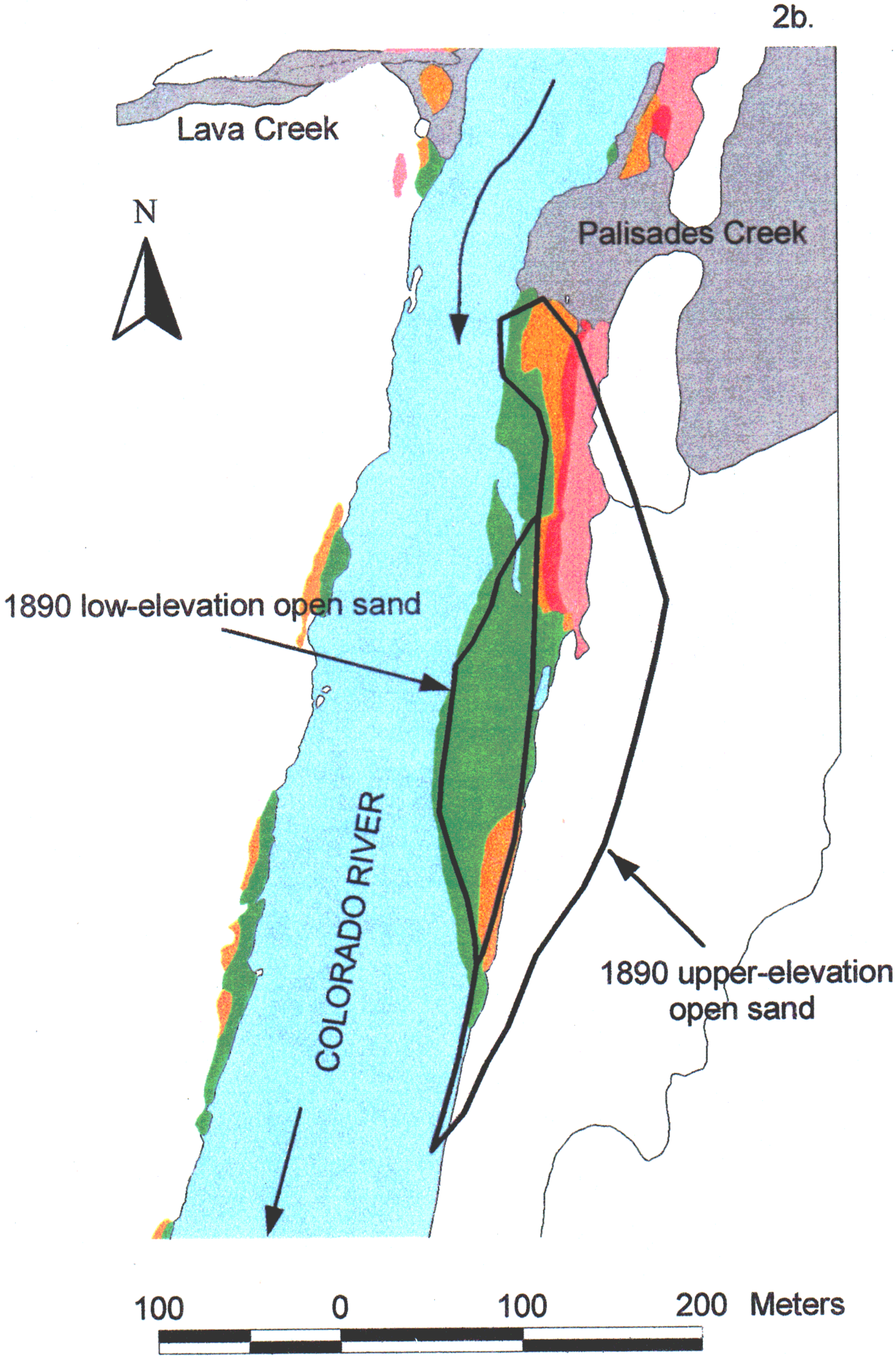

Lava Canyon
Lava Canyon Rapids
Palisades Creek
fs
ff
hf
dF
Separation Bar
profile 1
profile 2
Reattachment Bar
N
100 0 100 200 Meters

1b.

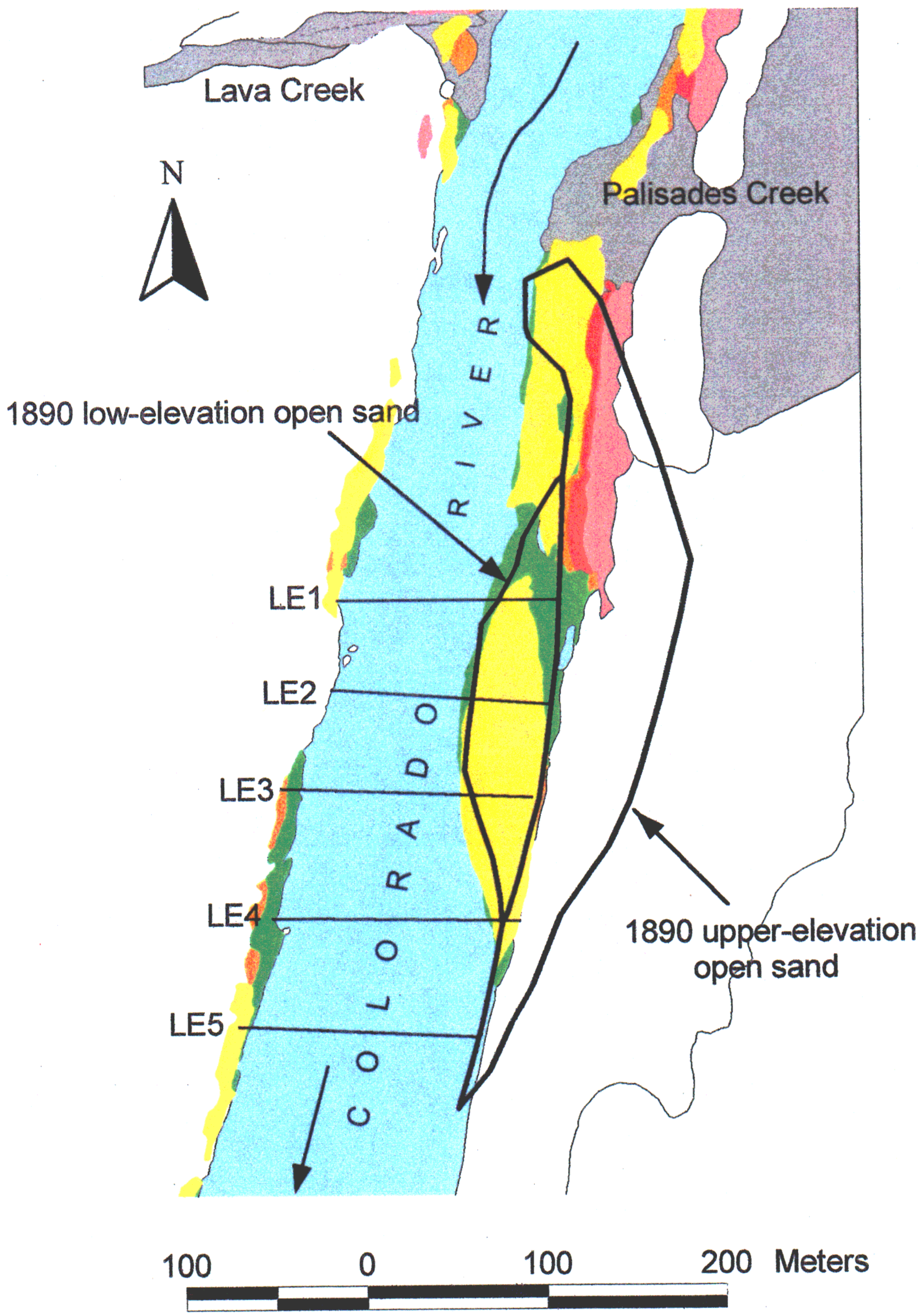

Lava Canyon
Rapids
COLORADO RIVER
Beamer
Trail
100
0
100
200 Meters

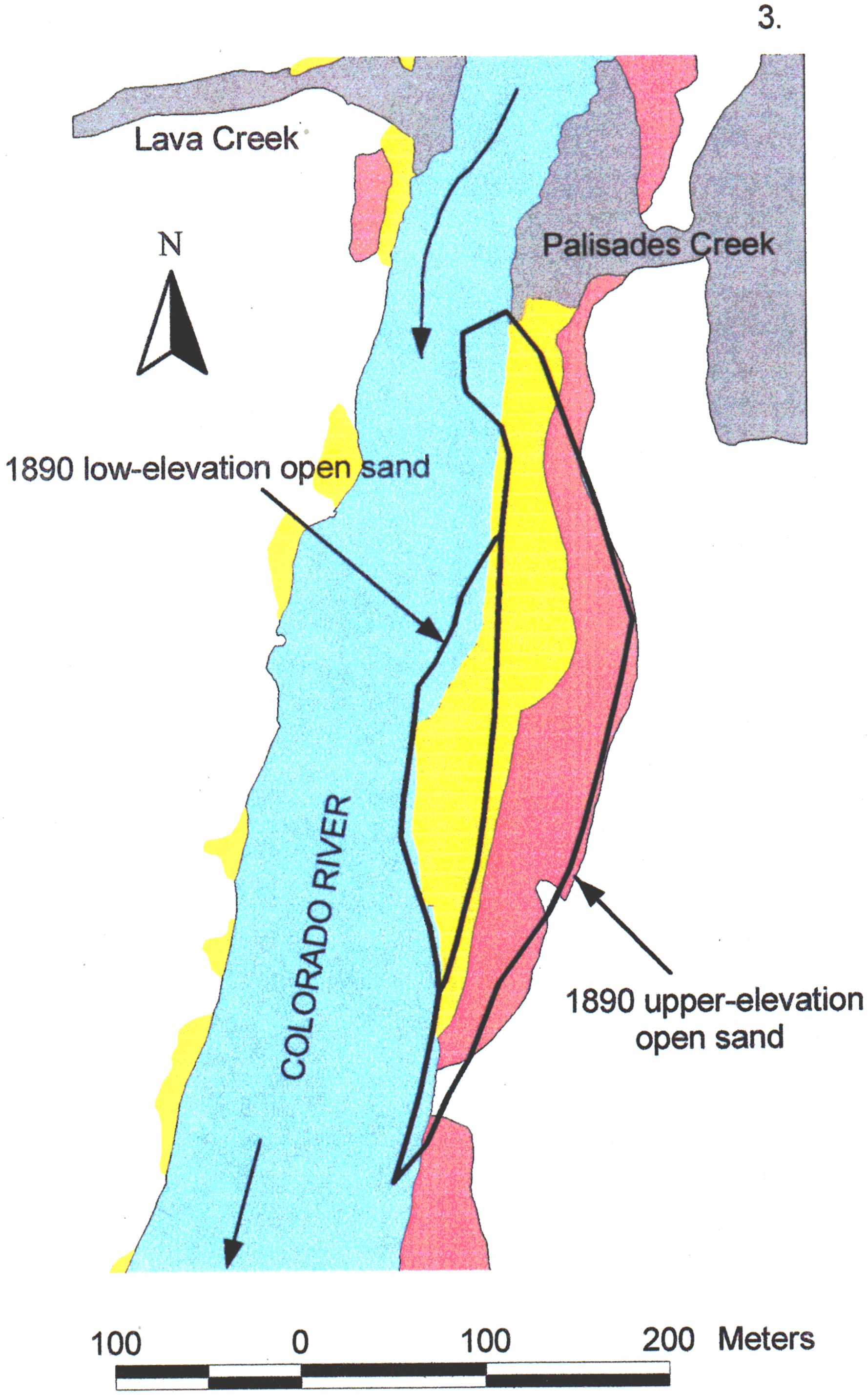
2a.


Lava Creek
Palisades Creek
N
sand-bar profiles
1890 low-elevation open sand
COLORADO RIVER
1890 upper-elevation open sand
100 0 100 200 Meters

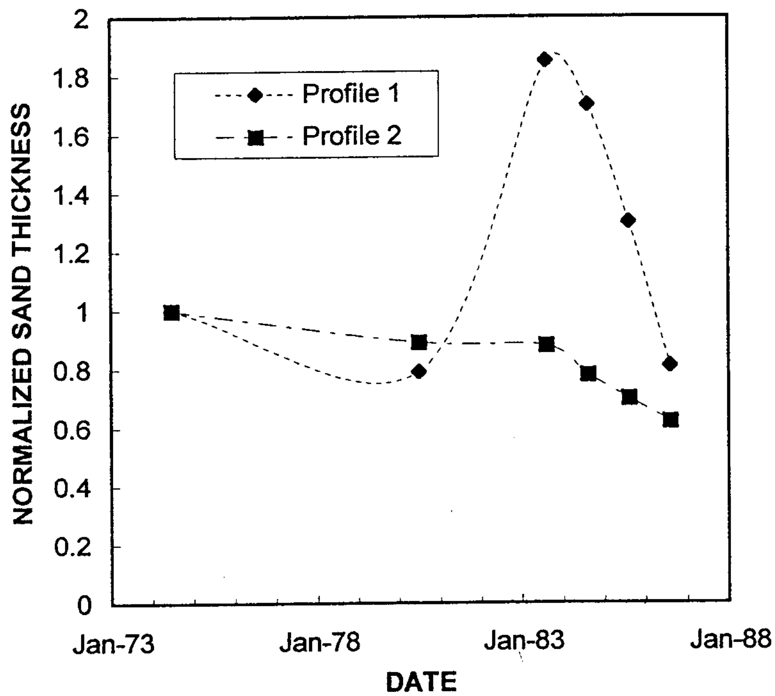

2b.
Lava Creek
N
Palisades Creek
1890 low-elevation open sand
COLORADO RIVER
1890 upper-elevation open sand
100 0 100 200 Meters

2c.

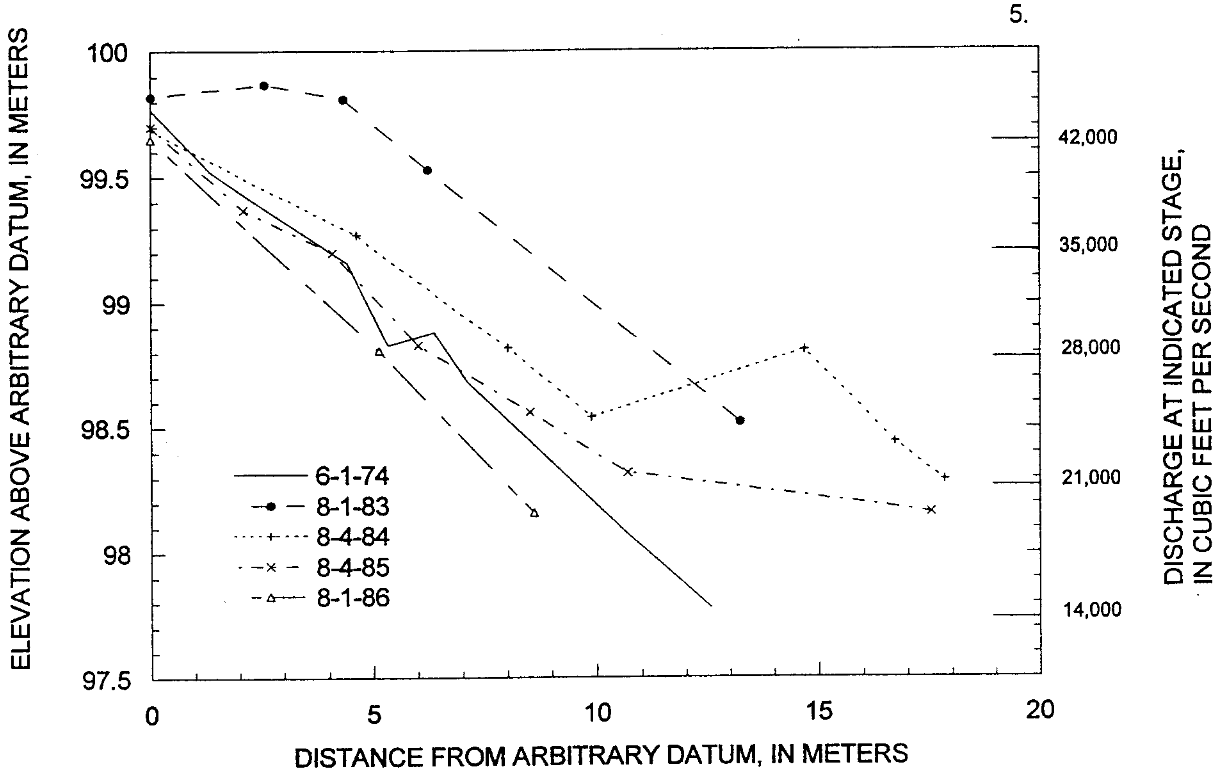

Lava Creek
N
Palisades Creek
1890 low-elevation open sand
R I V E R
LE1
LE2
LE3
LE4
LE5
C O L O R A D O
1890 upper-elevation open sand
100 0 100 200 Meters

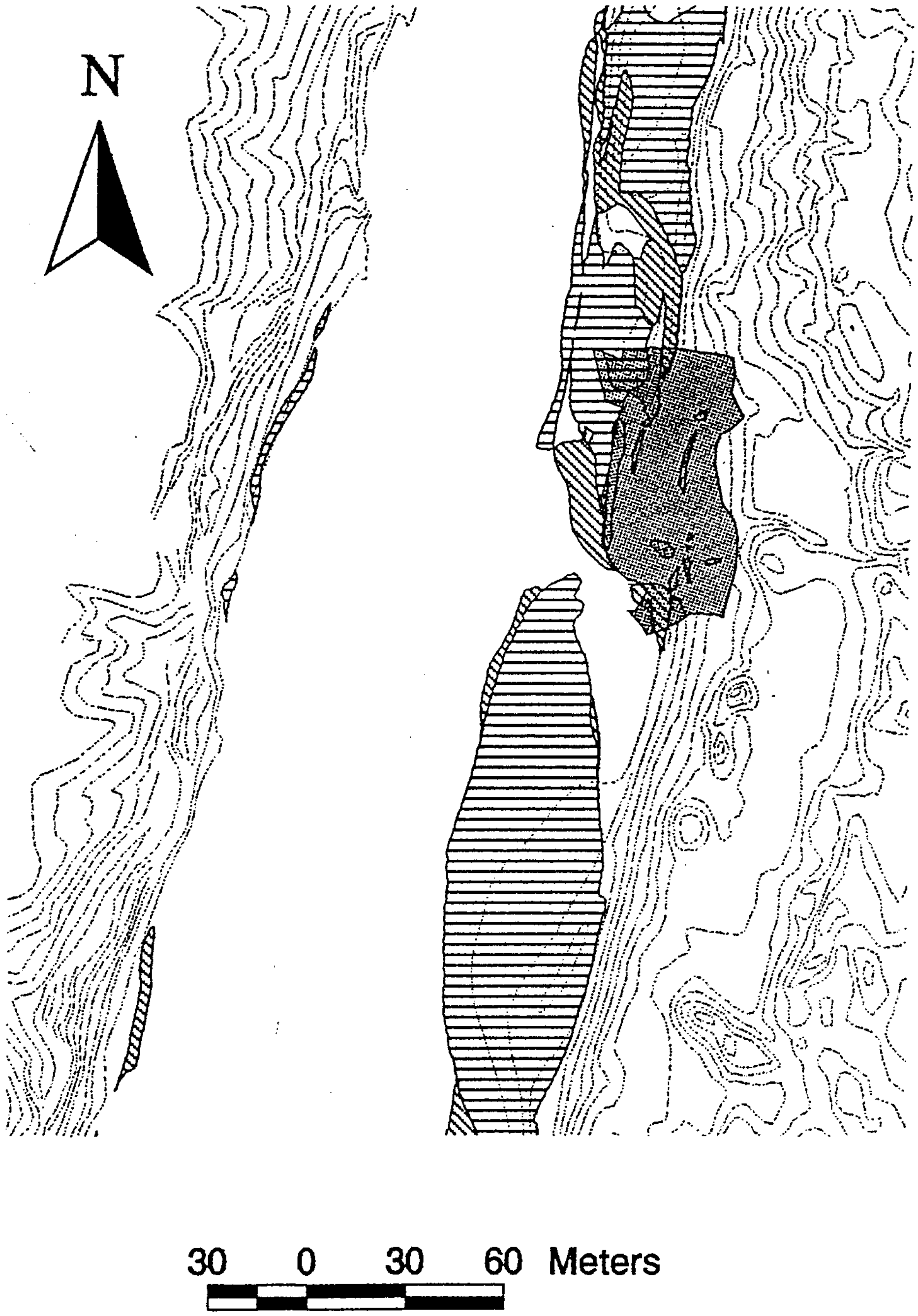

3.
Lava Creek
Palisades Creek
N
1890 low-elevation open sand
COLORADO RIVER
1890 upper-elevation open sand
100 0 100 200 Meters

4.

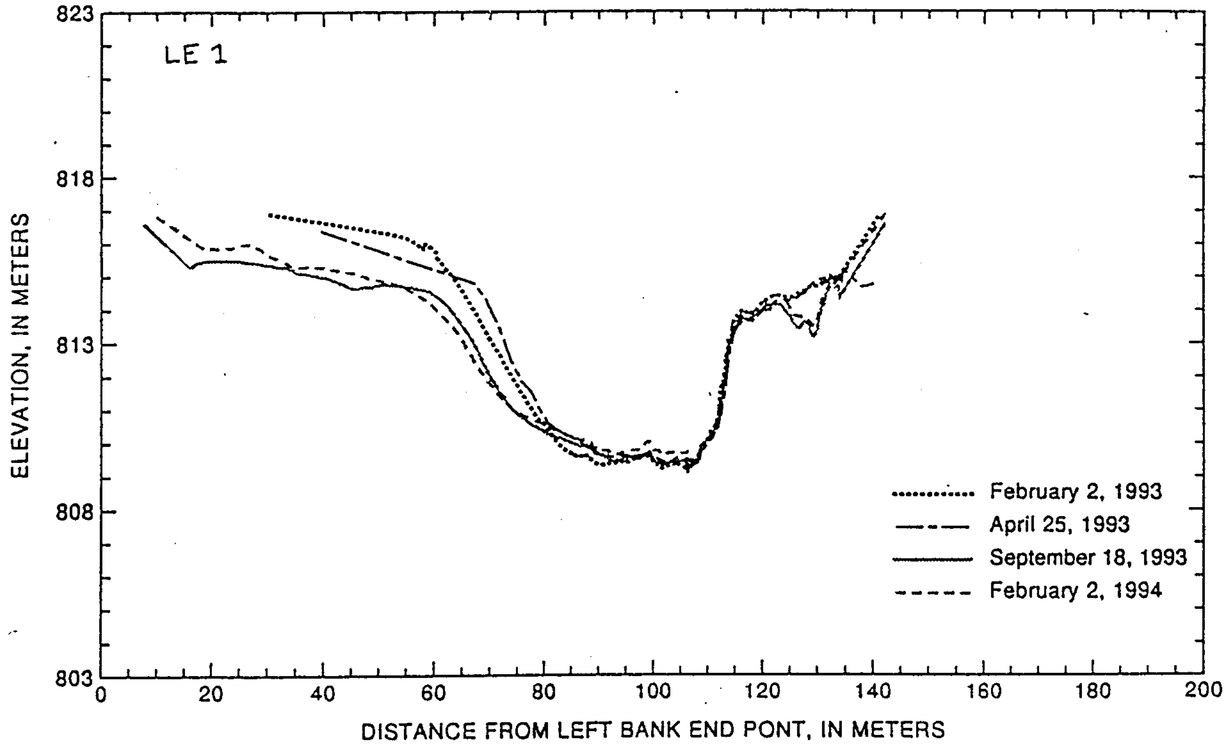


NORMALIZED SAND THICKNESS
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Profile 1
Profile 2
Jan-73
Jan-78
Jan-83
Jan-88
DATE

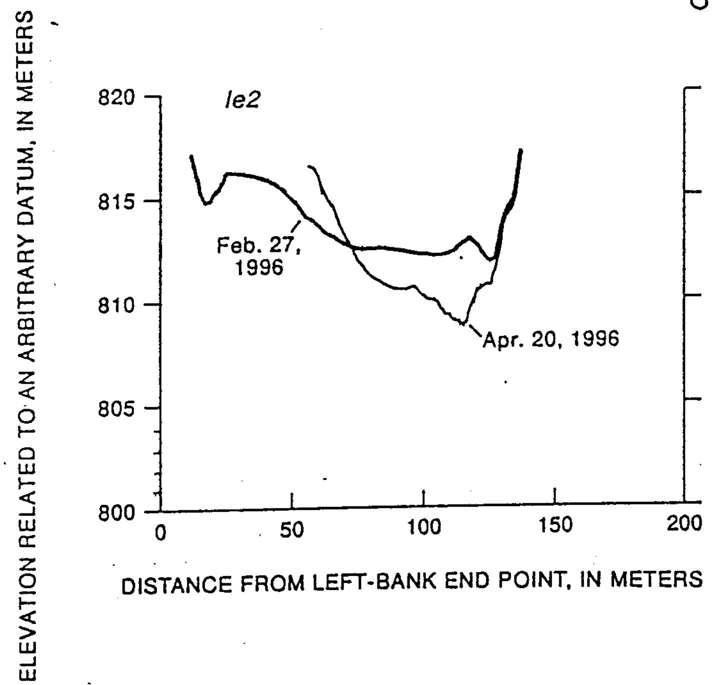

5.
ELEVATION ABOVE ARBITRARY DATUM, IN METERS
100
99.5
99
98.5
98
97.5
0
5
10
15
20
DISTANCE FROM ARBITRARY DATUM, IN METERS
DISCHARGE AT INDICATED STAGE, IN CUBIC FEET PER SECOND
42,000
35,000
28,000
21,000
14,000
6-1-74
8-1-83
8-4-84
8-4-85
8-1-86


N
30 0 30 60 Meters

7.


LE 1
823
818
813
808
803
0
20
40
60
80
100
120
140
160
180
200
ELEVATION, IN METERS
DISTANCE FROM LEFT BANK END PONT, IN METERS
February 2, 1993
April 25, 1993
September 18, 1993
February 2, 1994

8.



EXPLANATION

—— BEFORE CONTROLLED-FLOOD RELEASE —— AFTER CONTROLLED-FLOOD RELEASE

F. Tanner Detailed Site Report

ABSTRACT

The volume and area of sand stored within the eddy complex on river right upstream from Tanner Canyon, RM 68.4R, has been regularly monitored since 1990. Analysis of older photography provides a record of sand bar characteristics at this site beginning in 1935. These data demonstrate that the sand bar has been consistently present since at least 1935; the bar is stable or slowly erodes during periods that lack floods; and deposition typically occurs when the adjacent pool is filled with sediment derived from tributary floods. This bar was as large in 1984 as it was in 1935, demonstrating that post-dam deposition can form a bar as large as existed in the pre-dam era.

INTRODUCTION

Summary Characteristics of Site

1. This eddy occurs in the flow separation zone that forms in the lee of a large cobble bar on the inside of a tight bend, unlike typical debris-fan created eddy complexes in Grand Canyon.

2. The separation and reattachment bars are sometimes distinct, but sometimes merge to create a single continuous bar.

3. All methods used to measure sand bar area at this site have yielded consistent results. Agreement between areas of erosion and deposition measured by topographic map and air photo analysis is very good for most years the site was mapped by both methods.

4. The bar has been a persistent deposition site when mainstem suspended sediment concentrations are high or the adjacent channel is filled with sediment. The largest amount of deposition measured here occurred during summer 1993 following Little Colorado River floods that charged the reach with sediment.

5. Changes in the Tanner Canyon debris fan downstream increased the stage-discharge relation in the eddy and may have contributed to high rates of deposition in 1993 by enlarging the area of potential deposition.

this site in the past 100 yrs (Melis and others, 1995). The narrower constriction caused the stage-discharge relation in the pool above the rapid to increase by 1.0 to 1.5 m. Tributary streamflow immediately following the debris flow accomplished more debris-fan reworking than did mainstem flows between August and December 1993.

The 1996 experimental flood mobilized material in the debris fan resulting in significant debris-fan reworking. Webb and others (1996) measured a coarsening in the median diameter of debris-fan particles by about 80 percent, an increase in the constriction ratio of the rapid from 31 to 33 percent, a small decrease in the water surface slope through the rapid, and a decrease in the stage-discharge relation in the pool above the rapid by 0.2 m. Although some reworking did occur, these data show that two years of interim-flow operating criteria and one moderate flood were not sufficient to rework the fan and adjacent channel to pre-1993 debris flow conditions.

SAND-BAR MONITORING DATA

Available Monitoring Data

Monitoring data have been collected at RM 68.4R since July 1990. Detailed topographic and bathymetric surveys have been conducted by the Northern Arizona University sand bar monitoring program (Kaplinski and others, 1995; Hazel and others, 1997a; Hazel and others, 1997b). This database of topographic surveys is used to calculate sand bar area and volume relative to given stage elevations (Table 1). A pilot aerial photogrammetry project, the test-flow air photo study, produced maps of the area of exposed sand above 5000 ft^3s^{-1} from 10 air photo series taken between October 1990 and July 1991 (Cluer, 1992). Leschin and Schmidt (1995; 1996) mapped surficial geology of the reach including the sand bar at RM 68.4R, interpreting from several historic and recent air photo series (Table 2). These maps detail multiple depositional levels that allow calculation of areas of erosion and deposition (Table 1). Graf and others (1995a) mapped bathymetry for all of GIS Site 5 in 1992 and 1993. In a companion project, Graf and others (1995b; 1997) have completed repeat measurements of 5 monumented cross sections at RM 68.4R between February 1993 and present. This site is a frequently used campsite and is included in all campsite inventories (Weeden and others, 1975, Brian and Thomas, 1984; Kearsley and Warren, 1993; Kearsley and Quartaroli, 1997).

Agreement of Measurement Methods

Three different and independent methods have been applied to quantify changes in sand bar size at RM 68.4R between 1990 and present. The range of normalized values obtained by each of the measurement methods is comparable (Table 1). The values obtained by each method must be normalized because boundary areas and measurement techniques are different. The topographic/bathymetric survey data incorporate the most detailed measurements and allow calculation of the area of sand above the 5,000 ft^3s^{-1} stage elevation, regardless of the discharge at time of measurement. The air photos used for areal measurements were taken at similar discharges, usually during periods of steady flow. The evaluation discharge was 5,000 ft^3s^{-1} for 1990-91, and 8,000 ft^3s^{-1} for 1992-96; a correction was applied to account for this shift in the erosion-deposition calculations made from the surficial geologic maps (Schmidt and Leschin, 1995). The agreement between each of the air photo methods and the topographic surveys ranges from fair to good but is better for the surficial geologic maps (Figure 3) than for the test-flow air photo measurements (Figure 4). The slope of the best-fit correlation between the surficial geologic maps and the topographic surveys suggests that the surficial geologic maps consistently under-predict bar area.

Direct comparison of the measurements available in geo-referenced format provides the best means of evaluating agreement between methods. The results from four measurement intervals for topographic surveys and surficial geologic maps that had similar bracketing dates are compared in Figure 5. The greatest discrepancy between the results obtained from surficial geologic maps and topographic surveys is in the first interval compared, June 1990 to October 1992 (Figure 5a). Within the eddy complex, most of the area of erosion shown by the surficial geologic map overlaps with surveyed erosion. The thin strip of map-predicted erosion that overlies surveyed deposition is likely due to mapping error resulting from slight difference in discharge or the scale transformation process. Both show onshore erosion of the sand bar. The remaining comparisons (Figure 5b-c) show very good agreement for measurement areas that overlap.

SEDIMENT-STORAGE CHANGES

Time Series of Topographic Changes

Historic air photos show that the RM 68.4R eddy has been a persistent site of sand deposition. All measurements of sand bar area made by surficial geologic mapping and repeat topographic surveys (Table 1) were normalized to overlapping dates of measurement. The measurements of bar area made by surficial geologic mapping were first corrected for differences in discharge at the time of aerial photography. This correction was made by developing a relationship between bar area and discharge using the bar topography measured following the 1996 experimental flood (Figure 6). This curve was then moved up or down on the graph to intersect each plotted measurement of bar area. Then for each measurement, the bar area at 8,000 ft^3/s was determined as the intersection of the curve and a vertical line passing through 8,000 ft^3/s. The normalized size of the sand bar in each year for which air photography is available is plotted in Figure 7. The 1935 air photo, taken at about 4000 ft^3s^{-1}, shows a large sand bar and very little vegetation on either the sand bar or the adjacent gravel bar. The 1965 air photo, taken at about 25,000 ft^3s^{-1}, shows a similar area of high-elevation sand compared to 1935, although low-elevation sand cannot be compared due to the extreme discharge difference between the photos. The 1965 photo also shows a large increase in the extent of vegetation on the downstream end of the reattachment bar and along the boundary between the sand bar and the gravel bar. The 1973 air photo, taken at 10,000 to 15,000 ft^3s^{-1}, shows a continued increase in vegetation and corresponding decrease in the area of high-elevation sand. The 1984 air photo, taken at about 5,000 ft^3s^{-1}, shows less vegetation than the 1973 photo, indicating that the 1983 and 1984 spillway and bypass releases scoured vegetation. The size of the sand bar in 1984 is similar in size to the bar shown in the 1935 photo, which was also taken at low discharge.

Since 1984, large changes in sand-bar area have occurred during periods that include mainstem or tributary floods, while bar area fluctuated about a mean condition during periods that lack these floods (Figure 7). The January 1993 Little Colorado River flood (Figure 8) caused deposition in most bars in the reach downstream from the confluence (Schmidt and Leschin, 1995; Kaplinski and others, 1995). However, at RM 68.4R erosion by bank failure occurred on the descending limb of the flood hydrograph (Kaplinski and others, 1995) and up to 5 m of deposition occurred in the channel (Kaplinski and others, 1995; Graf and others, 1995). Channel cross sections surveyed by Graf and others (1995) show 1-3 m of deposition in the center of the channel and along the channel margin, near the sand bar monitoring site. Thus, while the flood resulted in a large net accumulation of sand in the reach, deposition did not occur in the eddy.

A large volume of deposition that greatly increased the area of the bar did occur later that summer, between the topographic measurements made April 6, and October 13, 1993 (Kaplinski and others, 1995). Photos from remote cameras show that this deposition occurred throughout the late summer and early fall (J.E. Hazel, personal communication, 1997). During the same interval that this deposition occurred on the sand bar, mostly below the 9,000 ft^3s^{-1} stage, erosion occurred in the adjacent pool (Kaplinski and others, 1995). This pattern is consistent with cross-section measurements that show scour in the center of the channel at each of the five sections in the reach between April 1993 and September 1993 (Graf and others, 1995). Redistribution of sediment from the pool to the sand bar may be related to several events that occurred that summer and fall. The August 22, 1993 debris flow from Tanner Canyon increased the stage of the pool by at least 1.0 m. This effectively increased the available sediment-storage capacity of the eddy, increasing the likelihood of a large sand bar (Hazel and others, 1997b). On October 6, 1993, a flood from the Little Colorado River of about 8800 ft^3s^{-1} caused an instantaneous peak discharge of about 17,500 ft^3s^{-1} on the Colorado River. This event very likely contributed significantly to the redistribution of sediment deposited in the channel by the earlier LCR flood and contributed additional sediment. During the October 1993 bar survey, the NAU survey party identified a mud drape at about the 17,000 ft^3s^{-1} stage that was deposited by this event (J.E. Hazel, personal communication, 1997). However, since much of the measured deposition occurred below the 9,000 ft^3s^{-1} stage, the summer 1993 high flows of about 17,000 ft^3s^{-1} may have been sufficient to redistribute the LCR flood sand.

There was a net decrease in the total area of exposed sand between October 1993 and February 1996 (Kaplinski and others, 1996). This period of erosion was interrupted by a depositional event that occurred between November 1994 and April 1995 (Figure 7). During this period, two LCR floods occurred, of 6,260 and 7,700 ft^3s^{-1}, respectively.

Deposition during the 1996 experimental flood was measured by repeat topographic/bathymetric surveys and by repeat surficial geologic maps from pre- and post-flood air photos. Both methods measured deposition across most of the sand bar and erosion along the margin of the sand bar towards the channel (Figure 5d). The amount of deposition that occurred during the experimental flood was much less than the amount that occurred in 1993.

Generalized Response to Floods

The time series of sand-bar area (Figure 7) shows that deposition has occurred at this site in response to nearly all tributary or mainstem floods. In some cases, such as 1993, tributary floods cause deposition only in the channel and subsequent events are required to redistribute the sediment from the pool to the sand bar. Erosion of the bar occurred in the interval that included the January 1993 LCR flood while deposition occurred in the interval that included the smaller October 1993 and March 1995 LCR floods. Deposition also occurred during the 1996 experimental flood but was much less than the maximum amount of deposition at this site. Hazel and others (1997b) argued that the largest amount of deposition measured at this occurred primarily as a result of the increase in the stage-discharge relation in the pool caused by the Tanner Canyon debris flow.

Status of the Campsite

The RM 68.4R monitoring site lies within a reach that is considered non-critical with respect to campsite availability. The 1973, 1983, and 1991 campsite inventories all listed a large campsite at this location (Table 1). Campsite inventories made before and after the 1996 Experimental Flood indicated an increase in the campable area and area of sand (Kearsley and Quartaroli, 1996). These data suggest that, although this large bar has always been a usable campsite, the size and quality of the site are enhanced by new deposition caused by floods.

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Table 1. Summary of available monitoring data for RM 68.4R.

		Area of Sand above base level					Volume	
Date	Method of Measurement	Campsite Area (Subjective)	Surficial geologic map[1]	Test-flow air photos[2]	Topographic survey[3]	Normalized Area4	Sand bar[5]	Pool[6]
6/1/73	campsite inventory	L						
6/1/83	campsite inventory	L						
6/14/09	campsite inventory	L						
3/15/96	campsite inventory	L						
4/15/96	campsite inventory	L+						
2/8/91	photo (2316a, 2316b)							
1/22/1890	photo (2316a, 2316b)[7]							
12/31/35	surficial geologic map		7093			0.92		
5/14/65	surficial geologic map		5916			1.79		
6/16/73	surficial geologic map		5674			1.13		
10/21/84	surficial geologic map		7854			0.94		
6/30/90	surficial geologic map		6124			0.93		
10/11/92	surficial geologic map		6080			1.00		
5/30/93	surficial geologic map		5609			1.00		
3/24/96	surficial geologic map		6505			1.01		
4/4/96	surficial geologic map		7474			1.01		
10/30/90	test flow air photo			4379		1.04		
12/30/90	test flow air photo			4196		1.00		
1/12/91	test flow air photo			4216		1.00		
1/26/91	test flow air photo			4388		1.05		
2/9/91	test flow air photo			4596		1.10		
4/20/91	test flow air photo			4186		1.00		
5/19/91	test flow air photo			4116		0.98		
6/2/91	test flow air photo			4443		1.06		
6/30/91	test flow air photo			4279		1.02		
7/27/91	test flow air photo			4499		1.07		
7/15/90	topographic survey				2990	1.02	3348	
7/29/90	topographic survey				2649	0.90	2894	
9/16/90	topographic survey				2764	0.94	3174	
10/14/90	topographic survey				3163	1.08	3940	
10/28/90	topographic survey				3155	1.07	3827	
11/12/90	topographic survey				3116	1.06	3490	
12/16/90	topographic survey				2943	1.00	3536	
12/30/90	topographic survey				2940	1.00	3511	
1/14/91	topographic survey				2971	1.01	3579	
1/28/91	topographic survey				2963	1.01	3469	
2/10/91	topographic survey				3063	1.04	3478	
4/21/91	topographic survey				2954	1.00	3269	
5/5/91	topographic survey				3288	1.12	3459	
5/19/91	topographic survey				2808	0.96	3020	
6/2/91	topographic survey				3019	1.03	3256	
7/1/91	topographic survey				2998	1.02	3409	
7/14/91	topographic survey				3162	1.08	3919	
7/29/91	topographic survey				3077	1.05	3723	
9/29/91	topographic survey				2659	0.90	3410	
10/29/91	topographic survey				2818	0.96	3426	
10/22/92	topographic survey				2979	1.01	3171	0
4/6/93	topographic survey				2102	0.71	2389	23448
10/13/93	topographic survey				4828	1.64	6341	15871
4/14/94	topographic survey				4557	1.55	5589	20634
11/24/94	topographic survey				3738	1.27	5510	21760
4/30/95	topographic survey				4273	1.45	4858	21338
2/21/96	topographic survey				3860	1.31	4850	11194
3/31/96	topographic survey				4026	1.37	6731	1039
4/22/96	topographic survey				4280	1.46	6320	3913
9/19/96	topographic survey							

[1] Area of exposed sand above 8,000 ft^3s^{-1} stage measured by surficial geologic map, corrected for discharge differences between aerial photographs.

[2] Area of exposed sand when air photos were taken at 5000 ft^3s^{-1}.

[3] Area of sand above the 5000 ft^3s^{-1} stage.

[4] Measurements from surficial geologic maps are normalized to June 30, 1990. Measurements from the test-flow air photos and topographic maps are normalized to December 30, 1990.

[5] Volume of sand above 5000 ft^3s^{-1} stage.

[6] Volume of sand increase since 1992, below the 5000 ft^3s^{-1} stage

[7] Numbers refer to established photograph locations (Melis and others, 1995).

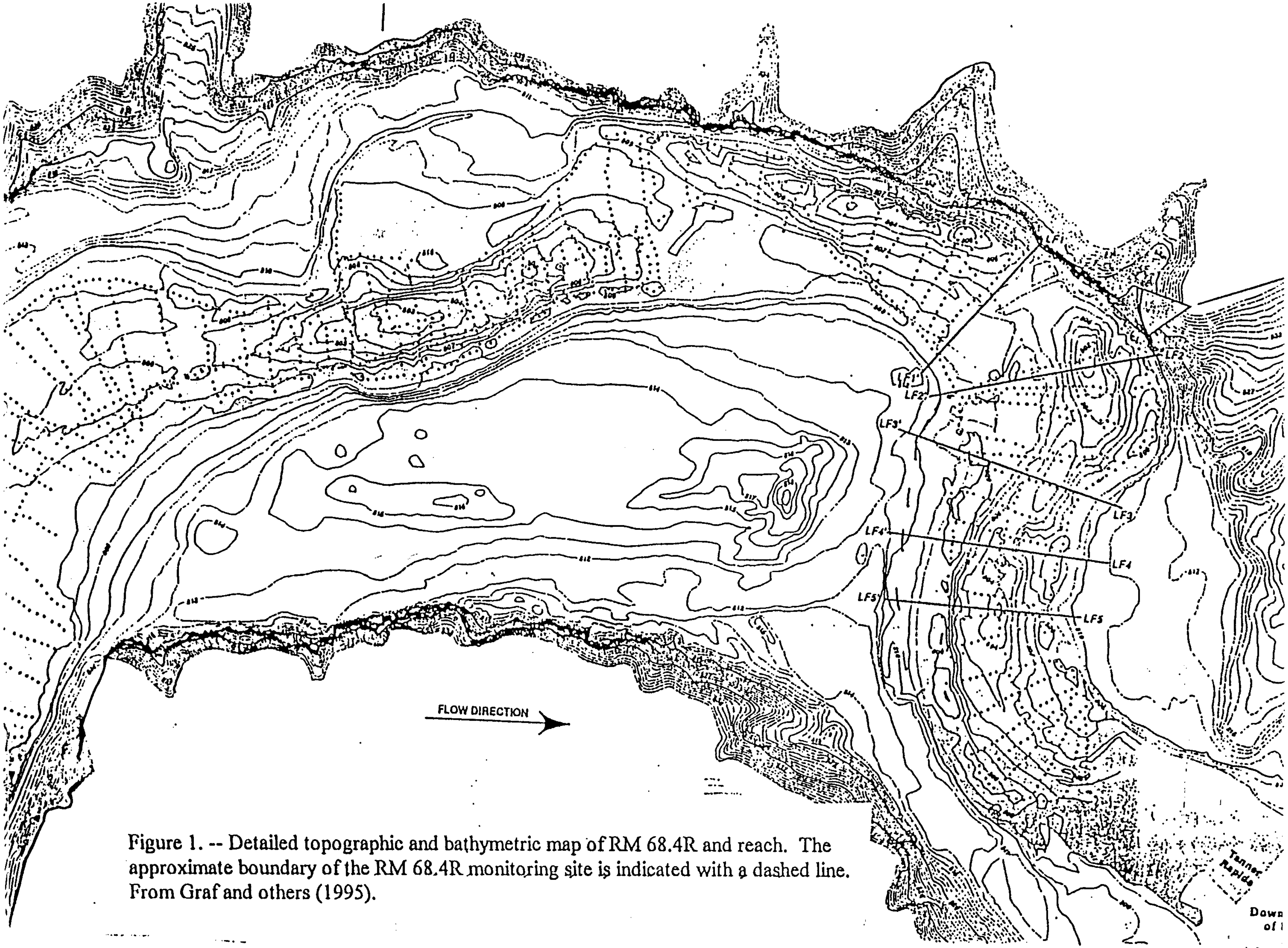


Figure 1. -- Detailed topographic and bathymetric map of RM 68.4R and reach. The approximate boundary of the RM 68.4R monitoring site is indicated with a dashed line. From Graf and others (1995).

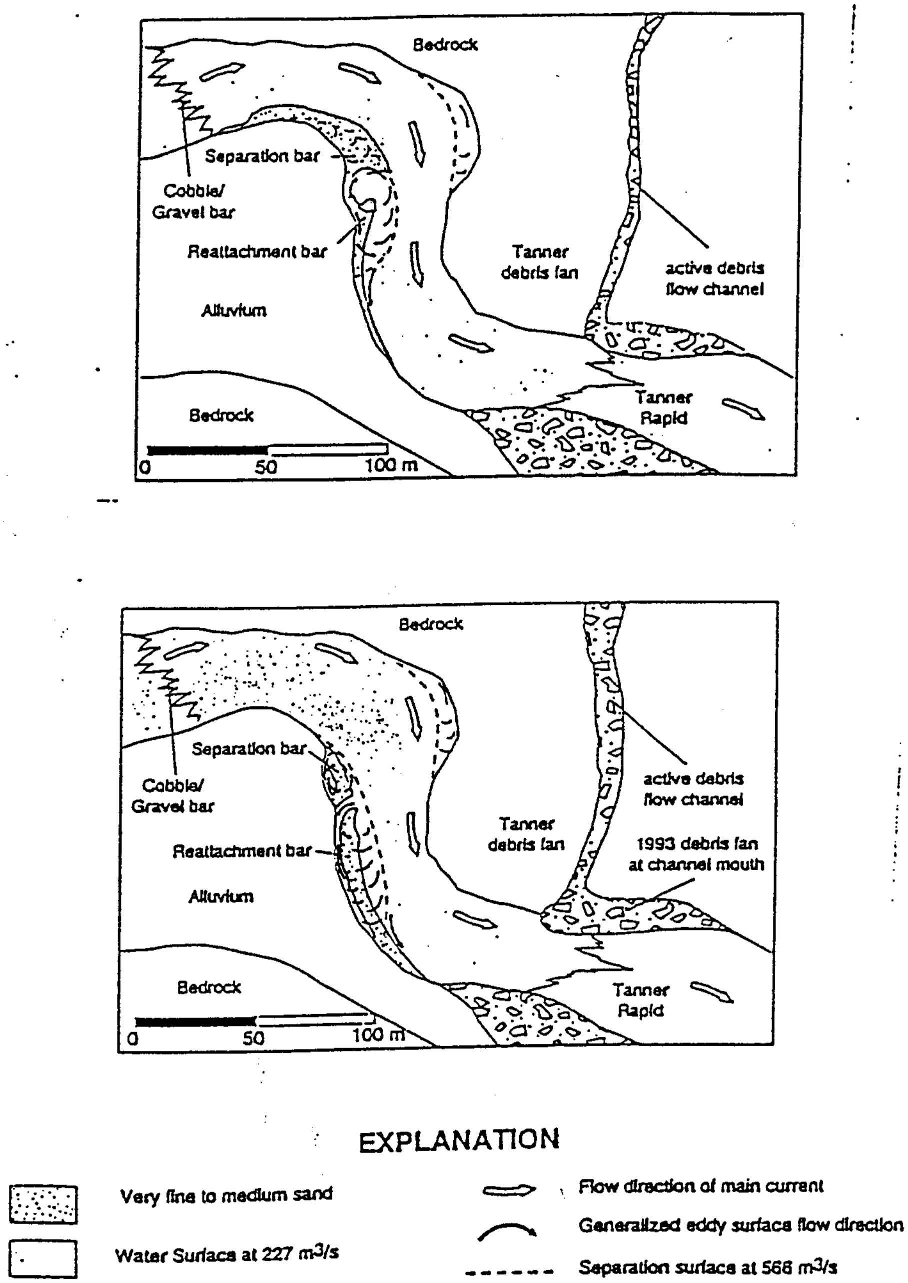
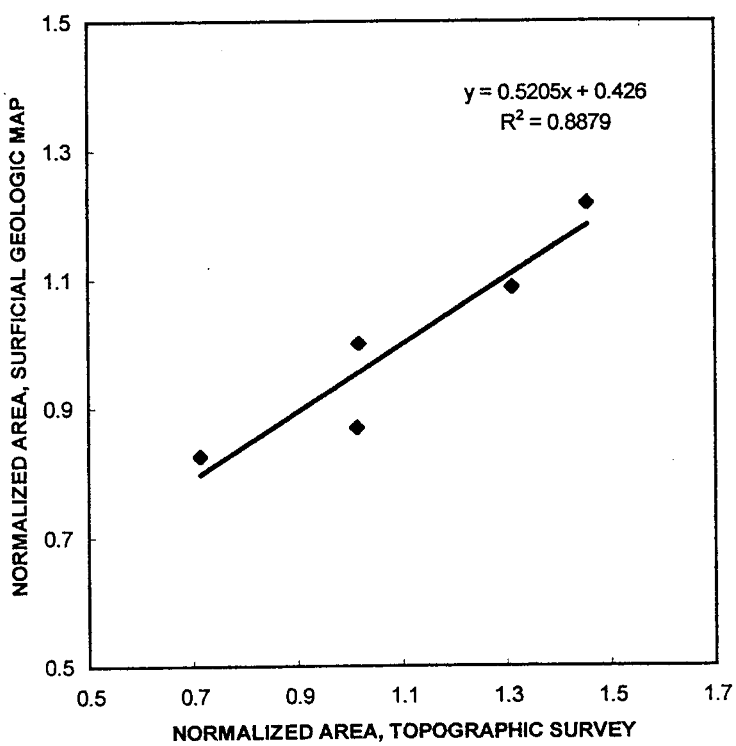


Figure 2. — Map of recirculation zones and flow patterns at 20,000 ft^3s^{-1} when the separation bar is large and the reattachment bar is small (a) and when the reattachment bar is large and eddy-sediment storage is greatest (b). From Hazel and others (1997).

3.


y = 0.5205x + 0.426
R2 = 0.8879
NORMALIZED AREA, SURFICIAL GEOLOGIC MAP
1.5
1.3
1.1
0.9
0.7
0.5
0.5
0.7
0.9
1.1
1.3
1.5
1.7
NORMALIZED AREA, TOPOGRAPHIC SURVEY

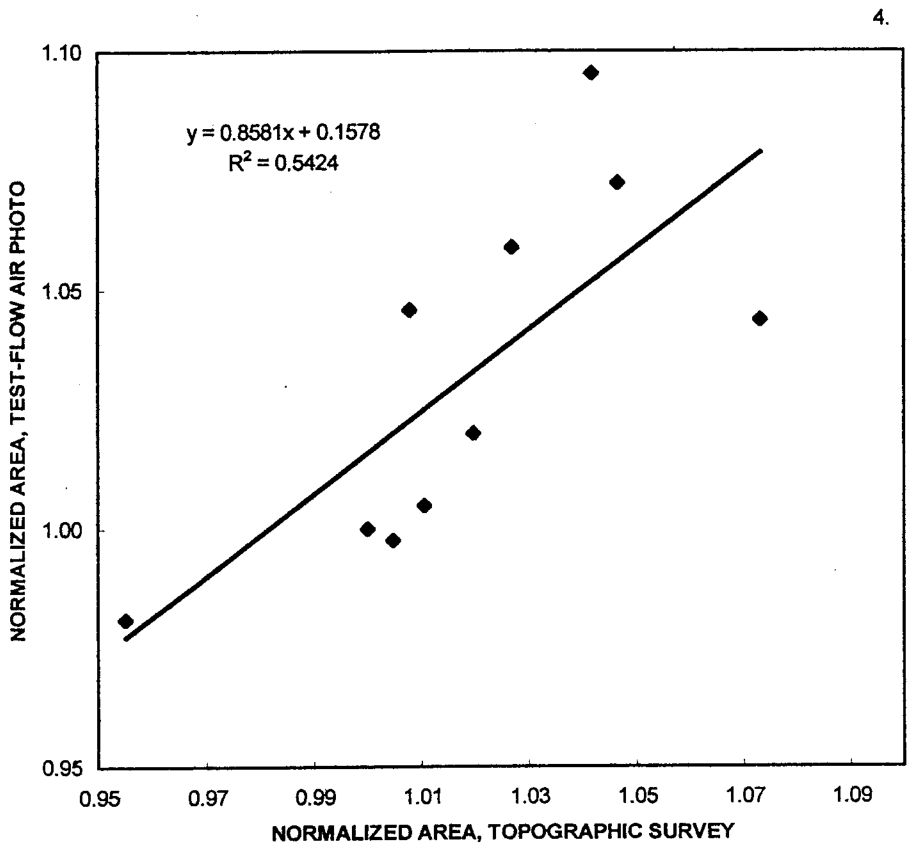

4.
y = 0.8581x + 0.1578
R2 = 0.5424
NORMALIZED AREA, TEST-FLOW AIR PHOTO
1.10
1.05
1.00
0.95
0.95
0.97
0.99
1.01
1.03
1.05
1.07
1.09
NORMALIZED AREA, TOPOGRAPHIC SURVEY

Figure 5a . -- Overlay of erosion and deposition measured by topographic survey and surficial geologic map. Topography was measured July 15, 1990 and October 22, 1992. Surficial geologic maps were made from air photos taken June 30, 1990 and October 11, 1992.

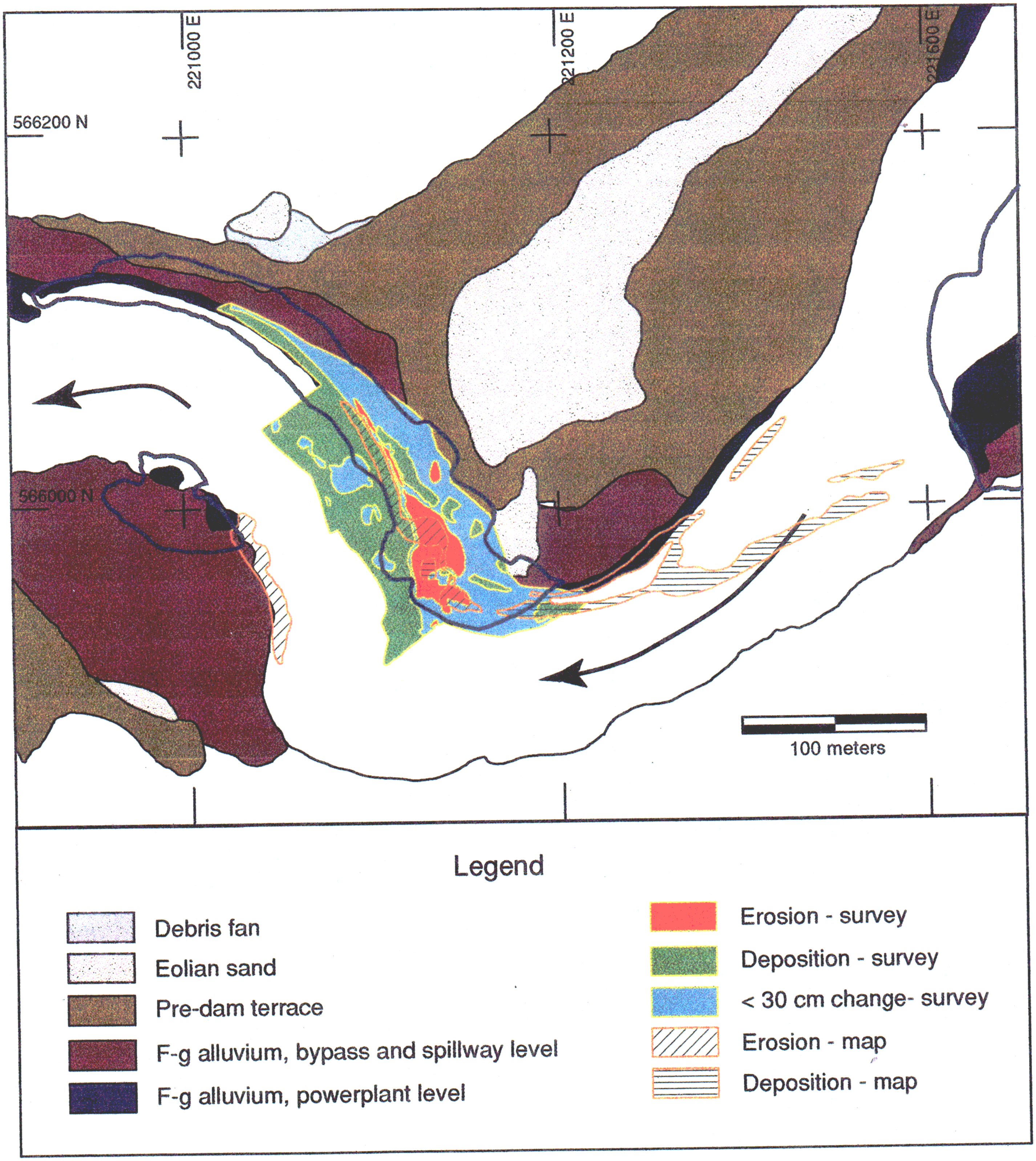


Figure 5b. -- Overlay of erosion and deposition measured by topographic survey and surficial geologic map. Topography was measured October 22, 1992 and April 6, 1993. Surficial geologic maps were made from air photos taken October 11, 1992 and May 30, 1993.

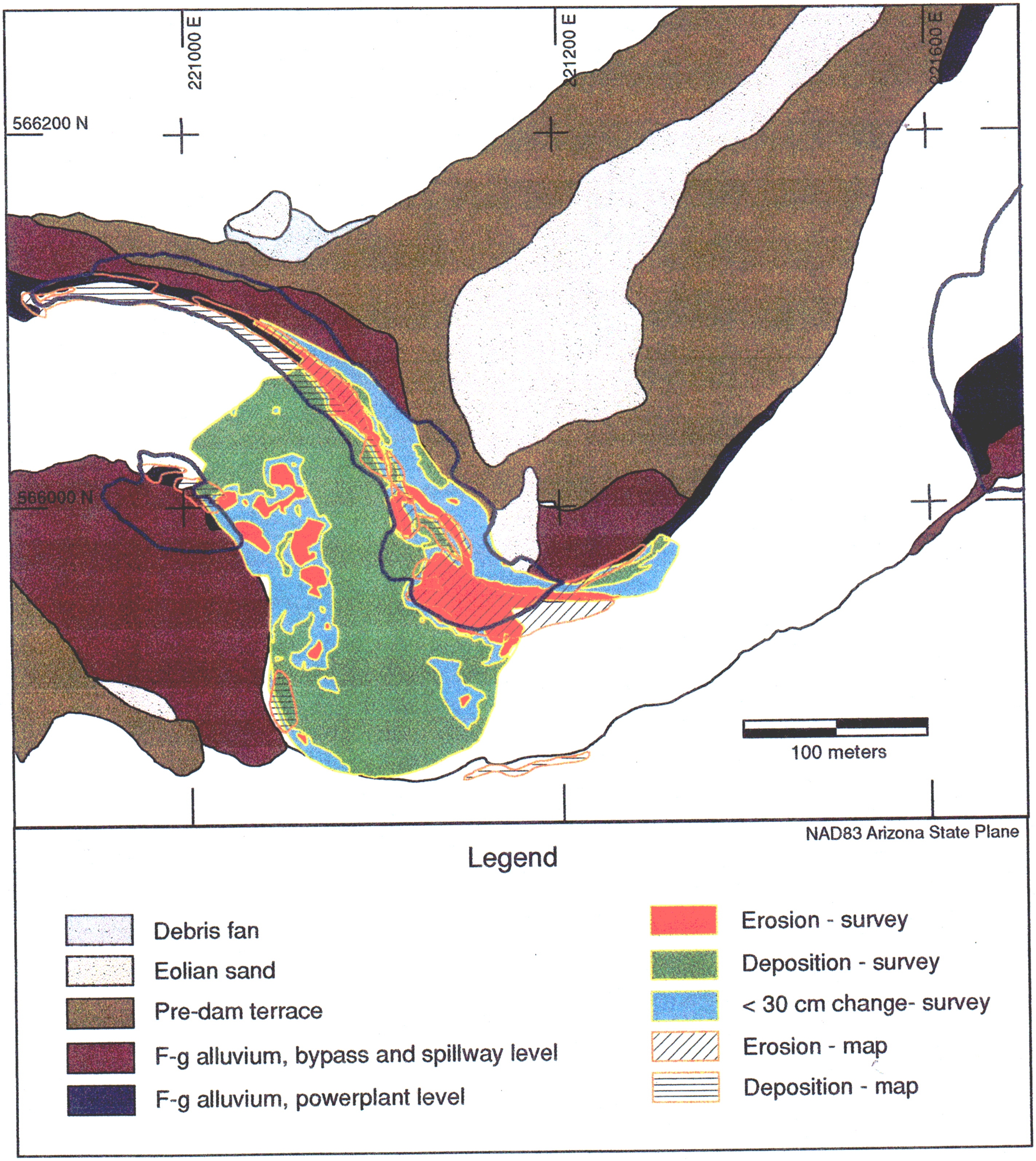


Figure 5c. -- Overlay of erosion and deposition measured by topographic survey and surficial geologic map. Topography was measured April 6, 1993 and February 22, 1996. Surficial geologic maps were made from air photos taken May 30, 1993 and March 24, 1996.

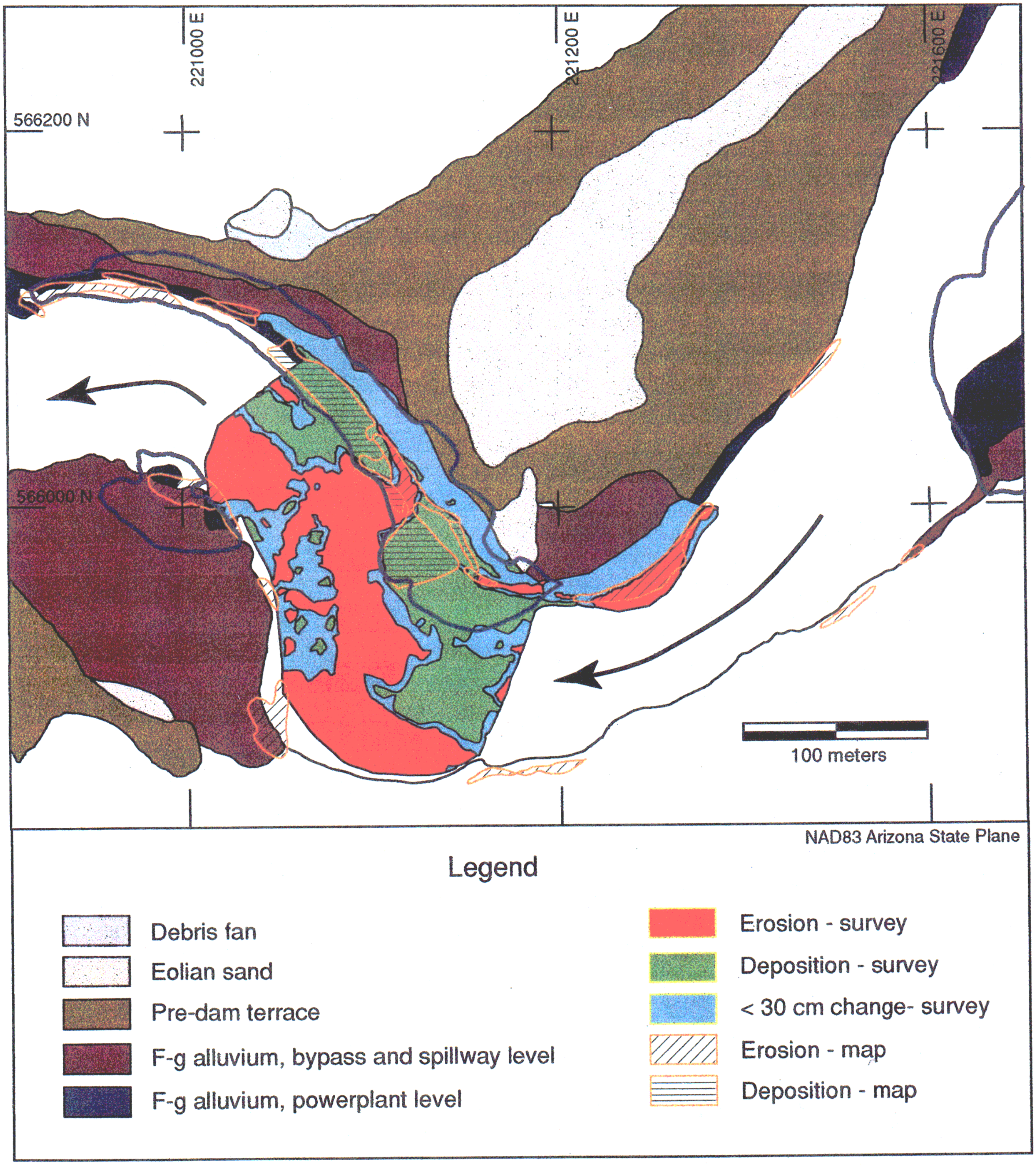
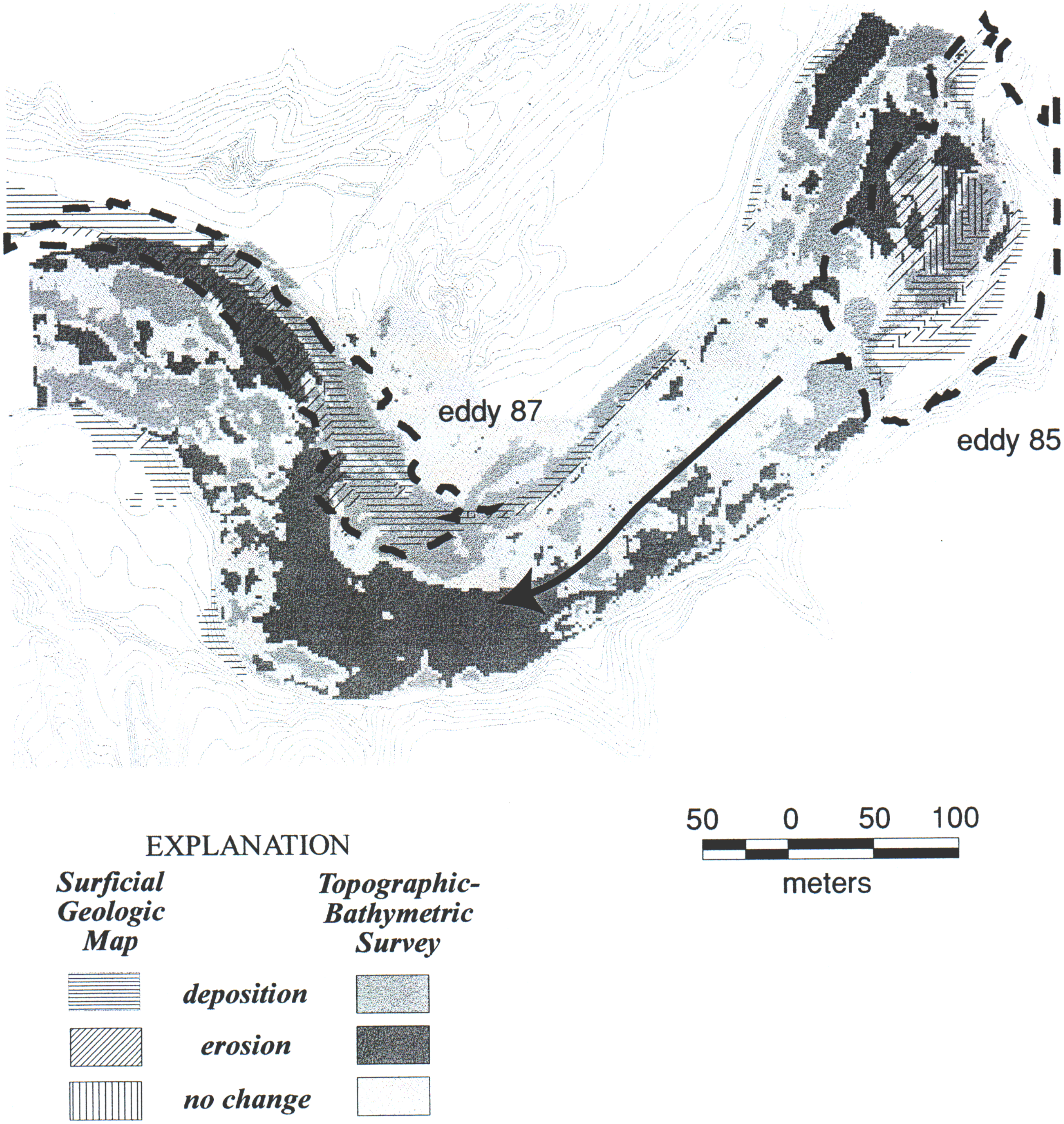
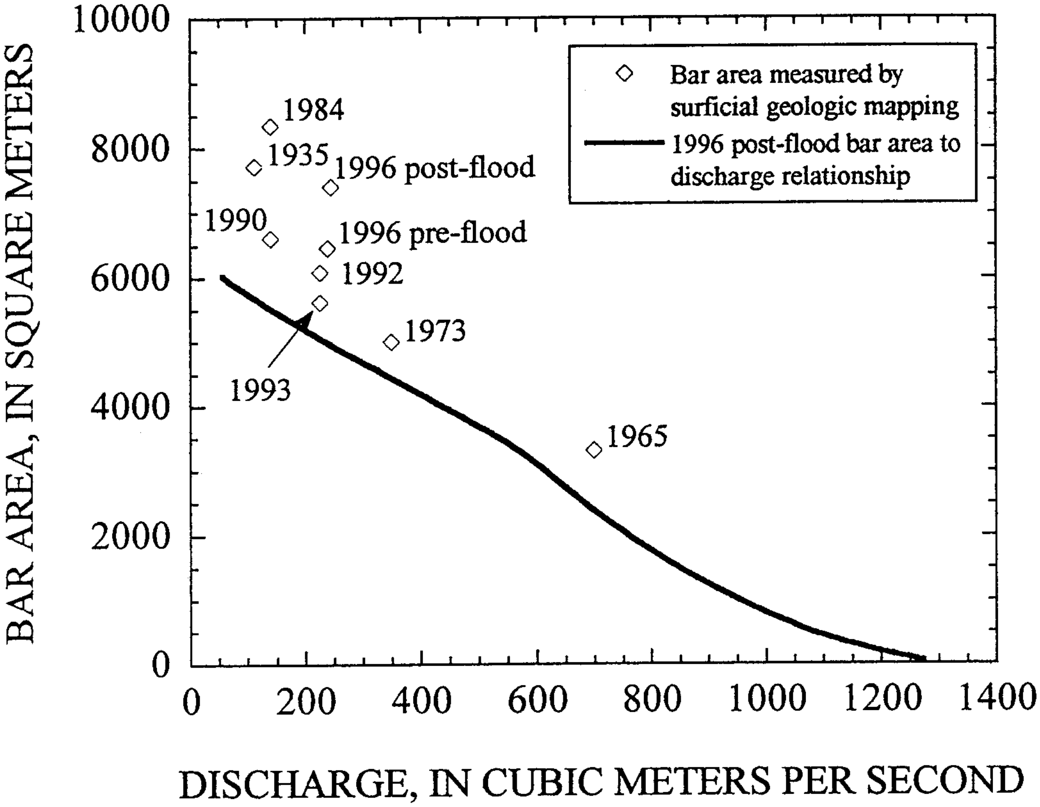


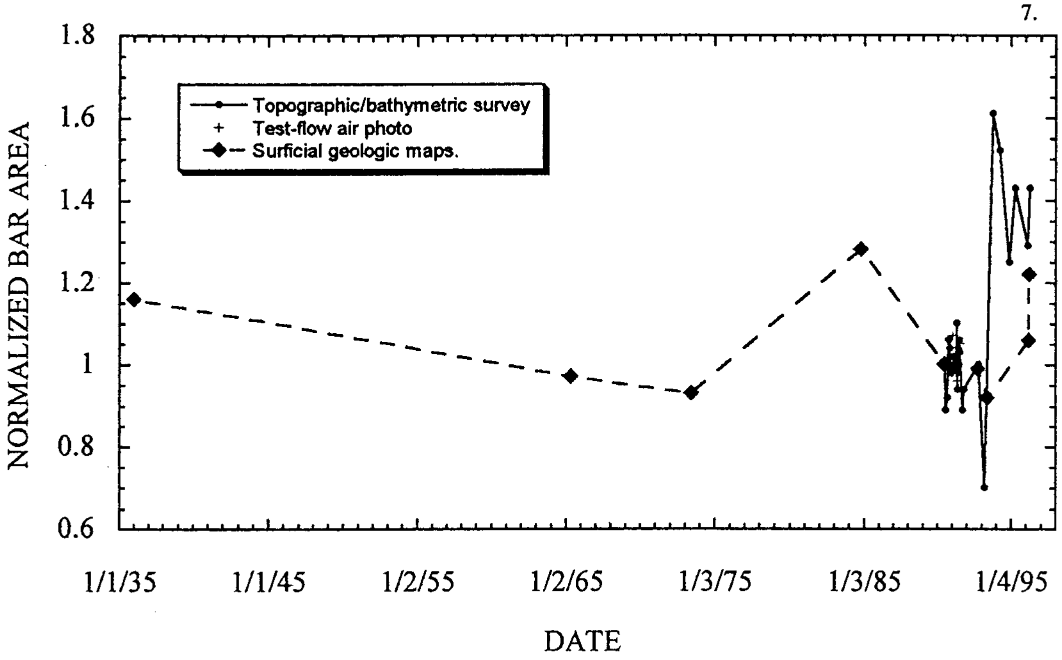
Figure 5d. -- Overlay of erosion and deposition measured by topographic survey and surficial geologic map. Topography was measured February 22, 1996 and April 4,1996. Surficial geologic maps were made from air photos taken March 24, 1996 and April 4, 1996.



6.



10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
1200
1400
BAR AREA, IN SQUARE METERS
DISCHARGE, IN CUBIC METERS PER SECOND
Bar area measured by surficial geologic mapping
1996 post-flood bar area to discharge relationship
1984
1935
1996 post-flood
1990
1996 pre-flood
1992
1973
1993
1965


7.
1.8
1.6
1.4
1.2
1
0.8
0.6
NORMALIZED BAR AREA
Topographic/bathymetric survey
Test-flow air photo
Surficial geologic maps.
1/1/35
1/1/45
1/2/55
1/2/65
1/3/75
1/3/85
1/4/95
DATE

Mean Daily Discharge for Little Colorado River near Cameron, Arizona and Colorado River near Grand Canyon, Arizona