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LESSONS FROM AN UNREGULATED REACH OF THE COLORADO RIVER: PROCESSES OF EROSION AND DEPOSITION AND COMPARISON WITH THE REGULATED RIVER IN GRAND CANYON

[05/23/96]

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TO: list

FROM: Brian Cluer, Hydrologist, NPS Water Resources Division, Fort Collins, CO and Grand Canyon National Park

SUBJECT: Report on unregulated stream studies, Colorado River near Moab, Utah

Enclosed is a report entitled "Lessons From An Unregulated Reach of the Colorado River: Processes of Erosion and Deposition And Comparison With The Regulated River in Grand Canyon". The report represents the completion of an important part of my Ph.D. research in the mechanics of sediment transport in flow recirculation zones. For the academics on the list, this report can be viewed as a major chapter of my dissertation and for the Park Service and BOR personnel on the list, this is a belated 'annual progress report'. The rest of the list consists of people with similar interests who might find the observations from the naturally flowing river interesting.

The report describes four years of monitoring and other detailed measurements from selected sand deposits along the unregulated Colorado River near Moab, Utah. The sand deposits studied are analogous to Grand Canyon sand deposits in geomorphology and size, and comparisons are presented of erosion and deposition rates and of processes of sediment transport and temporary storage of sand in incised river channels. There are some interesting parallels between erosion events observed in the regulated and unregulated rivers that indicate the long term stability of sand deposits and associated habitats as well as implications for the fate of sand deposits following floods such as the experimental flood in Grand Canyon this spring.

In an effort to decrease the size of the report, the lengthy appendices (maps and cross-sections) are not included, but are available upon request. If you have any questions or would like to discuss this report, please call me at (970) 225-3512.

Brian Cluer

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ABSTRACT

Recent scientific investigations and monitoring activities of fluvial sand deposits along the Colorado River in Grand Canyon, downstream of Glen Canyon Dam, have revealed that sand deposits are much more dynamic than previously thought, undergoing several erosion/deposition cycles per year. An unregulated river analogue site was studied through four annual flood cycles in order to compare erosion and deposition rates and processes between the regulated and unregulated bedrock river gorges where coarse debris fans cause channel constrictions that promote deposition of sand-sized fluvial sediment. In this investigation, a combination of still and automatic oblique photography, terrestrial sand bar surveys, hydrographic channel surveys, and aerial photographs were analyzed to document the processes and rates of change in physical channel geometry and sand storage in deposits along the channel margins at various physical and temporal scales. These results were compared to data from similar monitoring activities in the Grand Canyon.

Aerial photographs provided information from the longest time scale. Between 1952 and 1993, changes in sand storage at three neighboring eddy deposits were statistically insignificant (overall) although the individual deposits were dynamic by +/- 50% in area. A slight long term decrease in median size is correlated with increasing Fall discharge and vegetation encroachment. Periodic photography, surveys, and intervals of automatic daily photography provided information from four floods between 1992 and 1995. The eddy deposits were eroded during the rising limb of floods and re-deposited during the peak or recession limb. Eddy deposits underwent annual cycles of erosion and deposition driven by annual floods with long periods of stasis between floods. This is compared to several cycles of erosion and deposition per year for similar eddy deposits downstream of Glen Canyon Dam.

One flood cycle with 1-2 year return period was studied in detail with seven repeated bathymetric surveys and daily time lapse photography. More adjustment in pool geometry occurred during the low flow season than during the flood. During the extended low flow season prior to the flood, the pool lengthened in both the upstream and downstream directions. The pool was deepened and shortened from downstream during the rising limb of the flood. This channel adjustment was measured about one week before the eddy deposit was scoured as

discharge continued to increase. With increasing discharge the recirculation zone elongated and the pool shortened, resulting in eddy deposit erosion during flood initiation. The pool lengthened following the flood, resulting in increased area for recirculating flow and low eddy velocities in which the eddy deposit was stable. Small floods eroded eddy bars that were created by large floods. Discharges that accumulated sand in eddies during the recession limb eroded that sand during the rising limb of the next flood cycle.

The results from the 1995 flood were unique in that the eddy bar was not re-deposited after being eroded during the rising limb. This may be explained by two episodes of erosion and only one episode of deposition as a result of the uncommonly long duration and two pronounced secondary peaks of the 1995 flood.

Several processes were observed in the unregulated river that do not occur in the regulated river. They are discussed because the processes might have biological and/or management significance in the regulated river environment. Off-channel aquatic habitat formed in return current channels during the low flow season, promoted by prolonged relatively consistent discharges. This led to aquatic plant colonization and utilization by juvenile fishes during the winter months. The shallow backwater habitat was protected from predation by an ice cover and a shallow inlet. Because the bare sand eddy deposits were exposed for 10-11 months annually, wind redistributed sand from the eddy surface to the vegetated reattachment deposit and banks. The 1983 flood (20-30 year recurrence) did not effect the trend of increasing riparian vegetation, indicating that vegetation displacement through flow management would have limited success.

INTRODUCTION

BACKGROUND

The deeply incised bedrock canyons of the western United States contain alluvial deposits of all sizes that are transported and temporarily stored over different time scales depending on grain size and flow competence. Over the last 3-4 decades, all major rivers in the western U. S. have been affected by engineering structures (Gore and Petts, 1989; Dynesius and Nilsson, 1994) that store and regulate flow and trap the mobile components of the alluvial sediment in incised bedrock gorges. The sand and finer alluvial deposits are important because they provide the physical environment for rich, diverse and dynamic riparian and aquatic ecosystems. As society learns more about ecosystems in regulated and unregulated rivers, naturally functioning ecosystems have become more valuable (National Research Council, 1996), and prefatory steps have been taken to restore natural processes to some of the most affected regulated rivers through dam re-operation (USBOR, 1995) and designed floods (Wegner et al., 1996).

As the downstream environmental impacts of river regulation in the canyons of the western US have been realized in the last 3 decades, fluvial geomorphologists have specialized in quantifying and monitoring changes in the alluvial components of bedrock canyon rivers. Pioneering studies of these features were conducted on the Colorado River downstream of Glen Canyon Dam in the Grand Canyon. Early monitoring investigations used various temporal scales, depending upon the perceived response time-scale of the alluvial deposits, but based also upon the information available. Typically, studies of the early physical responses to flow regulation were based on decade-scale channel cross-section measurements (e.g.

Pemberton, 1976) or regional or national programs of high altitude aerial photography that were repeated about every 5 years, supplemented with land surveying at similar time steps (e.g. Howard and Dolan, 1976; Beus et al., 1982). Modern studies that measure alluvial deposit changes in other bedrock gorge rivers continue to rely heavily on decade scale aerial photography (e.g. Lyons et al, 1992; Schmidt et al., 1995) largely because that is often the only antecedent information available, but also because image processing and analysis techniques are now readily available. Such decade scale information is usually supplemented with annual or seasonal channel measurements from US Geological Survey (USGS) gaging stations. Gage stations are ideally selected for channel stability, and therefore gaged cross section monitoring selectively excludes channel adjustments in most cases. Although USGS stream gages operate on most major rivers and tributaries in the western US, sediment transport measurements at the network have been largely curtailed since the 1980's, so modern sediment yields are only estimated for many rivers.

Typically, river monitoring funds are associated with biological resources (i.e. endangered fishes) and physical measurements of the channel and alluvial deposits or sediment transport at time steps shorter than annually are not conducted. In river research and monitoring there is a prevalent disconnect between biological and physical resource investigations, to the detriment of both sciences. One of the largest recent environmental river studies in the western US was supported by US Bureau of Reclamation (USBOR) on the Colorado River in Glen and Grand Canyons. Physical and biological responses to various dam and powerplant operation alternatives were tested with a series of designed flows in 1990-1991. The test flows were conducted over two week periods; eleven days of a particular operation alternative followed by a three day evaluation interval for measurement of the

effects. While many in the scientific community considered the two week tests to be grossly short of the perceived response time scale, the schedule was tractable for the competing uses of the river; water storage and delivery, power production and marketing, and fishing and river running activities. During these designed flows topographic surveys of a sample of alluvial sand deposits were repeated before and after each of the flow tests and unexpectedly large gains and losses were measured at several deposits (Beus and Avery, 1991). An automatic camera system, taking three photographs daily, documented that one of the large alluvial sediment losses measured over a two week period in 1990 actually occurred in less than eight hours and partial re-deposition had taken place prior to the bimonthly survey (Cluer, 1991).

This discovery of rapid erosion of sand bars during the 1990 designed flows led to expanded automatic camera monitoring in Grand Canyon between 1992 and 1993. During that time 70% of 43 widely spaced sand deposits underwent 1 to 8 erosion/deposition events in 20 months. Over this period, the sample mean size variance was approximately 44% (Cluer and Dexter, 1994). Other contributions of this monitoring included the documentation of; 1) periods of sand deposition culminating in rapid erosion and repetition of the cycle, 2) unique cycle lengths for individual sand deposits, and 3) spatially widespread and geomorphically ubiquitous cycles in that all deposit types were affected between 18 miles and 240 miles downstream of the dam. These findings were compared to previous and ongoing monitoring studies by Cluer (1995), who discussed the biases in various monitoring designs and some of the resource management implications.

After the initial discovery of cyclic large-scale rapid erosion of alluvial sand deposits was made using automatic photography in 1990 (Cluer, 1991), rapid erosion was independently validated by continuous recording water level and land tilt instrumentation

installed at several sites in Grand Canyon in 1991-1992. In fact, several erosion events not revealed by photography were detected underwater by these methods (Carpenter et al. 1991; Cluer et al., 1993). Rapid erosion of large volumes of sand out of these channel margin storage zones was recognized as an episodic process that occurred during conditions that were not previously documented or well understood. The term 'erosion event' was adopted to distinguish between the newly documented episodic style of erosion and the more well known, or well accepted, concept of gradual linear or logarithmic 'erosion rates'. Finally, one of these erosion events was witnessed by a group of scientists while camped at one sandbar for 10 days in 1991 (Cluer, 1991). Another erosion event was measured in detail in 1993 (Cluer et al., 1993) with channel bathymetry and three-dimensional acoustic doppler velocity mapping equipment. The eddy deposit was scoured 6 meters deep in this event that lasted about 65 hours. Analysis of these data is the subject of reports in preparation.

These observations showed that sand deposits were cyclically eroded and re-deposited in the Grand Canyon by a wide variety of fluctuating hydropower discharges (Cluer and Dexter, 1994; Cluer, 1995). Cyclic erosion processes primarily influence that portion of sandbars below the elevation of maximum discharge fluctuation. However, the low elevation eddy deposits cover and provide protection to the toe of higher elevation reattachment deposits. During the time between scour and re-deposition of eddy bars, higher elevation sand deposits erode as steep banks retreat toward the angle of repose. Thus, the erosion of high elevation reattachment bars is periodic with the period controlled by the cycle period of eddy bar erosion/deposition events. The time period when sand deposits at higher elevations were susceptible to erosion from bank retreat varied in the Grand Canyon from two weeks to several months, and the susceptible erosion period was repeated several times annually at many

locations studied (Cluer and Dexter, 1994). Figure 1 is an idealized diagram of the relationship between erosion/deposition cycles of eddy bars and the long term effect on higher elevation deposits in the Grand Canyon.

The spatial distribution of eddy bar erosion events was documented using 43 widely distributed automatic camera set ups during the period 1992-1994 (Cluer and Dexter, 1994). Documentation that erosion events were significantly large and were temporally and spatially ubiquitous in the Grand Canyon invokes several questions with management implications. 1) What are the causes and 2) the processes? 3) Do similar processes operate on naturally flowing rivers and 4) if so, are the cycle lengths similar? 5) How do cyclic erosion/deposition processes bias infrequent measurements, and are there better ways to monitor sand bars?

PURPOSE

Deposition processes and the evolution of channel margin deposits in the Grand Canyon have received much attention (i.e. Rubin et al., 1990; Schmidt, 1990) and the erosion processes relatively little, even though erosion of sand deposits is denounced by land management agencies and the public as the result of flow regulation. This trend continues as the first experimental flood flow in Grand Canyon takes place in March 1996 and the only studies planned to measure the effects after 6-months are monitoring efforts that are not

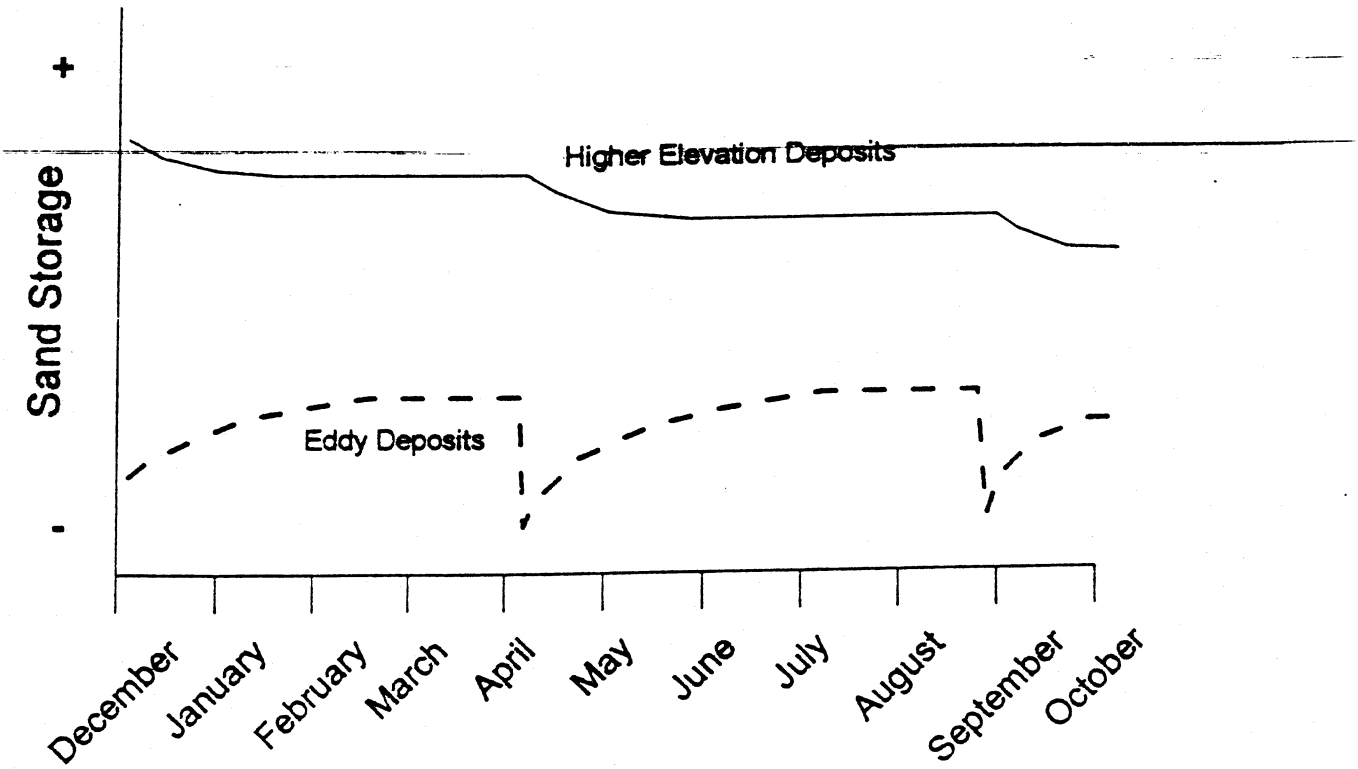


Figure 1. Temporal responses of eddy deposits and higher elevation sand deposits along the Colorado River banks in Grand Canyon.

designed to measure or document processes that cause erosion, only changes in sand deposit volumes or areas. There is now a large literature on alluvial deposits in bedrock gorges, but no studies were found that compared erosion and deposition rates or processes between the regulated and unregulated rivers in bedrock gorges. There have been comparisons of alluvial deposit erosion rates between regulated rivers (e.g. Schmidt et al., 1995; Schmidt and Rubin, 1995), but for the most part the processes and rates of change in sand storage along unregulated rivers are undocumented. That was the major impetus for the investigation described in this report.

It was hypothesized that regulated river sandbars undergo erosion processes similar to those in the naturally flowing river setting and the processes could be observed operating over longer time scales . Longer time scales would provide opportunities more conducive to thorough measurement and description of the processes. It was also hypothesized that rapid erosion events were a naturally occurring part of annual flood cycles on unregulated streams. To test these hypotheses a bedrock canyon river with debris fan channel constrictions and a natural hydrograph was required. It was also necessary that the naturally flowing river include sandbars with similar dimensions and geomorphic setting to sandbars in the Grand Canyon. A reach of river with these qualifications was chosen on the Colorado River near Moab, Utah. Reconnaissance of the reach showed that semi-regularly spaced debris fans create conditions where sandbars are deposited with dimensions and morphology very similar to Grand Canyon sandbars. A multi-temporal and multi-spatial monitoring program was implemented at one debris fan/sand bar complex that included: daily oblique sandbar photography, detailed periodic surveys of sandbar and channel topography, and historic aerial photography. Continuous river flow measurements were available from a USGS gage a few miles upstream. The results and

interpretation of this phase of research, as well as a comparison to erosion rates and processes from the Grand Canyon, are presented in this report.

SITE SELECTION

The Colorado River near Moab Utah was selected to approximate an unregulated river analogue for comparison to regulated river conditions down stream of Glen Canyon Dam. The site is located approximately 30 miles upstream of Moab, Utah, at the upstream end of Professor Valley in a deep bedrock gorge, 5.7 river miles downstream of the confluence with the Dolores River (figure 2). The well known West Water Canyon is a few miles upstream of the area. This river reach is deeply incised into upper Jurassic Entrada Sandstone (Baars, 1972) with steep canyon walls and regularly spaced short side canyons or tributaries emanating from regional joints, fractures or faults. The study site is located adjacent to mile post 26 (MP26) on Utah highway 128 which follows the river's course for 30 miles from the historical Dewey Bridge to Moab, Utah. 4.8 miles upstream of the study area a USGS stream gauging station has operated continuously since 1914.

The main stem geomorphic setting is very similar to that in the Grand Canyon where the river has deeply incised, forming a gorge. Coarse debris delivery to the river channel is from side canyons which are located at local joints or fractures or along more regional geologic structures. Over decade time scales, the river is not competent to transport the coarsest debris delivered to the river and debris fans constrict the channel. The debris fans

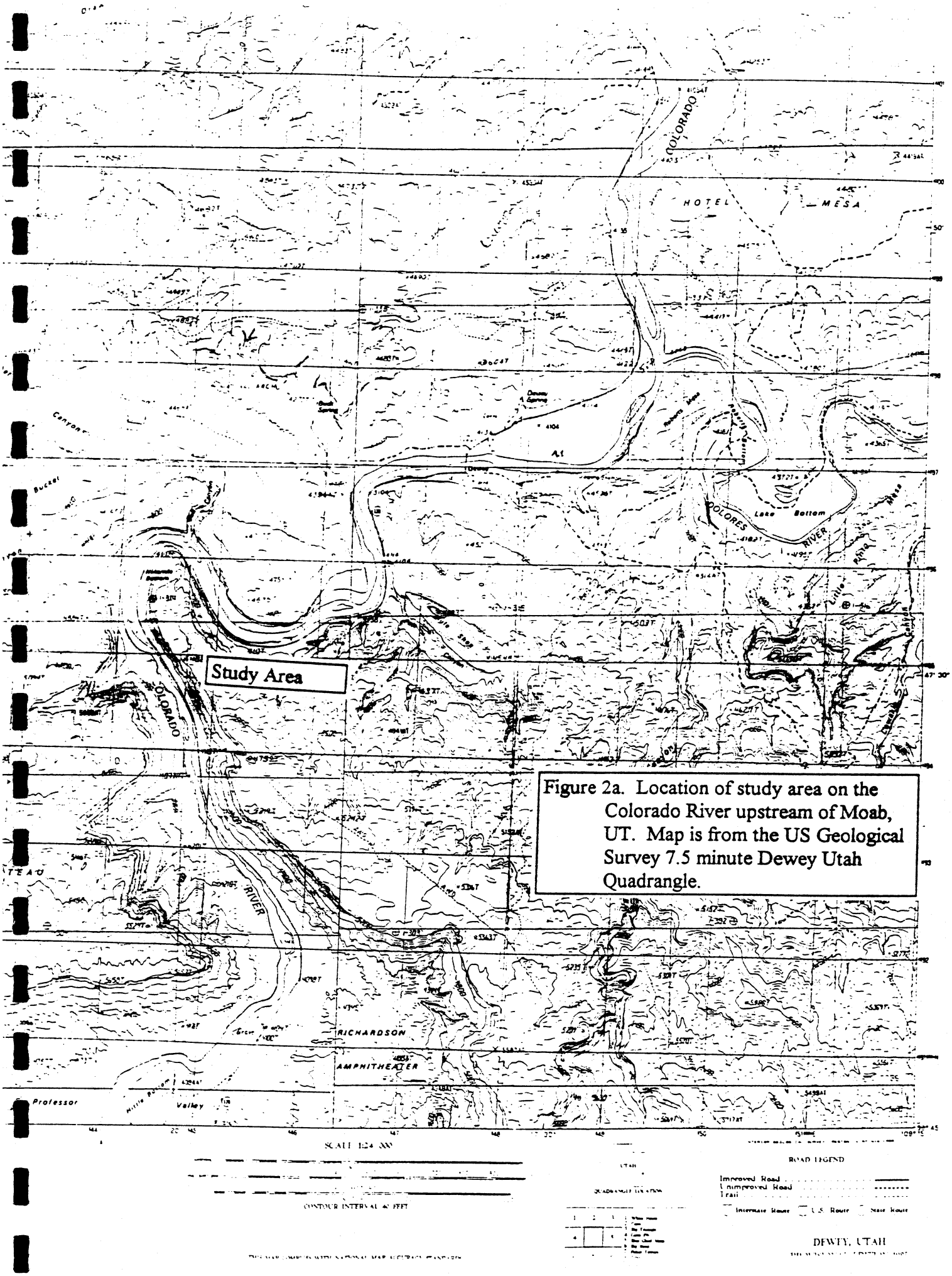


Figure 2a. Location of study area on the Colorado River upstream of Moab, UT. Map is from the US Geological Survey 7.5 minute Dewey Utah Quadrangle.

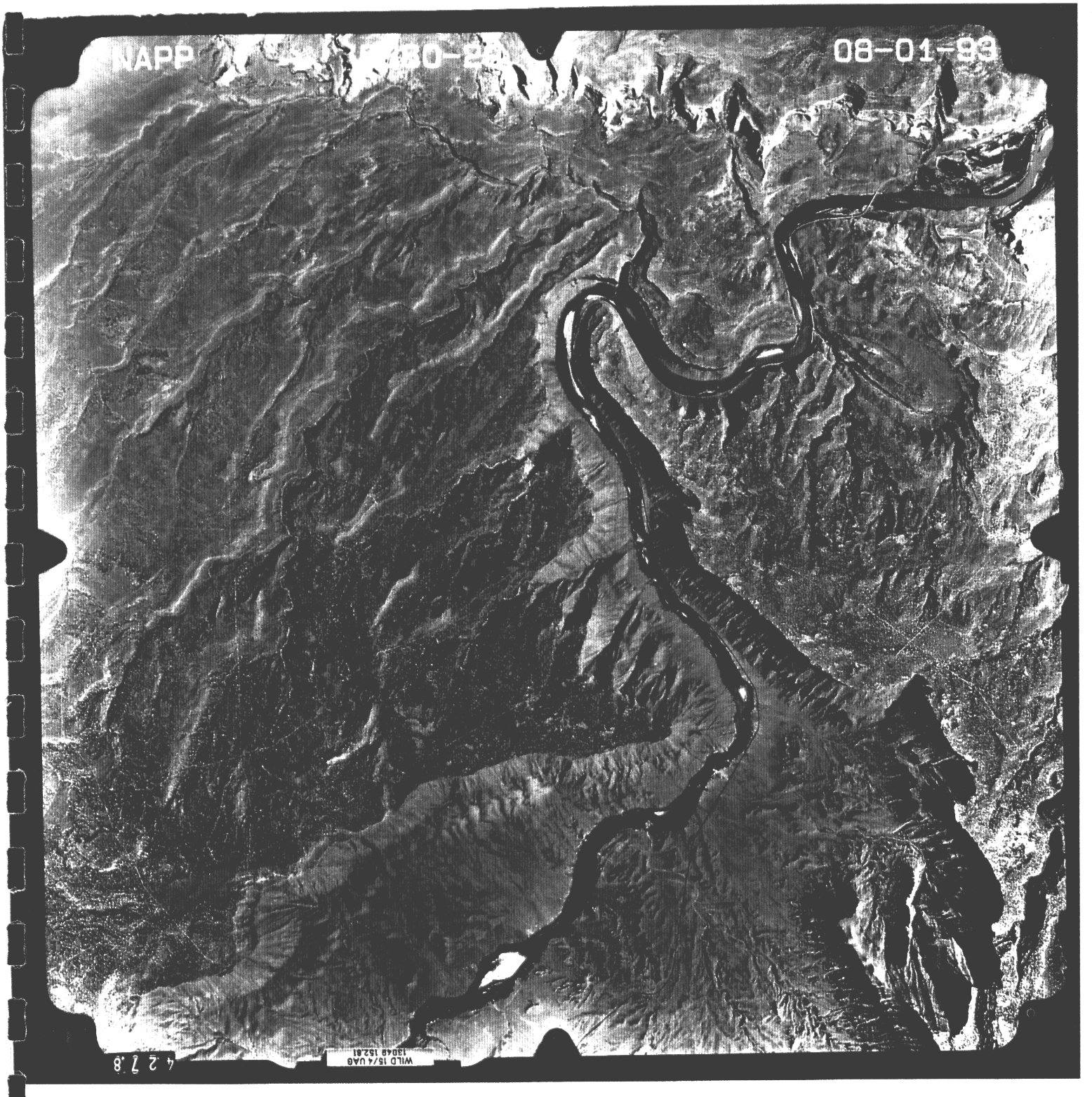


Figure 2b. 1993 aerial photograph of study reach showing the main sand deposit studied in detail and secondary deposits that provided additional information.

form constriction and expansion environments where lateral flow separation zones result in low energy environments where fine-grained alluvium is deposited. Constrictions and expansions are plan view descriptions of three-dimensional features that are more accurately described as pool and riffle channel forms. The 'eddy-rapid complex' is a descriptive term of the particular channel geometry patterns discussed in this report, although rapids are not necessary for eddy development. Rapids are a consequence of channel constriction.

Channel geometry at MP26 is very similar to that of sites in the Grand Canyon where channel widths are on the order of 80-100 m and the low flow constriction ratio is approximately 0.5. Reattachment and eddy deposits (terminology of Schmidt and Graf, 1990) occur down stream of the debris fan channel constriction. The origin of the debris is from a short, steep, side canyon entering from the west. The debris fan is broad, low in elevation, and is overtopped by flows in excess of 12,000 to 15,000 cfs (1 year recurrence).

The Colorado River in the Moab reach is not unregulated as there are a number of storage reservoirs in the headwaters and numerous irrigation diversions along its route. The largest flow regulation facility is Blue Mesa Reservoir on the Gunnison River, which was constructed in 1965 and is operated to store spring peak discharges for summer irrigation use. McPhee reservoir on the Dolores River was completed in 1986. However, the affects of headwaters development on this reach of the Colorado River are minor compared to the complete flow regulation of Glen Canyon Dam. The Colorado River near Moab is still characterized by a distinct annual flood cycle and high sediment load which facilitated the objective of comparing a naturally flowing river to the completely regulated river in Grand Canyon.

METHODS

NATURALLY FLOWING RIVER NEAR MOAB

The sand deposits at one channel constriction were selected for monitoring in March 1992 by staff of the National Park Service, Water Resources Division, who were familiar with channel constriction and sandbar geometry in the Grand Canyon. The initial monitoring activities consisted of establishing locations for repeat photography of the exposed channel margin sand deposits. Following the spring 1992 flood, subsequent measurements included baseline topographic surveying of the exposed sandbars. Photographs were repeated whenever staff had occasion to travel through the area on other assignments. Periodic opportunistic photography was replaced by automatic daily photography in March 1993 and this system was operated until November 1995. Topographic surveys of the exposed sand deposits were repeated twice annually through 1993. In September 1993 the local benchmark system was expanded to include 19 pairs of cross section markers at 25 meter intervals and periodic bank to bank channel bathymetric surveys ensued so that channel changes could be measured prior to, during and after the 1994 annual flood cycle. The monitoring history and methods employed at the Moab locale are graphically portrayed in figure 3.

In addition to the detailed channel and sandbar monitoring conducted during the period 1992-1995, aerial photographs from 1952, 1956, 1975, 1980, 1987, and 1993 were obtained from the USGS National Aerial Photography Program. Photo analyses included assessment of relative sandbar sizes, changes in debris fan geometry, and the amount of vegetation coverage. The MP26 sand deposit and two additional debris fan-sand deposit complexes were analyzed so as to include data from more sites and better represent reach scale adjustments to flow

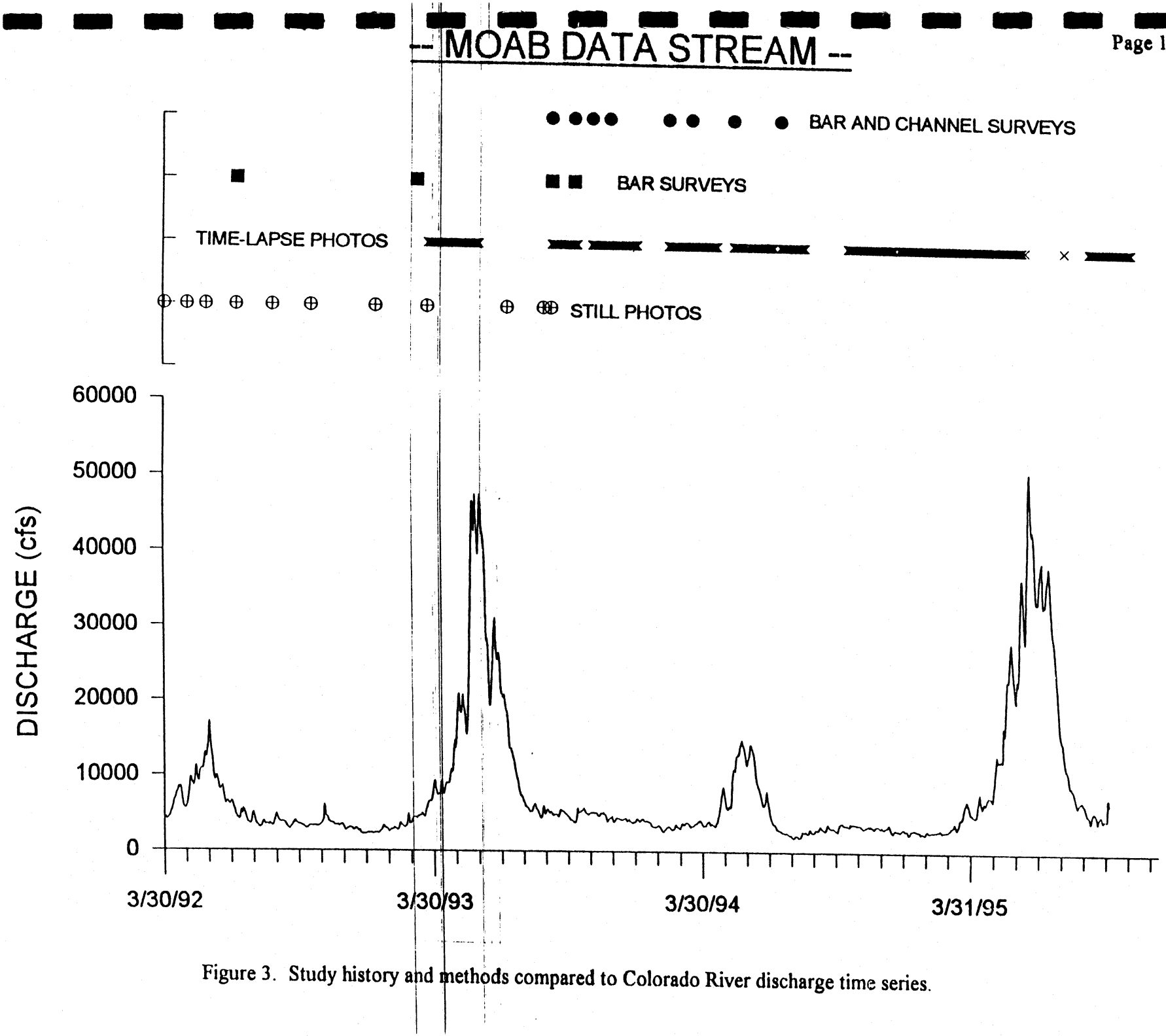


Figure 3. Study history and methods compared to Colorado River discharge time series.

dynamics. The three deposits are all eddy-rapid complexes and are representative of the deposits in the reach. The 1952 aerial photograph was selected as the initial condition where the exposed sand deposits were assigned 100% size. The relative sizes of exposed sand deposits were measured by scaling each subsequent photograph to the 1952 scale and visually estimating the bare sand area. More sophisticated techniques would allow calibrated true area measurements or even georeferenced area measurements (i.e. Dexter et. al., 1995) but would not significantly change the relative sand bar sizes as reported. An ancillary result of photo analysis was a history of vegetated area which was similarly estimated by setting the area of dense riparian vegetation observed in the 1993 photograph equal to 100% and visually estimating the relative coverage in previous photographs. The vegetated area was assessed from both banks along 4-5 river miles surrounding the MP26 site.

Channel topography was measured using hydrographic surveying techniques developed specifically for this setting. Hydrographic surveying is commonly conducted on cross sections using suspended cables for referencing measurements in the horizontal plane. For this study it was necessary to obtain sufficiently detailed topographic measurements, over a reach 400 meters long with a minimal crew and field equipment, to create reliable topographic maps using automatic contouring algorithms. This was accomplished by navigating a small inflatable kayak with reference to two or three vertical poles placed over semi-permanent surveyed rebar cross section markers on the right bank. Water surface elevation and horizontal position with respect to the cross section reference points were measured with a total station or tape and level depending on personnel and equipment available for each survey. The kayak was equipped with an electric trolling motor and an echo sounder and chart recorder which recorded water depth. A string distance meter (Hip Chain®) displayed distance along cross

section from the reference starting point. Tick marks on the echo sounder chart were manually spaced to correspond to even meter distance marks. These data were combined and transformed into a local Cartesian coordinate system to produce maps of three dimensional channel topography. Precision of the hydrographic surveying measurements was within +/- 5 meters horizontal and 0.1 meter vertical using these methods. The number of points on each cross section averaged about 50-60 and the topographic models typically had >1000 points. This point density resulted in reliable creation of contour maps using micro computer contouring techniques.

Stream flow data were obtained from the USGS stream flow gage (Colorado River near Cisco, Utah; station number 09180500) located 4.8 miles upstream of the study area near the historic Dewey Bridge. The Cisco gage was installed in 1914 and had 77 years of continuous record at the end of water year 1995. Sediment measurements were made beginning in 1930 and discontinued in 1984. A sediment rating curve has not been published for this gage station (Rod Tibbetts, USGS-Moab, personal communication 3/5/96).

REGULATED RIVER IN GRAND CANYON

Daily time lapse photographs from sand bar sites in the Grand Canyon were geographically referenced and digitally processed. The oblique photographs were scanned and rectified to the horizontal plane, producing vertical images much like orthographic aerial photos, using PC and UNIX micro computers and ERDAS Imagine® software. These methods resulted in plan area measurements for 20 widely dispersed sand bars and qualitative histories of 23 additional sand bars. Area measurements were made from photographs that captured

low water levels at monthly intervals and when events occurred. The details of these methods and their development are described in a series of contract reports (Cluer and Dexter, 1993, Cluer and Dexter, 1994; Dexter and Cluer, 1995), proceedings (Dexter et al., 1995) and a peer reviewed journal article (Dexter and Cluer, in review).

RESULTS AND DISCUSSION

The information from the unregulated river sites analyzed here is from three distinct time intervals. Because the time span of the information determines the way in which it can be analyzed and interpreted, the results are presented and discussed in order of decreasing time interval. The shorter time step information has the greatest value for improving our understanding of processes, consequently the greatest effort was spent on the most frequent information.

FIVE TO TEN YEAR INFORMATION

A series of aerial photographs were obtained and used for description and measurement of exposed sand deposit size and morphology, relative vegetation coverage, and changes in channel constriction due to side channel debris inputs. The photo series consists of high altitude images at various scales taken in 1952, 1956, 1975, 1980, 1987, and 1993 . All of the photographs were taken during late Summer or Fall low-flow periods. The MP26 site and two similar debris fan sand bar complexes downstream were included in this analysis.

The areal extent and surface morphology of the three debris fans did not change during the period of time covered by the aerial photographs, so changes in channel hydraulics or local

flow patterns caused by episodic debris flows was ignored. However, sand deposit size and vegetation coverage both varied markedly. Over the period from 1952 to 1993 there was a slight overall decrease in median deposit size (figure 4a). The median was chosen rather than the mean to describe central tendency of the measurements because the sample distribution was strongly skewed toward the high end of the scale. The standard deviation (STD) of the 5-10 year data was about 14% while the STD determined from short time step monitoring over the period 1993-1994 for sand bar MP26 was about 25%. When error bars of one standard deviation (1 STD=25%) are plotted about the sample median of the 5-10 year data, it is evident that the changes that occurred over the period 1952-1993 for the three bar sample were not statistically significant. Although within the range of +/- 1 STD, the period 1952-1957 showed a slight increase in median bar size. This response coincides with a period of low peak discharge (figure 5a). The minor overall decreasing trend, although insignificant according to the statistical definitions used here, could be explained in part by the general increase in discharge at the time each subsequent photograph was taken and in part by vegetation encroachment on sand deposits (figure 4b). The range in median sand deposit area for the three bar sample was from +25% to -25% of original area, while individually the deposits ranged from +50% to -50% of their original areas. In fact, it was common that each of the three neighboring deposits had unique responses at each of the time steps analyzed. Unique conclusions would be reached if these deposits were analyzed independently or not within the context of the large STD determined by more frequent measurement.

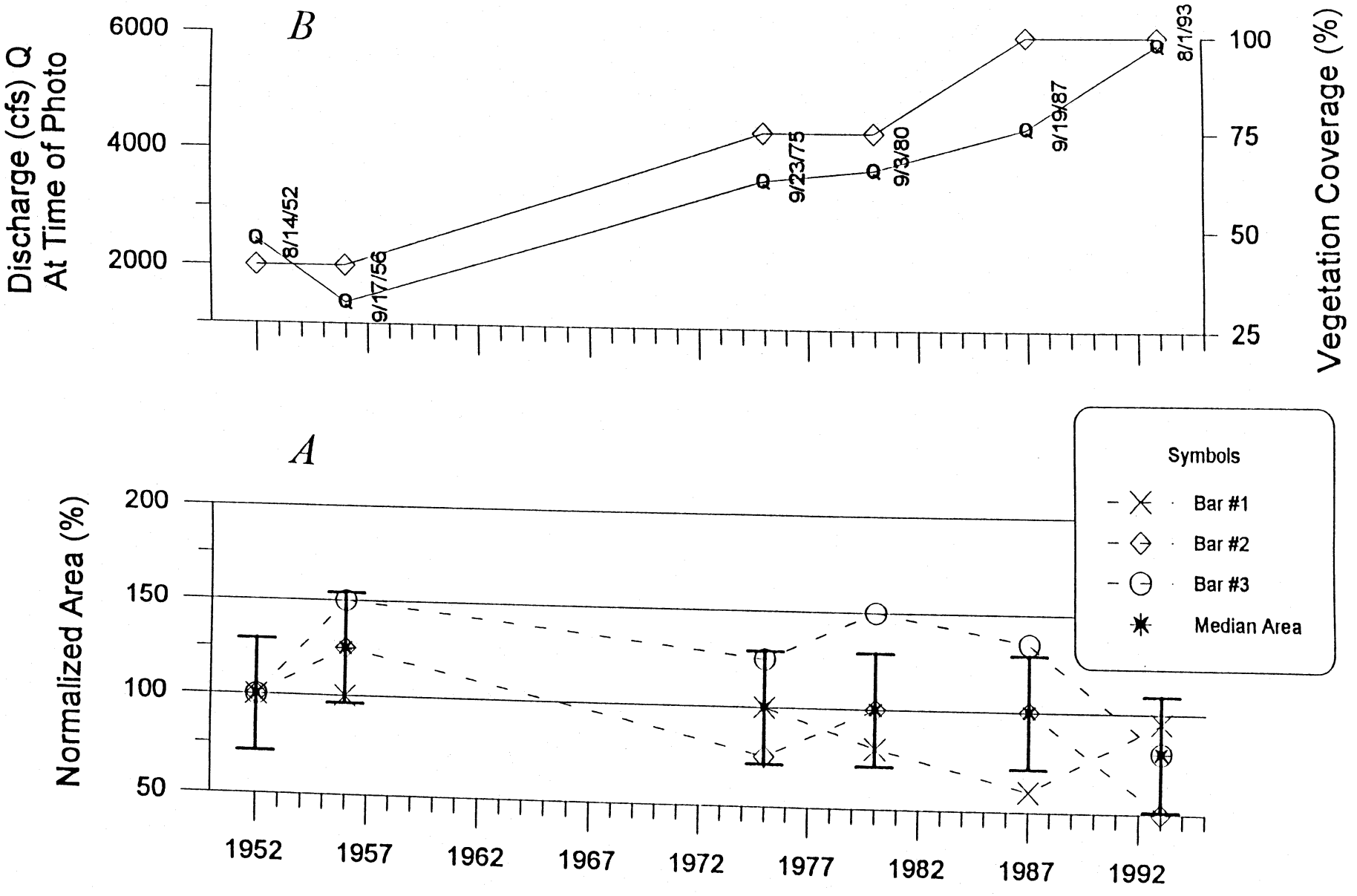


Figure 4. (*A*) Time series area plot of three sand bars in study area, from aerial photography. (*B*) Time series plot of vegetation coverage and Fall discharge.

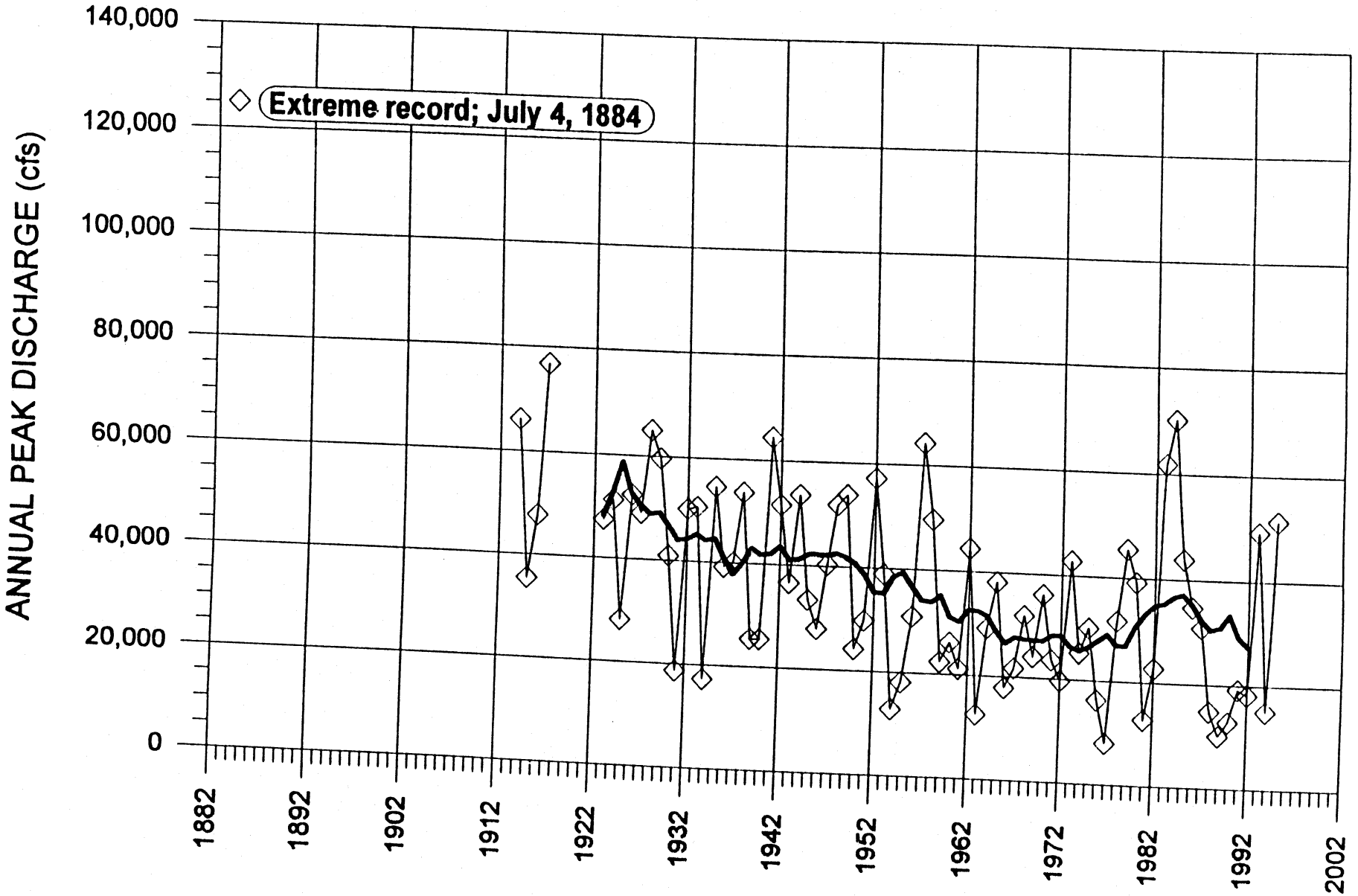


Figure 5a. Time series plot of annual peak discharge for the entire record at Cisco gage. Bold line is the 11-year running average.

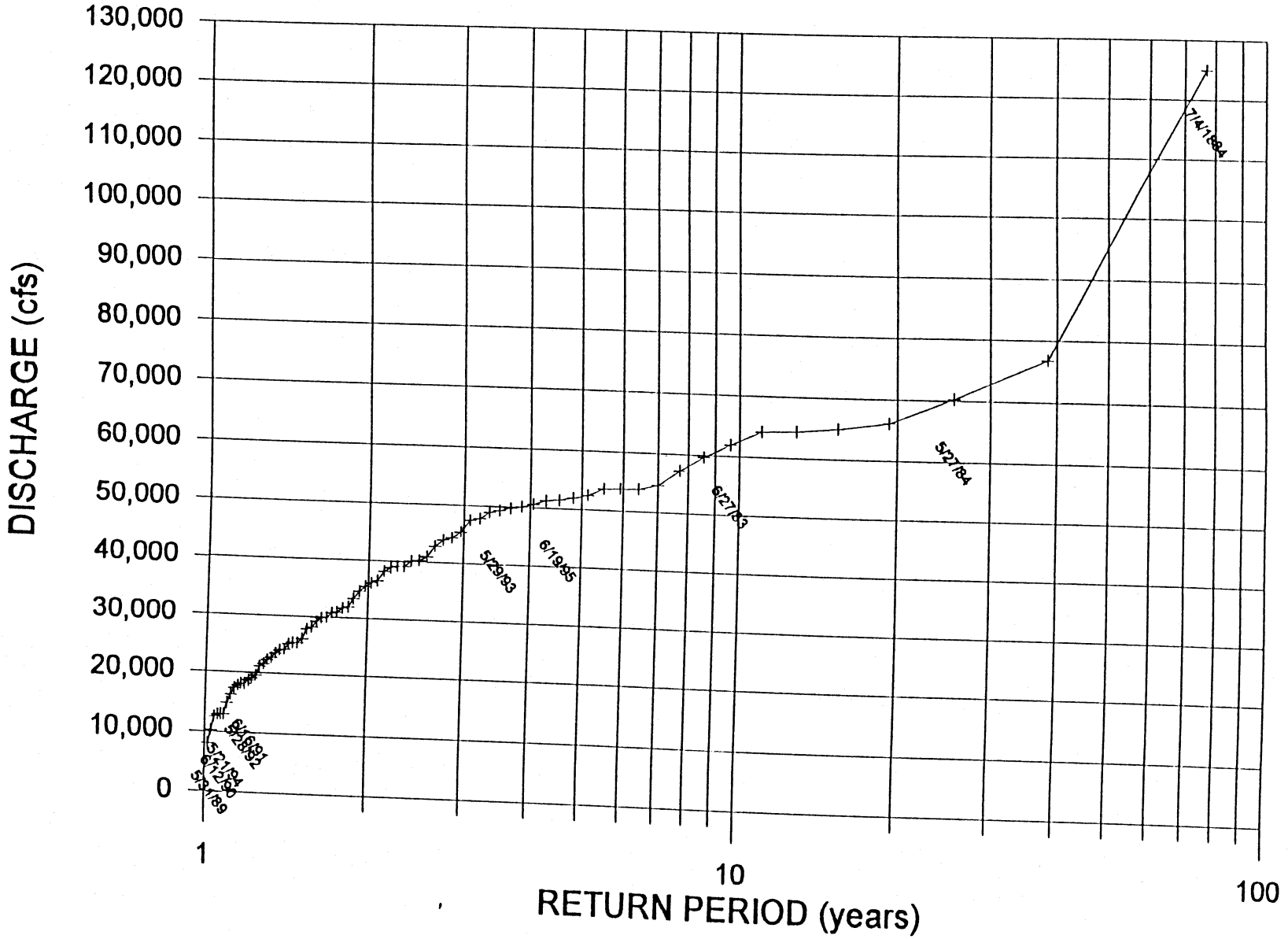


Figure 5b. Ranked flood probability plot with specific years labeled for discussion.

Stream flow for the period 1952-1993 is characterized by declining annual peak discharges as shown by an 11-year running average (figure 5a). The 1984 peak discharge was the third largest flow recorded at the Cisco gage (figure 5b), and the aerial photographs indicate that between 1980 and 1987, two out of three sand deposits in the MP26 reach decreased in size. The actual response of the sand deposits to the 1984 high flow is unknown but photographs from 1980 and 1987 show that the high flow was not a significant event in terms of sand bar size and geomorphology after 3 years.

The results presented from the aerial photography must be qualified in that only areal extent of features was measured. Sand deposits adjust in elevation in relation to maximum river stage, thus the greatest limitation of monoptic aerial photography is that it does not depict changes in elevation. Consequently, the sand deposits in the MP26 reach may have adjusted to past discharges in the vertical dimension as well as in the horizontal dimensions but this could not be determined. Stereoptic photographs are available from the time period used in this report and more detailed three-dimensional analyses are possible. However, it is not expected that more detailed three-dimensional analysis would substantially change the results presented here.

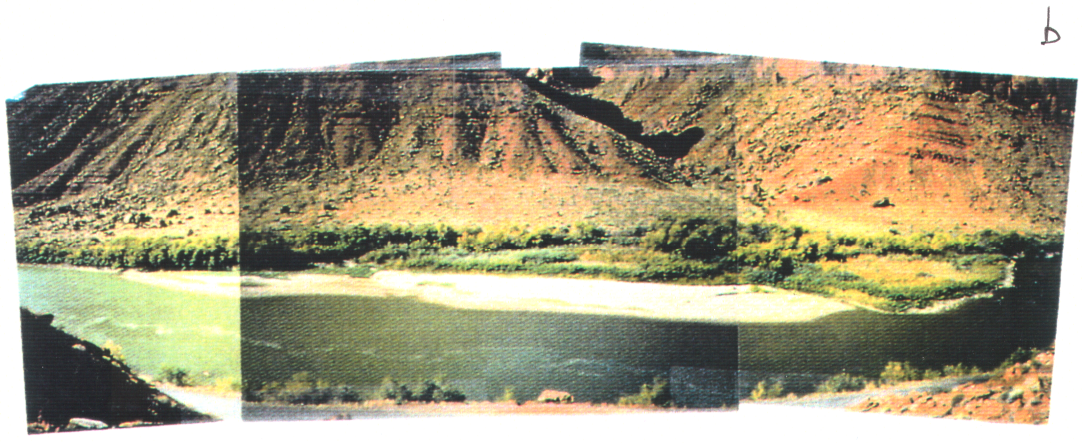
SEASONAL INFORMATION

The annual floods that occurred during this research/monitoring project are placed in perspective by graphs of the annual peak flow time series (figure 5a) and the ranked return period (figure 5b). Peak discharges in the range 10,000 to 35,000 cfs have return periods of 1-2 years and the 1992 and 1994 floods were in this range. The 1993 and 1995 floods were in the range of 3-5 year return period flows. The highest flow recorded at the Cisco gage,

125,000 cfs, occurred on July 4, 1884. This flow record is an extreme outlier and its accuracy is questionable because it was an indirect discharge measurement. The gage was not operating previously nor was it operating subsequently until continuous records began in 1913. Removing this questionable value from the flood frequency analysis would significantly increase the ranking and return periods of the flows examined. Peak values for the high flow years 1983-1984 and the recent period 1989-1995 are labeled on the return period graph (figure 4b). The 1993 high flow of 49,300 cfs ranks as a 3-4 year flood and it followed a four year period of peak discharges that did not exceed 20,000 cfs. The 1994 flood was in the 1-2 year return period range and the 1995 flood reached 51,400 cfs. An 11 year running average of annual peak discharge shows a distinct downward trend (figure 5a). Peak discharges in 1983-1984 were the most significant departures in five decades from the general downward trend.

Between March 1992 and March 1993, eight repeated photographs document the relative exposed sandbar size and morphology at the time of the photograph. The first photographs of the sandy channel margin deposits at MP26 were taken on March 30, 1992 (figure 6a). A panorama shows a large vegetated reattachment deposit exposed approximately 2-3 meters above winter low flow river stage, a broad low elevation vegetated eddy deposit exposed only about 1 meter above winter low flow river stage, a narrow bare sand levee in front of the eddy deposit and only a very thin veneer of sand over the downstream face of the debris fan where separation deposits occur. A backwater with connected upstream and downstream outlets was formed between the eddy bar and the reattachment bar and bank. The morphology was the result of four consecutive years of lower than normal peak discharges. The reattachment bar was vertically faced and undergoing erosion.

a



b

c

d

e

f

g

Figure 6. Oblique photographs from the MP26 sand deposits. (A) March 30, 1992. (B) October 15, 1992. (C) October 11, 1993. (D) June 8, 1994. (E) July 14, 1994. (F) May 19, 1994. (G) October 8, 1995.

The reattachment and eddy deposits were first surveyed in July 1992 following recession of the Spring 1992 flood flow. At 17,100 cfs peak discharge, the Spring 1992 flood was in the range of 1-2 year recurrence (fig. 5b). The topographic survey showed that the eddy deposit was enlarged from approximately 1800 m^2 (estimated area from photographs) to 2700 m^2 (surveyed area) as a result of the Spring 1992 flood. The volume of sand temporarily stored in the 1992 eddy deposit was approximately 5100 m^3 above the local datum 98.17 m. No information exists to describe if the eddy bar was scoured and re-deposited but photographs taken during the July 1992 survey show that the bar was substantially elongated and elevated. The original geomorphology was retained and the backwater was still open on both ends.

Photographs taken in October 1992 (figure 6b) show that the deposits had not changed since July. The next information from the study area is from photographs taken on January 10, 1993. Sometime between August 24, 1992 and January 10, 1993 the eddy deposit was scoured, resulting in elimination of the entire bare sand eddy bar and a small area of the vegetated reattachment bar. Photographs taken on January 10, 1993, at discharge of approximately 2400 cfs, show that ice had formed across the river. A meandering lead in the ice was directing the river flow toward the eddy, explaining erosion of the eddy bar during low flow conditions. Topographic surveys in July 1992 and March 1993 show that the reattachment and eddy bars together were approximately 3800 m^2 before the erosion event and only about 1000 m^2 after. Subsequent separated measurements of the reattachment bar and eddy bar areas showed that the eddy bar area was eroded from approximately 2700 to 100 m^2 and the reattachment bar was largely unaffected by the river-ice caused flow-pattern changes.

If temperature was recorded at the Cisco gage it would be possible to identify when icing conditions occurred. The large backwater area that existed between the eddy bar and bank was affected by the erosion event in that it became open to recirculating flow. The results were similar but the processes differed between this event along the unregulated Colorado River and erosion events in Grand Canyon because it is unlikely that river ice could form downstream of Glen Canyon Dam due to frequently changing releases and constant temperature of the released water. Other natural processes associated with seasonal icing, ice dams, ice transport and drift, etc., may play important biological roles in naturally flowing rivers and serve Winter ecosystem functions such as nutrient releases.

Spring 1993 peak discharge reached 49,300 cfs (3-4 year recurrence) and photographs taken in August 1993 show that a significantly enlarged eddy bar was deposited. Compared to its previous morphology, the new eddy deposit was extended in the downstream direction and elevated so that it was fully connected to the reattachment deposit. The eddy bar was surveyed in September 1993 and it measured approximately 4000 m^2. Daily time-lapse photography began in March 1993, and between March and October 1993 (figure 6c) the eddy and reattachment deposits were stable during the period between late Spring deposition and early Fall measurement (figure 7).

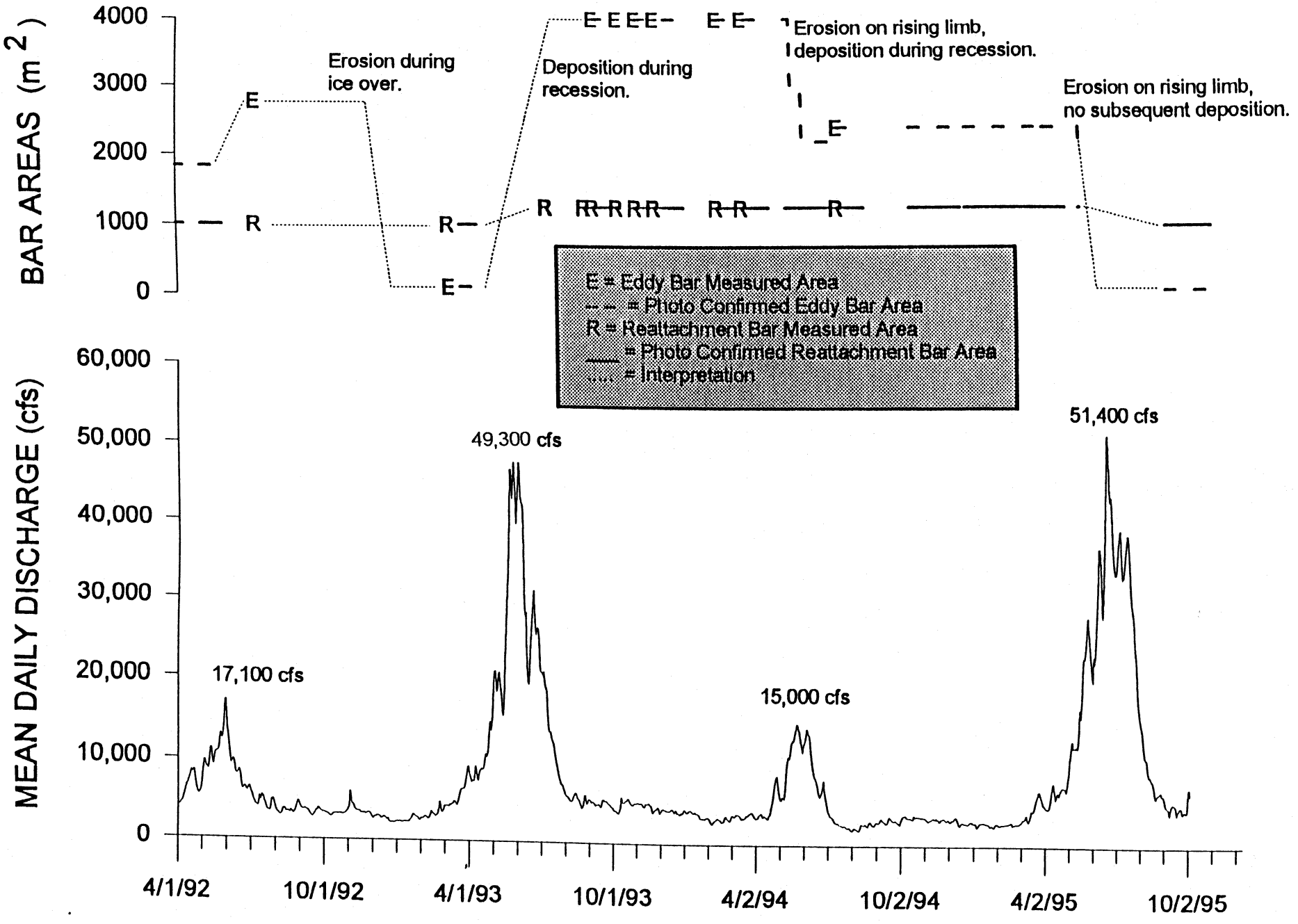


Figure 7. Time series plot of results from surveys and photographs showing the changes in the eddy deposit (E) and reattachment deposit (R) compared to mean daily discharges at the Cisco gage for four floods

CONTINUOUS INFORMATION - THE 1994 FLOOD

The system of local surveying benchmarks was expanded in September 1993 to include 19 equally spaced channel cross sections. An initial channel topography survey was conducted in September 1993 and seven channel surveys were repeated between the 1993 and 1994 high flows. Results from the channel surveys will be discussed in detail in the following section. A series of repeated surveys and nearly continuous daily time-lapse photography show that the eddy and reattachment deposits were stable in their post-1993 flood morphologies for the remainder of the year. The 1994 flood flow reached about 15,000 cfs, and time-lapse photographs taken during May and June 1994 (figure 6d) show that the eddy deposit was eroding from recirculating flow during the rising limb, affecting approximately 50% of its pre-flood area before it became completely inundated. Photographs taken after the July 1994 flood (figure 6e) at a discharge of approximately 2700 cfs show that the eddy deposit was re-deposited during the peak or receding limb of the flood hydrograph to approximately its pre-flood size, but at somewhat reduced elevation consistent with the lower peak stage of the 1994 flood. However, the eddy bar remained attached to the reattachment deposit and the large single-outlet backwater channel was still well developed and remained wetted during low, winter flows. No changes in size or morphology were observed during the remainder of 1994 and Winter 1994-1995 (from nearly continuous daily photography).

Nineteen closely spaced cross sections provided thorough coverage of the channel topography and morphology from the downstream end of the upstream riffle, through the pool and ending where flow depth increased beyond the crest of the downstream riffle. This detailed set of repeated bathymetric measurements documents an evolution of channel changes

occurring throughout one annual flow cycle from Fall low flow to Spring flood and back to Fall low flow. The series of six channel topography maps and five surface comparison maps (Appendix A) documents the evolution of channel changes over an annual time scale and a resetting of those changes by the 1994 flood flow.

When the initial channel survey was conducted in October, 1993, the deepest part of the pool was located at the downstream pool area (range 1125) at 84 m elevation. During the Fall low flow season the pool lengthened and deepened in the upstream direction (figure 8a). By late Winter an equilibrium condition existed where only minor channel adjustments occurred subsequently (figure 8b-c). At that time there were two pools with elevations around 84 m separated by a bedform about 3 m high. The mid-May survey, assembled during the rising limb of the flood, shows that the mid-pool area (around range 1000-1100) deepened as much as 2 m to an elevation of 83 m. Also during the rising limb, a large dune shaped body approximately 3 m thick and 50 m long formed on the pool exit slope around range 1100-1150 (figure 7d). The pool was deepened and contracted in the upstream direction by these two adjustments. The eddy bar was generally stable during the initial period when pool geometry was adjusting. The cross sections (Appendix B) show minor aggradation in the eddy as discharge continued to increase. The eddy bar began eroding about one week after the channel survey on May 12, 1994.

The survey taken in July following flood recession in late June shows that the upstream pool area aggraded between ranges 950 and 1075 and the dune shaped body of sediment that was evident on the pool exit slope was eroded (figure 7e). These two adjustments expanded the pool in the downstream direction while making it shallower and returning it to a geometry similar to the post-flood configuration surveyed the previous October where there was one

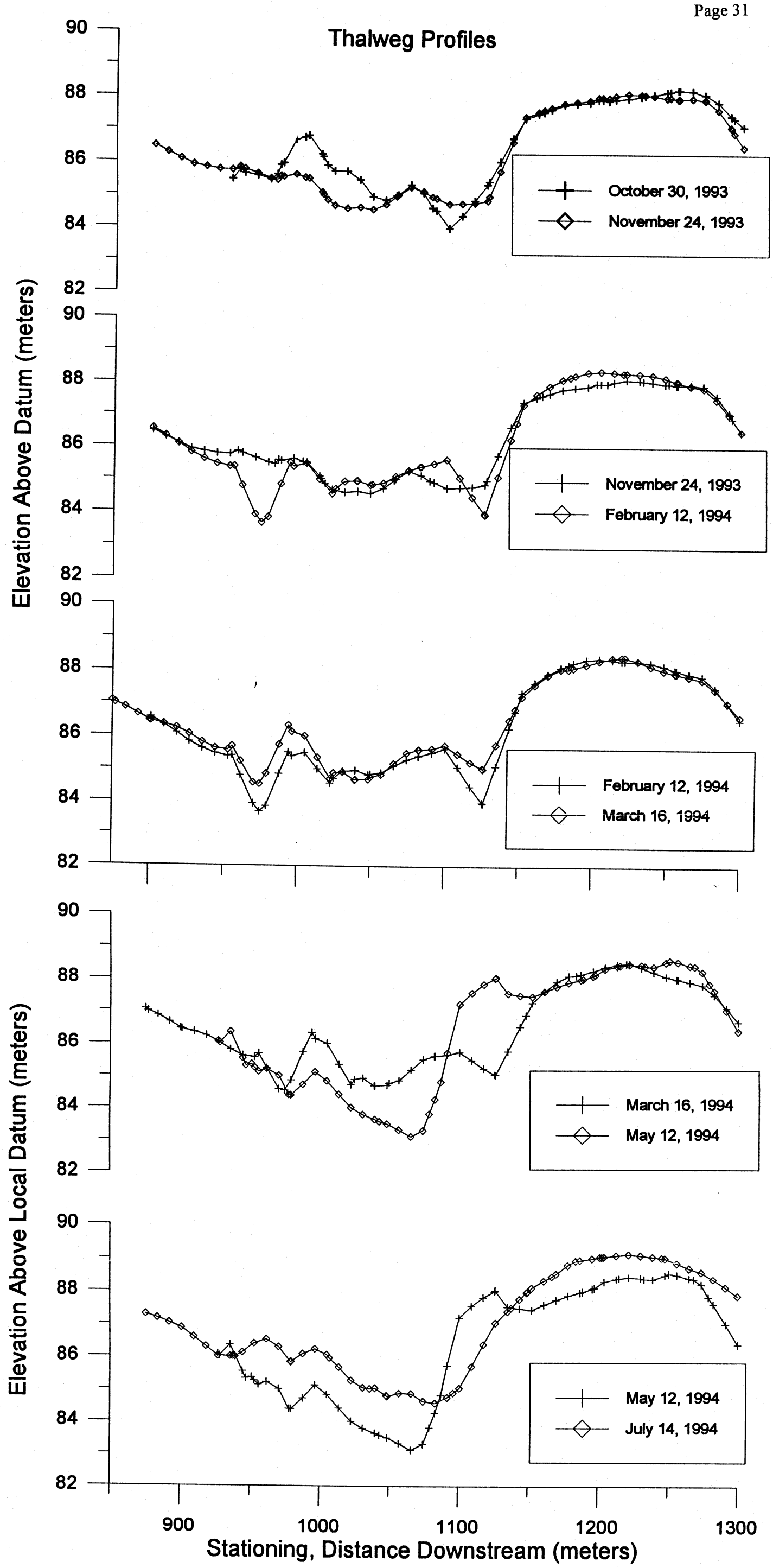


Figure 8. Thalweg profiles for dates shown.

dominant pool located in the distal pool area around range 1100 at 84-85 m elevation (figure 9). The May and July surveys document the only significant adjustment in the downstream riffle area which increased in elevation about 0.75 m overall (figure 8e). It is unknown if the riffle adjustments occurred during peak discharge or during the flood recession because it was not possible to survey the channel during peak flow with the available equipment.

The repeated channel surveys show that the pool progressively enlarged during low flow conditions to a longer and overall deeper pool. During the rising limb of the 1994 flood, the middle part of the pool was deepened and approximately the same volume of sediment scoured was deposited on the pool exit slope forming a large dune (about 4000 m^3).

The response of the eddy deposit to changes in pool geometry and discharge can be interpreted in terms of the expenditure of energy in the eddy-pool environment. As discharge increases the length of eddy recirculation zones expand because the flow separation point migrates upstream and the reattachment point migrates downstream. During the 1994 flood, the pool contracted and shifted upstream while the recirculation zone was expanding downstream. I hypothesize that these hydraulic and geomorphic changes associated with the rising limb of the flood combined to result in eddy velocities capable of entraining the eddy sands, as suggested by the semi-circular scour pattern photographed at MP26, and visible sand suspension in the eddy. Scour of the eddy deposit increased the recirculation zone area which resulted in decreased eddy velocity as a new, but temporary, equilibrium was reached between flow velocity and entrainment of eddy sand. As the flood discharge continued to increase, erosion continued until the eddy deposit was largely eroded and the temporary pool deposits were also scoured. At that time, the lengthened pool geometry allowed the recirculation zone to expand downstream as well as into the eddy laterally, which

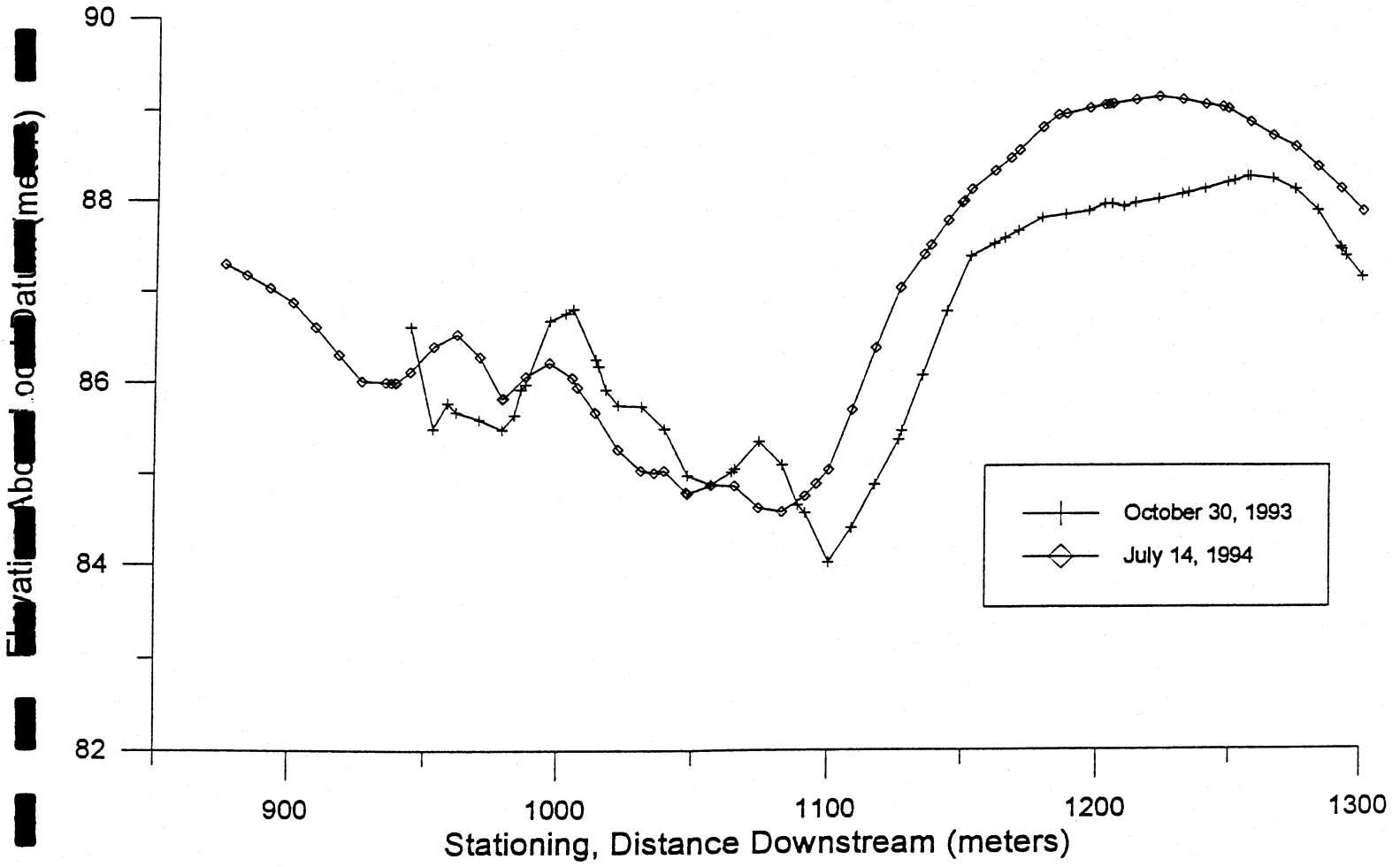


Figure 9. Comparison of post flood thalweg profiles, 1993 and 1994.

minimized velocity in the recirculating eddy. With this set of conditions, the eddy recirculation zone changed from an erosional to a depositional environment and deposition of a new eddy bar began. Following the 1994 flood, the channel, pool and eddy deposit had attained geometry similar to the post 1993 flood channel, pool and eddy deposit (figure 9). The low flow season pool geometry produces a large and low velocity recirculating eddy in which the sandy eddy bar is stable for the remainder of the year. Upstream and downstream lengthening of the pool, followed by localized deepening during the rising limb, and resetting of the pool geometry to previous conditions appears to be a cyclic process that is active during low flow seasons as much as it is during flood flow.

SEDIMENT TRANSPORT DYNAMICS

The local channel processes of scour and fill are linked to the local depletion and accumulation of transportable sediment in the reach. For a pool to scour, the transport of sediment out of the pool has to exceed the supply of sediment reaching the pool. Conversely, for a pool to aggrade, the supply of sediment to the pool has to be greater than the amount of sediment transported out of the pool. The MP26 pool was aggraded to maximum extent measured immediately after the flood receded and slow progressive scour ensued during the low flow season until the pool reach maximum length in mid-winter. This pattern suggests that sediment transport capacity through the pool exceeded the supply to the pool during the low flow seasons. During the rising limb of the 1994 flood, the pool was shortened by deposition at the upstream and downstream ends and locally deepened, suggesting that the supply of sediment increased at a rate higher than transport capacity increased. This relationship is

supported by measurements from the Cisco gage (Figure 10) as well as many other dryland rivers where plots of water and sediment discharge from pronounced hysteresis loops.

The observed sequence of annual scour and fill of pools as it relates to flood passage is more complex than the normal concept (e.g. Lane and Borland, 1954; Leopold and Wolman, 1960). It is typically thought that pool filling occurs during the low flow season and that pool scour occurs during flood flows. More recent investigations (i.e. Lisle and Hilton, 1992) show that some pools fill immediately after flood passage. The complexity of seasonal pool adjustments observed at MP26 is probably the result of strong segregation between sand and gravel sized sediments, and variations in the temporal availability of sand for downstream transport.

Erosion of the MP26 eddy bar would increase the volumetric sand concentration by 0.5 for 24 hours at 20,000 cfs. If several eddy bars eroded within a short period of time, the results would be that the rising limb of floods would load the river with a large volume of sand sized sediment during the early phase of a flood cycle. Some of that increased load would be temporarily deposited where transport capacity was lowest. A volume of sediment transported into a pool during increasing discharge would temporarily deposit on the pool entry and exit slopes, as observed at MP26. Temporary deposition in the pool entry and exit areas contracts the pool, resulting in shortening the pool and the associated eddy recirculation zone, which in turn causes increased eddy velocities. Increases in eddy velocity would result in erosion of the adjacent eddy bar to increase the area of flow recirculation and reduce flow velocity. A cascading series of pool deposition and eddy erosion events might progress downstream during an annual flood event as sediment enters the channel from eddies. Clearly, throughout an

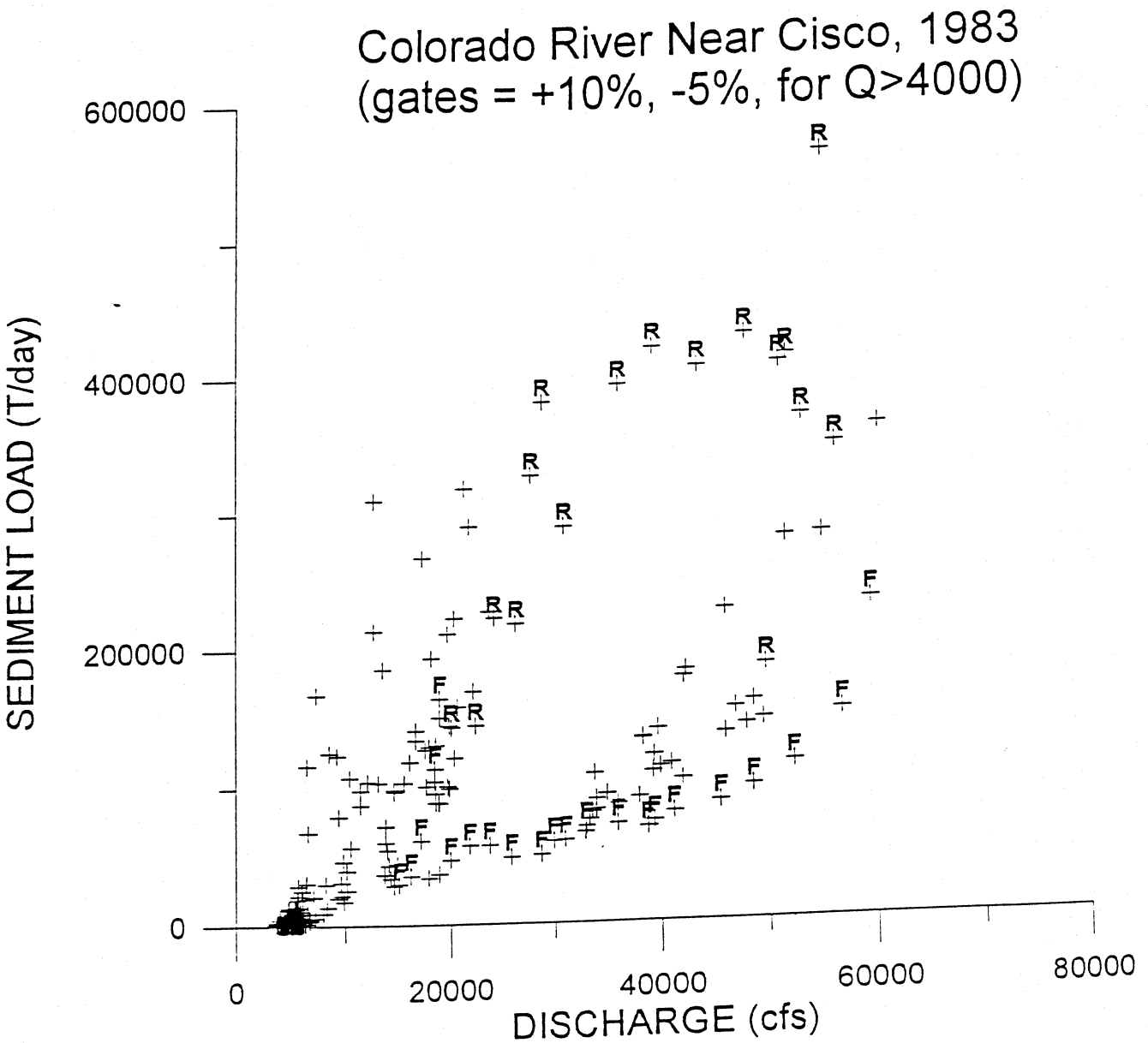


Figure 10. Plot of sediment load and water discharge showing pronounced hysteresis effets between the rising limb (R) and falling limb (F) of the 1983 annual hydrograph at the Colorado River near Cisco gage.

annual flood cycle, eddies are sometimes erosional and sometimes depositional environments for sand. However, such cyclic dynamics require a certain amount of mobile sediment in the river channel that can modify pool geometry before eddy scour and re-deposition can occur.

RESULTS OF THE 1995 FLOOD

The highest flow observed during the study period occurred in Spring 1995 when flood flow reached 51,400 cfs in June (4-5 year recurrence). Time-lapse photographs show the eddy bar eroding during the rising limb of the flow, in an arc shape due to erosive eddy recirculation (figure 6f). The relatively low elevation eddy bar became completely submerged during the early part of the rising limb of this flow on June 5 when discharge was 12,200 cfs. Flow had receded to approximately 5000 cfs early in September 1995 and photographs show that the entire eddy deposit was eroded during the flood but was not re-deposited (figure 6g). Vertical cut banks extending into the large woody vegetation of the reattachment deposit indicate that the toe of that deposit was also eroded during the flood. Based on previous photographs of exposed deposits calibrated by topographic surveys, the Spring 1995 flood eroded an area approximately 2500 m^2 (figure 7) and the minimum volume eroded is estimated at 8000 m^3.

This response differs from the previously observed pattern where the rising limb of flood flows (or icing conditions in 1992) eroded the eddy bars but they were subsequently re-deposited during the peak or recession limb with sizes, elevations and morphologies controlled by the magnitude of the flood. Deposition of an eddy bar depends on adequate sediment supply and recirculating flow patterns for a certain period of time. Erosion of the eddy bar also depends on sediment of sufficient supply to change the channel geometry and switch the

eddy from a depositional to an erosional environment. So what processes might explain the vast differences between the results of the 1993, 1994 and 1995 floods? Several possible reasons for the different responses of the sand bar are presented in the following section. Although thorough, other reasons may exist that are not presented.

The 1993 and 1995 peak magnitudes were very similar, 49,300 and 51,400 cfs, respectively (figure 11a). This corresponds to a stage height difference of only 0.12 m at the Cisco gage, which would be less in the MP26 area because the channel is wider. The debris fan is broad and low angle and is overtopped by discharges exceeding 10,000-12,000 cfs. Daily photographs show that a recirculation zone existed throughout the flood flow of 1993, including the peak discharge. Less frequent photos in 1995 also show a large and well developed recirculation zone at high discharges. Consequently, recirculating flow existed throughout the range of discharges observed, so the slight differences between the peak discharges do not seem capable of producing such differing results. The 1995 peak discharge was not significantly greater than the 1993 peak but the duration was considerably longer. Flow volumes were 5.5 maf compared to 4.9 maf for 1993 and 1995, respectively (figure 11b) (calculated as cumulative flow greater than 8,000 cfs).

Another factor that may explain the different results is the duration of discharge over some specific value greater than the discharge at which the eddy deposit formed previously. The 1994 flood flow reached a peak value of approximately 15,000 cfs and in 1995 the eddy bar was inundated at discharges around 12,000 cfs. For all three years the MP26 debris fan was overtopped at discharges around 12,000 cfs, so 20,000 cfs discharge seems an appropriate threshold for comparing flood duration. During the 1993 flood, discharge exceeded 20,000 cfs

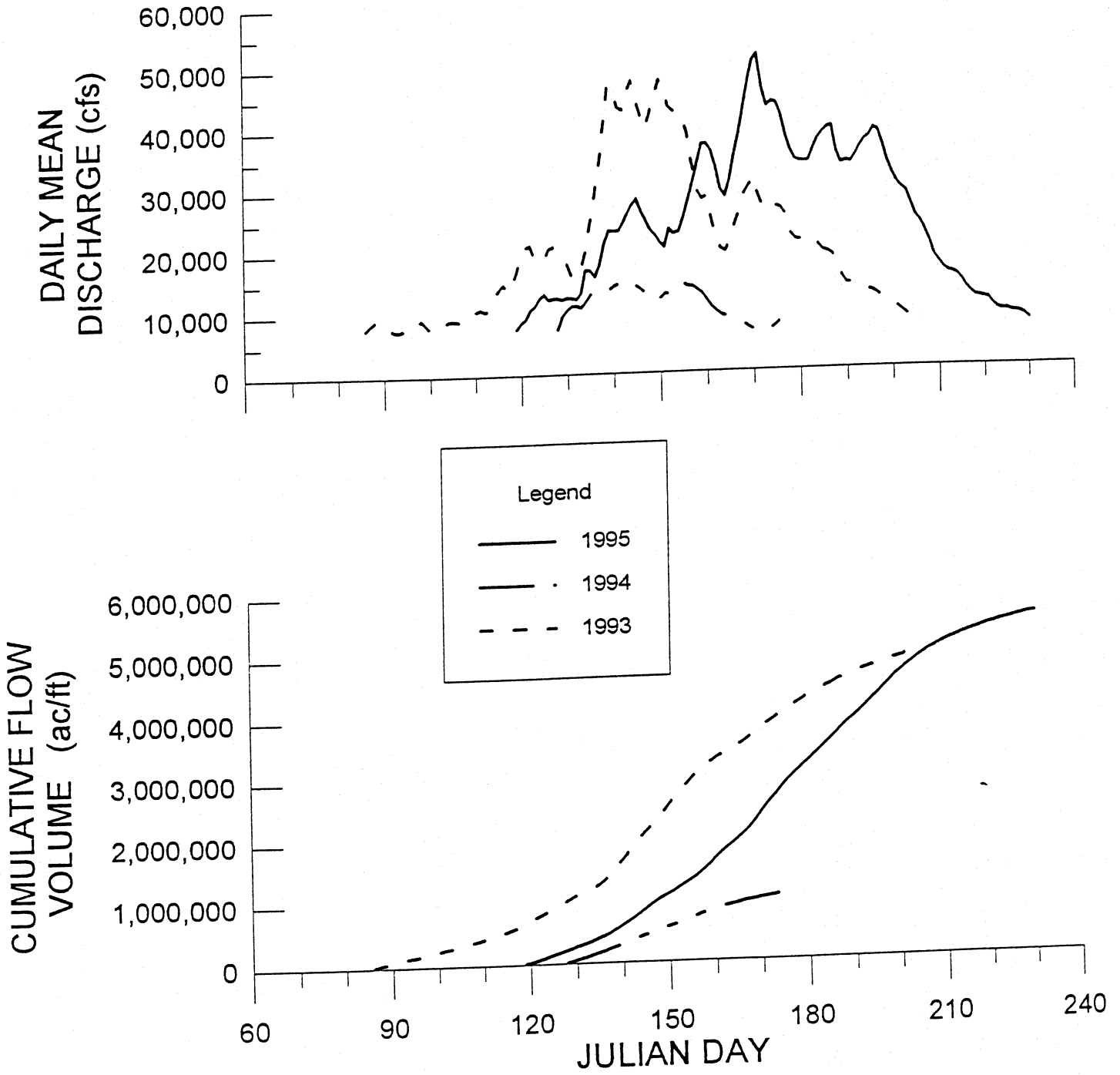


Figure 11. Comparison of daily mean discharges (*a*) and of cumulative flow volumes above 8,000 cfs (*b*) for three floods, 1993, 1994 and 1995.

for 48 days and for 71 days in 1995, an increase of 67%. So the volume and duration differences between the 1993 and 1995 floods might explain the different bar responses through the dynamic balance between sediment supply and sediment transport.

This reach is essentially gravel bedded with patches of sand in temporary storage as sand bars, as bedforms or in storage among the gravel on the channel bottom. The prolonged flood duration in 1995 may have resulted in local depletion of the sand supply needed to form an eddy deposit at MP26. However, the 1994 flood was small by comparison to the 1993 and 1995 floods and sand supply should have remained abundant in the local reach following the 1994 flood. Sand storage may have actually increased beyond average conditions because the 1995 flood was one month later than normal and Spring 1995 was wetter than average. There was a prolonged time period for deposition to occur in the eddy at MP26 during the 1995 flood and the deposit should have become large before sediment depletion occurred in the channel. Also, if the local sand supply depletion theory was correct, adjacent eddy bars should record similar responses. An inventory of sand deposits in flow separation zones along the reach indicated that other deposits that existed in 1993 and 1994 still existed in 1995. They consisted of bare sand, were fully connected to adjacent reattachment bars, and appeared to have been reworked (emergent vegetation was scoured) and re-deposited at higher elevations by the 1995 flood. This line of reasoning leads to the conclusion that depletion of the local sediment supply is probably not the cause of failed eddy bar deposition at MP26 in 1995.

Another difference between the 1993 and 1995 floods is the timing. The initial rises from base flow to 8,000 cfs were on March 27, 1993 and on April 29, 1995. Flow recession below 8,000 cfs was on July 22, 1993 and August 17, 1995. Peak flood discharge was reached on May 18 in 1993 and on June 19 in 1995. Essentially, the 1995 flood was one month later

than the 1993 flood. Might the timing have an effect on sediment supply? The tributaries supplying sediment to the river are formed in highly erodable, sparsely vegetated badlands between Grand Junction, Colorado and Green River, Utah. Such terraines are characterized by low annual precipitation and flash floods that occur most often in the Summer months due to thunderstorms. That is when sediment would be delivered to the main channel. Because the 1995 flood was one month later than the 1993 flood it is not likely that there was significantly less sediment supply in the river channel. Again, sediment transport measurements are not taken at the nearby USGS gage.

Another aspect of the 1995 flood flow was two secondary peaks of approximately 40,000 cfs following intermediate troughs of slightly less than 34,000 cfs (figure 11a). The scour of eddy deposits occurred during increasing discharge at MP26 during the 1993, 1994 and 1995 annual flood events. It has also been documented multiple times in the regulated Grand Canyon reach that eddy bars were scoured on the rising limb of daily fluctuating flows (Carpenter et al., 1991; Cluer, 1991; Cluer et al., 1993; Cluer and Dexter, 1994).

As explained previously, temporary changes in sediment supply and transport capacity can result in temporary modification of the pool geometry which changes eddies from depositional to erosional environments. This process was observed during increasing flows in the unregulated river at MP26. It has been observed in the regulated river that eddy bars erode during increasing discharge also. A conceptual model has been emerging from the Grand Canyon eddy scour observations that an eddy deposit attains a maximum size (depending on maximum discharge) whereupon a critical stability threshold is reached. The bar is then susceptible to large-volume erosion by flow fluctuations that were similar to or even identical to 10's or 100's of flow fluctuations that occurred prior to and that actually deposited the bar.

Erosion events may be triggered by changes in pool geometry. Erosion occurs during increasing discharge and over a period of a few hours thousands of cubic meters of sand can be scoured from eddy deposits. This idea might explain the unexpected response of the MP26 eddy deposit to the 1995 flood flow. Applying this concept to MP26 for the 1995 flood flow; following scour of the 1994 eddy deposit during the rising flood flow in May 1995, deposition in the eddy recirculation zone proceeded at a high rate due to high peak discharge. A large eddy bar would have been deposited by the time of the primary peak flow period because of the prolonged flow duration, and then during either the first or second subordinate peaks, the eddy bar would have been scoured. Because flood recession was rapid after the secondary peaks, there was not sufficient time for deposition of a new eddy bar before low summer and fall discharges occurred, and the eddy recirculation zone remained without an exposed eddy bar for the remainder of the annual flow cycle.

The automatic camera malfunctioned for the first time in three years during the peak of the 1995 flood flow. This unfortunate incident prevents confirming the critical threshold concept from this example, but the concept is consistent with observations from the regulated river. This conceptual model will be tested by analysis of detailed hourly channel topography and velocity field data obtained by the author in the Grand Canyon prior to and during an eddy scour event in Summer 1993.

SYNTHESIS

Eddy deposits, and other types of channel margin deposits, represent temporary off-channel storage of the fine grained fluvial sediments that exist in a bedrock river system. The sand stored in channel margin deposits is both a source of sand for future entrainment by the river and a sink of sand deposited by the river in the past. The amount of time that sand remains in storage as a channel margin deposit depends mostly on the frequency and timing of discharges that engage the deposits or deposits that protect higher elevation deposits. The unregulated river deposits were in static storage throughout the 10-11 month low flow seasons between floods. The regulated river deposits are adjusted more frequently, sometimes daily, by hydropower discharges.

The unregulated river deposits formed by flows with 4-5 year recurrence were scoured by floods with 1-2 year recurrence. Erosion occurred during the rising limb. Eddy bars were re-deposited with volume and elevation controlled by the magnitude as well as the duration of the peak. The eddy bars were then exposed during flow recession. Observation of erosion events in the Grand Canyon showed that the entire volume of sand stored in eddy deposits was entrained on the rising limb and transported into the channel and downstream (Cluer et al., 1993). These observations from the regulated and unregulated rivers leads to the idea that it is common for a large number of, if not all, eddy deposits to be scoured on the rising limb of floods. On a reach length scale this represents a significant volume of sand that comes from off-channel storage during the rising limb, increasing the sediment concentration of the sand size fraction in transport. Sediment transport/discharge hysteresis loops are common in plots

for many dryland rivers as are pulses of sediment transport unrelated to variations in water discharge (Lekach and Schick, 1983).

A pulse of sediment moving through a pool-eddy system that was in equilibrium might provide an alternative explanation for the failed 1995 eddy bar at MP26 as well as an explanation for some eddy erosion observations in the Grand Canyon. A high concentration of sediment entering the pool might temporarily deposit in the entry and exit areas, thus modifying pool geometry and associated eddy flow velocities much like the sequence of events that occurs annually during the rising limb of floods. A sediment pulse could effect a local pool and eddy at any time over a wide range of discharges.

There is one major annual cycle of erosion and deposition in the naturally flowing river setting. In the regulated river environment downstream of Glen Canyon Dam, Cluer and Dexter (1994) documented several cycles of erosion and deposition at the eddy bars they photographed daily. The mean number of erosion/deposition cycles was 2.1 (STD = 2.3) for a sample of 20 sand bars during low fluctuating 'interim operating criteria' discharges over the period March 15, 1992-December 31, 1993. This corresponds to a mean annual number of cycles equal to 1.2, however none of the sand bars experienced the mean. Six sand bars experienced no cycles, and three sand bars experienced 5-8 cycles over the 20.5 month period of time. Similar numbers of erosion/deposition cycles were documented during 1994 and 1995 by continued monitoring of the same sample (Dexter and Cluer, 1995). The erosion deposition cycle frequencies and periods are graphically presented in figure 12. Cycle period is annual for sand deposits along the naturally flowing river. On the regulated river the cycle periods ranged from a minimum of 6 days to a maximum of 390 days, with six deposits undergoing no erosion/deposition cycles. Each cycle of erosion/deposition transports large quantities of sand-

sized alluvium from temporary storage to the channel where it is transported downstream. Each cycle also incorporates some sand from higher elevations above the most frequent maximum discharge.

THE UNREGULATED RIVER - OTHER OBSERVATIONS

Eddy deposits are inundated during floods with annual duration of 30-50 days. The rest of the year provides an extensive period when the bare sand eddy deposits are exposed. During this time, the large exposed surface of MP26 was dry and significant quantities of sand were transported from this surface by wind. Entrainment of sand by wind was especially pronounced during the late Summer and Fall seasons when strong afternoon winds were common. Winds blowing through the canyon were strongest along the axis of the river and diffusion occurred outward across the channel margins where the sand deposits occur. Although winds blow up and down the river, the prevailing direction of sand transport was away from the river. Sand was transported from the bare sand eddy deposit surface near the river to the vegetated reattachment deposit and bank along river right. A large sand dune, with average thickness of approximately 0.75 m, formed on top of the eddy deposit. The dune consisted of an estimated sand volume of 2000 m^3 eroded from the eddy bar and transported up slope where it was deposited and stored at an elevation that was greater than the eddy deposit that formed in 1993 (49,300 cfs). Although the 1995 flood inundated the aeolian dune, part of the aeolian sand deposited along the vegetated river bank was not reached by the 1995 flood (51,400 cfs). The aeolian processes transport sand from low elevations from the large

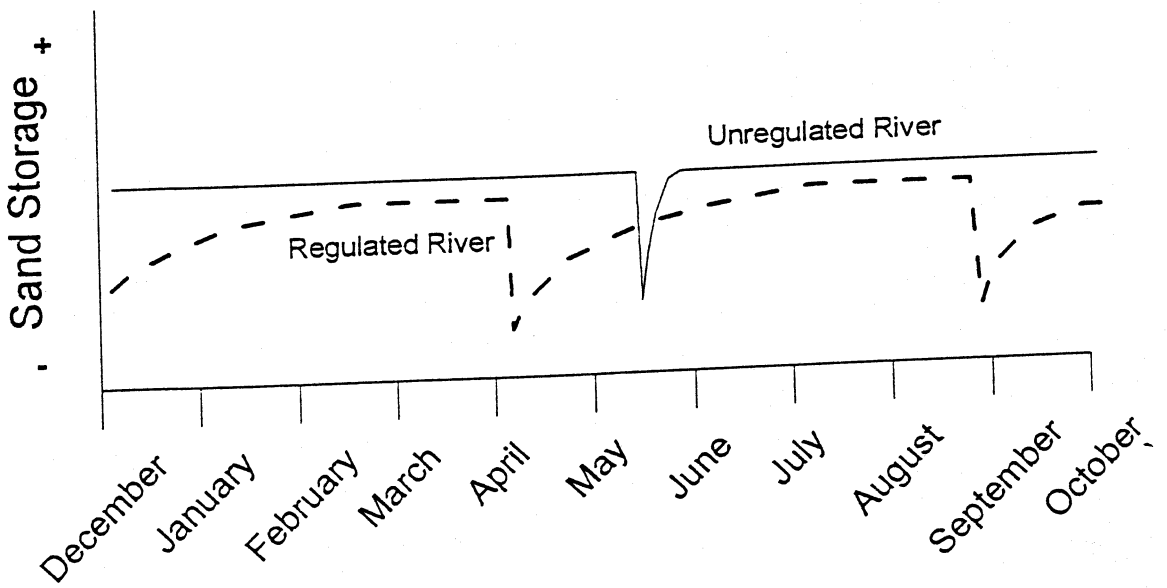


Figure 12. Diagram showing the differences in cycle period lengths for regulated and unregulated rivers.

dry eddy bar surface to high elevations that are protected by vegetation and out of reach from flood discharges with 4-5 year return period and greater. In the regulated river environment these processes are limited by the range of fluctuating flow and minimum discharge because the bare sand eddy deposits are typically re-wetted daily or become heavily vegetated between significantly large flow events (Stevens, 1989). Over long time periods, the aeolian transport of sand from the river to the banks may be important for soil development in the riparian environment at elevations not often reached by flood flows.

During the Winter of 1993-1994 several interesting observations were made of the return current channel (RCC) backwater environment. Dimensions of the backwater channel were about 30 m long, 2-5 m wide, and 08 m mean depth. The channel was open to the river through a constricted and shallow opening about 5-10 cm deep. On October 30, 1993 there was a thin covering of ice over the backwater. On February 12, 1994 the ice was approximately 5 cm thick and several hundred small (2-5 cm long) fish (unidentified) were actively utilizing the habitat that was closed to the river at that time. The water temperature was much greater to the touch in the backwater than in the river, or the ambient air temperature, as solar radiation penetrated the ice cover. Aquatic plants colonized the backwater and it appeared that the RCC had transformed into a productive off-channel nursery during the Winter months. These processes have not been observed along the regulated Colorado River in the Grand Canyon where daily flow fluctuation and unseasonably warm Winter dam releases prevent ice formation in backwaters.

The areal coverage of dense riparian vegetation more than doubled from 1952 to 1993 (from approximately 40% in 1952 to 100% in 1993, based on 1993 area) (figure 4b). Most of the increase occurred along the channel banks, although there was some measurable

encroachment of vegetation onto the bare sand eddy deposits. The species make-up was not analyzed but the woody exotic *tamarisk* currently makes up a significant part of the riparian vegetation in the reach from Dewey Bridge to Moab. It has been documented elsewhere in the Colorado River and Green River basins that tamarisk invasion has replaced the native Cottonwood and willow riparian species and resulted in decreased channel widths through bank stabilization over the past 2-3 decades (Graf, 1978; Andrews, 1986; Lyons et al. 1992).

An unexpected result of this study is the apparent correlation (figure 13) (correlation coefficient = 0.97) between increased riparian vegetation coverage and increased late summer discharges (figure 4b). Tamarisk is not an obligate phreatophyte species, but its germination and early root development are dependent upon water availability. The assertion that there is a temporal connection between tamarisk invasion and increasing growing season discharges may warrant further investigation, although the correlation may be spurious simply because the invasion of tamarisk in the upper Colorado River coincides with the period covered by the aerial photographs. Interestingly, the percentage of vegetation coverage continued to increase through the period of record high floods in the early 1980's. This suggests that floods with 20-30 year return periods are not capable of significantly reducing the existing exotic riparian vegetation. This too warrants further investigation because vegetation control, particularly control of exotic species, is an important issue in modern river resource management.

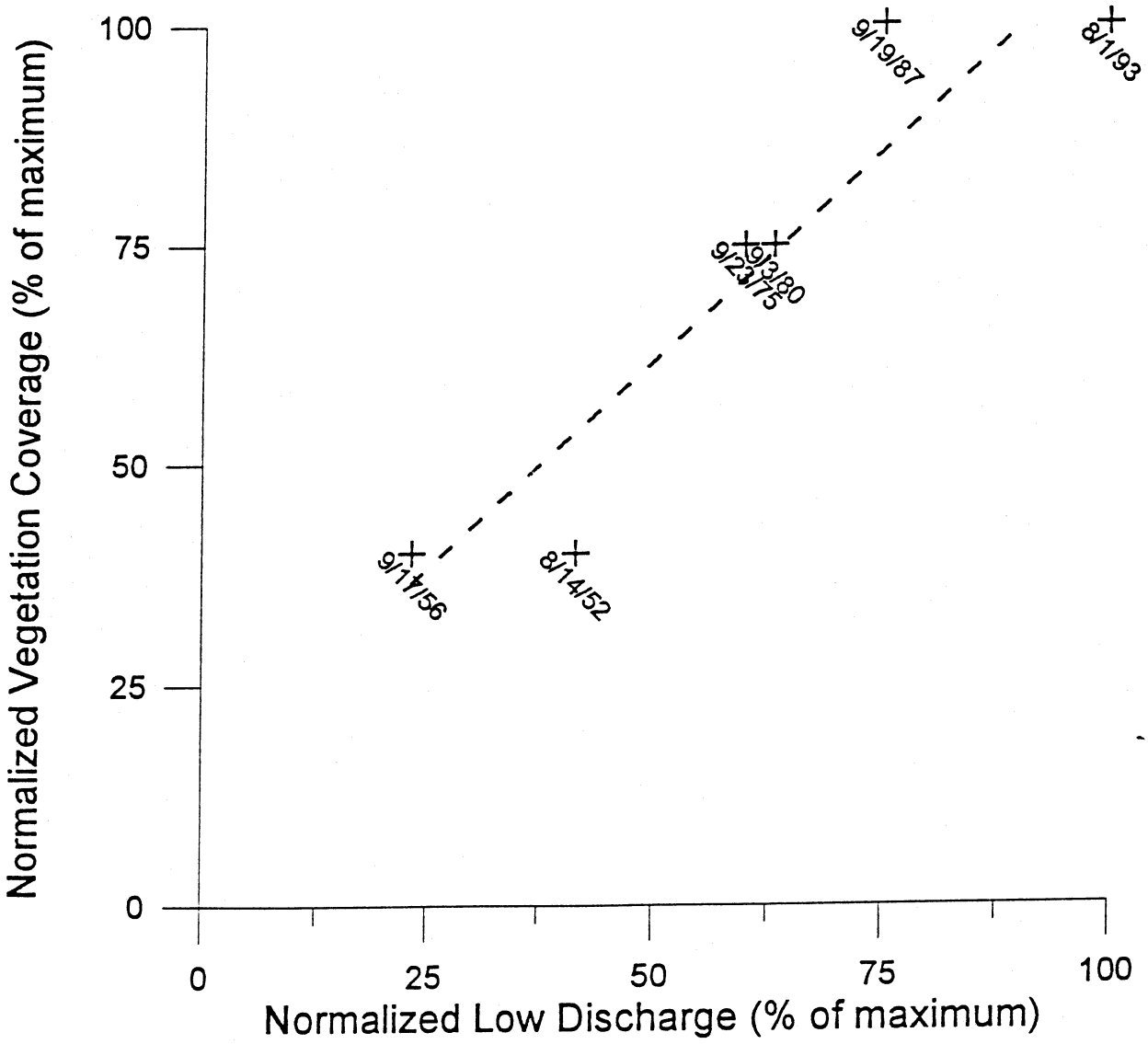


Figure 13. Plot of percentage vegetation coverage versus discharge at the time of aerial photography (normalized to the highest discharge). Correlation coefficient between the two parameters is 0.97 and the regression R^2 is 0.86.

SUMMARY AND CONCLUSIONS

There was a progressive evolution of the unregulated river channel during the annual flow cycle. The pool scoured and elongated in the upstream direction between the period of flood recession and Winter low flow. During the rising limb of a flood with 1-2 year recurrence, the pool was deepened but shortened in the upstream direction. During the receding limb of the flood, the pool was aggraded as was the riffle. The unregulated river eddy bar was completely eroded during the rising limb and re-deposited during the receding limb of this flood. The eddy bar then stabilized throughout the low flow season until the next annual flood. Regulated river eddy bars also eroded during the rising limb of daily hydropower fluctuations with discharges in the range of 1-2 year flood recurrence on the unregulated river. Observations from both rivers suggest that the cause of eddy bar erosion is due to hydraulic conditions in the eddy recirculation zone that result from changes in channel geometry during increasing discharge.

Eddy deposits were eroded during the rising limb of floods in both the regulated and unregulated river environments. The longevity of the deposits is controlled by the return period of subsequent floods. Eddy bars are deposited during receding discharge, at discharges which scour on the rising limb. The management paradox is that small floods erode bars that were deposited by large floods and only large floods can deposit large bars.

Cycles of sand bar erosion and deposition occur in the naturally flowing river system and in the regulated river system. The cycles are more frequent but somewhat smaller magnitude in the regulated river system because the range of discharges is smaller. The major differences are in the timing and frequency of the cycles. In the natural river,

erosion/deposition cycles are an annual occurrence driven by the annual flood. In contrast, erosion/deposition cycles can occur several times per year and at any time of year in the regulated river. The frequency of cycles is important from a sediment storage and sediment transport perspective. The timing of erosion/deposition cycles are probably important from biological perspectives. The longevity and long term stability of high elevation sand bars, important resources in the Grand Canyon, are directly related to the frequency and magnitude of erosion cycles affecting the lower elevation eddy deposits. During periods when the low elevation deposits are re-depositing following erosion events, high elevation deposits retreat. Because high discharges are required to deposit sand at high elevations, and high discharges are infrequent in the regulated river environment, minimizing erosion cycles of low elevation deposits could prolong high elevation deposits.

On the unregulated river, the long-term variability in eddy bar size was much less than the short-term variability. Sand bars are spatially persistent through time because their hydraulic controls are stable over long time spans. However, the unregulated river eddy bars are completely reworked each year and return to similar size and morphology after a wide variety of flood magnitudes. Monitoring at a consistent time each year, after flood recession and before significant wind erosion, would allow detection of long term trends in sediment supply because the period of stasis is 10-11 months long. Regulated river sand bars also experience cycles of erosion and deposition but the cycles are not synchronized because there is not an annual hydrologic event. Furthermore, some regulated river bars undergo several cycles of erosion/deposition annually.

Monitoring regulated river sand bars on a calendar schedule unknowingly includes but does not quantify the significant effects of erosion/deposition cycles. The effects are significant

because the variance caused by an erosion/deposition cycle greatly exceeds the variance of long term adjustments. Quantifying the short term variance leads to different interpretations of long term information, and that information is needed to document trends caused by river management actions. Monitoring changes in high elevation deposits may be more productive than monitoring high and low elevation deposits together, as is the current practice in Grand Canyon.

Wind processes during the extensive low flow season on unregulated rivers are important in forming and maintaining high elevation sand deposits. These processes are diminished along rivers that are regulated for peaking hydropower, because the sand bars are either frequently wetted or become vegetated. Return current channels, or backwaters, along the unregulated river support biological processes that have not been observed in the regulated river return current channel environment. Processes associated with annual erosion and deposition of large volumes of sand along the river margins may affect biological processes, for example: the sudden release of sediment to the river during the rising limb of floods may be rich in nutrients, rejuvenation of the return current channels used by juvenile fish on an annual basis, and perhaps other processes not identified yet.

As floods become a valuable tool for regulated river resource management, predicting the outcome of floods is important. This is a difficult task because the result of a flood at an individual eddy depends on local variables such as sediment supply and the dynamic hydraulics of eddy recirculation and channel geometry adjustments in response to a vacillating sediment supply-sediment transport relationship. There may be other important processes and variables that are stochastic in nature, such as sediment transport in pulses, that are simply not known at this time.

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REFERENCES CITED

Andrews, E.D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97: 1012-1023.

Baars, D.L., 1972. Red Rock country-the geologic history of the Colorado Plateau. Doubleday/Natural History Press, New York, 73 p.

Beus, S.S., and Avery, C.C., (eds) 1991. The influences of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam. United States Department of Interior Bureau of Reclamation Glen Canyon Envrionmental Studies Program Report P3. Flagstaff, AZ.

Beus, S.S., Carothers, S.W., and Avery, C.C. 1985. Topographic changes I fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon. Journal of the Arizona/Nevada Academy of Science, v.20, p.111-120.

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

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

Cluer, B.L., 1995. Cyclic fluvial processes and bias in environmental monitoring, Colorado River in Grand Canyon. The Journal of Geology, v.103, p.411-421.

Cluer, B.L., and Dexter, L.R., 1994. Daily dynamics of Grand Cayon sandbars; monitoring with terrestrial photogrammetry. Final Report, U.S. Department of the Interior, National Park Service. Flagstaff, AZ. 200p.

Cluer, B.L., and Hoeting, J., 1995. Statistical analysis of aerial photography data base from the GCES-II test flow program. Final proposal and work plan, National Park Service National Natural Resource Center, Fort Collins, CO.

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

Dexter, L.R., and Cluer, B.L., 1995. Extension study: daily dynamics of Grand Canyon sandbars; monitoring with terrestrial photogrammetry. Draft Final Report, U.S. Department of the Interior, National Park Service. Flagstaff, AZ. 121p.

Dexter, L.R., Cluer, B.L., and Manone, M.F., 1995. Using land based photogrammetry to monitor sandbar stability in Grand Canyon an a daily time scale. *In,* VanRiper, C., III, *ed.*: Proceedings of the Second Bienial Conference of Research in Colorado Plateau National Parks. Transactions and Proceedins Series, National Park Service. p. 67-86.

Dexter, L.R., Cluer, B.L., *in review.* Erosional stability of sandbars in Grand Canyon. Manuscript submitted to Annals, Association of American Geographers.

Dynesius, M., and Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science, v.266, p.753-761.

Gore, J.A., and Petts, G.E., (eds), 1989. Alternatives in Regulated River Management. CRC Press, Inc., Boca Raton, FL.

Graf, W.L., 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geological Society of America Bulletin 89: 1491-1501.

Howard, A.D., and Dolan, R., 1976. Alterations of terrace deposits and beaches of the Colorado River in the Grand Canyon caused by Glen Canyon Dam and by camping activities during river float trips: summary, management implications, and recommendations for future research and monitroing. University of Virginia, Grand Canyon Study, Technical Report 7. 29p.

Kaplinski, M.A., Beus, S.S., Hazel, J.E., and Kearsley, L., 1994. Monitoring the effects of interim flows from Glen Canyon Dam on sandbar dynamics and campsite size in the Colorado River corridor, Grand Canyon National Park, Arizona. Draft Final report. National Park Service contract report, 38 p. plus appendix.

Lisle, T.E., and Hilton, S., 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. Water Resources Bulletin, v.28, n.2, p.371-383.

Lyons, J.K., Pucherelli, M.J., and Clark, R.C., 1992. Sediment transport and channel characteristics of a sand-bed portion of the Green River below Flaming Gorge Dam, Utah, USA. Regulated Rivers: Research and Management, v.7, p.219-232.

National Research Council, 1996. River resource management in the Grand Canyon. National Academy Press, Washington, D.C.

Lekach, J., and Schick, A.P., 1983. Evidence for transport of bedload in waves: analysis of fluvial sediment samples in a small upland channel. Catena, v.10, p.267-279.

Pemberton, E.L., 1976. Channel changes in the Colorado River below Glen Canyon Dam, *in* Proceedings of the Third Inter-Agency Sedimentation Conference. Water Resources Council Sedimentation Committee, v.5, p.61-73.

Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Progress in Physical Geography, v.3, p.329-362.

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

Schmidt, J.C., Grams, P.E., and Webb, R.H., 1995. Comparison of the magnitude of erosion along two large regulated rivers. Water Resrouces Bulletin, v.31, n.4, p.617-631.

Schmidt, J.C., and Rubin, D.M., 1995. Regulated streamfow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. *in* Costa, J.E., et al., *eds.* Natural and Anthroponeic Influences in Fluvial Geomorphology, American Geophysical Union, Geophysical Monograph 89.

Stevens, L.E., 1989. Mechanics of riparian plant community organization and succession in the Grand Canyon, Arizona. Northern Arizona University Ph.D. dissertation. Flagstaff, AZ.

United States Bureau of Reclamation, 1995. Operation of Glen Canyon Dam, Final Environmental Impact Statement. Bureau of Reclamation, Salt Lake City, UT.

Wegner, D.L., Stevens, L., and Melis, T., 1996. Controlled flood studies, Glen Canyon Dam, Spring 1996. Glen Canyon Environmental Studies Office, Bureau of Reclamation, Flagstaff, AZ.