Clark, Jeffrey J., 1992, Analysis of sediment storage changes of the Colorado River near Nankoweap Rapids in Grand Canyon, Arizona: Unpublished senior thesis, Middlebury College, Middlebury, Vermont, 95 p.

ABSTRACT

The construction of Glen Canyon Dam in 1963 has changed the hydrology, sediment transport, and geomorphology of the Colorado River in Grand Canyon. Changes in sand bars were evaluated in a wide reach 111-118 km downstream from Glen Canyon Dam by repetitive mapping of surficial geology. Mapping was on a base of 1:2400 scale topographic maps for 1965, 1973, 1980, 1984, 1985, 1987, 1988, 1989, and 1990. Changes in deposits were compared in terms of spatial pattern and area of exposed deposit. Longitudinal fathometer traces of the thalweg taken in 1973 and 1984 were compared. Topographic data collected between 1974 and 1987 at Lower Nankoweap camping beach were analyzed.

Area of exposed deposit comparisons show that the system was aggrading from 1965-1982, eroding from 1983-1986, and aggrading from 1987-1990. Topographic profiles from the detailed study site at Lower Nankoweap Beach show degradation from 1974-1982 and aggradation from 1983-1987. Results of the fathometer trace show net degradation of 2.4 meters for the bed from 1973-1984.

These results indicate that regulated floods occurring within a year of a previous flood cause widespread degradation both on the bed and in the banks of the river. Individual sand bars, however, respond differently in detail and can generally be divided into stable (changing in a predictable fashion) and unstable (changing unpredictably) sand bars. Variability may be due to geometry of debris fans and geometry of channel expansions. Because of this variability, inferences drawn from the evaluation of change at a few study sites may misrepresent reach scale changes.

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TABLE OF CONTENTS

		Page
List of Figures		v
List of Tables		vii
1.	Introduction and Purpose	1
2.	Background	4
	Hydrology	4
	Sediment Trapping and Transport	8
	Bed and Bank Response to High Flows	11
	Channel Characterisitcs	12
	Bank Stabilization	14
3.	Methods	15
	Surficial Geology	15
	Sand Bar Stability	17
	Correlation of Fathometer Traces	19
	Topographic Change	24
	Flow Duration Curves	27
4.	Results	28
	Fathometer Traces	28
	Unit Descriptions	33
	Distribution of Mapping Units	41
	Sand Bar Change	46
	Sand Bar Stability	53
	Historical Profiles	56
5.	Discussion	62
	Changes in Sediment Storage 1965-1990	62
	Change in Morphology of Nankoweap beach	66
	Characteristics of Unstable Sand Bars	69
	Impications for Dam Operational Strategy	69
	Future Work	71
6.	Conclusions	72
References Cited		73
Appendix 1		76
Appendix 2		77
Appendix 3		80
Appendix 4		90

LIST OF FIGURES

Figure		Page
1	Map of Study Area	2
2	Hydrograph showing discharge at Lees Ferry	5
3	Flow Duration curves for Colorado River	6
4	Bar Graphs of Flow Conditions 1965-88	7
5	Derrivation of Transport to Discharge Relation	9
6	Sediment Transport vs discharge for Canton Dam	10
7	Flow Patterns and bed deposits in a typical eddy	13
8	Fifteen minute map of study reach	16
9	Maps of Unstable sand bar	18
10	Map showin constriction, expansion and eddy length	20
11	Fathometer Traces for 1973 and 1984	22
12	Map view of fathometer traces in Figure 11	23
13	Map view of profiles at Lower Nankoweap beach	25
14	Howard and Dolan's field map of Lower Nankoweap	26
15	Sand waves on fathometer trace and in map view	29
16	Cobble Bar on fathometer trace and in map view	30
17	Normal Quanitle plot of change in depth 1973-1984	31
18	Hypothetical maps of boat coarse in 1973 and 1984	32
19a	Active reattachment bar	35
19b	Separation bar	35
20	1990 map of 55 mile marsh	37
21a	Channel margin deposit	38
21b	Fern Glen Beach	38
22a	Cobble bar	39
22b	Sand and Boulders	39
23	Submerged Sand	40
24a	Vegetated aeolian dune	42
24b	Unvegetated aeolian dune	42
25a	High terrace near Lower Nankoweap Beach	43
25b	High terrace near RM54	43
26a	"Pancake" flat top of high terrace	44
26b	Nankoweap Creek debris fan	44
27a	Debris fan near Furnace Flats	45
27b	Talus slopes	45
28	Change in area of sand for indicated year (uncorrected)	48
29	Area of water vs discharge	49
30	Area of indicated deposit exposed at indicated discharge	50
31	Residual of indicated deposit vs time	52
32	Expansion ratio vs shape factor	56
33	Lower Nankoweap Beach CS1	57
34	Lower Nankoweap Beach CS2	58
35	Lower Nankoweap Beach CS3	59
36	1973 and 1987 maps showing Nankoweap profiles	61

37 Cumulative sand storage in Colorado River near Grand Canyon Gage.......... 63
38 1973 and 1984 Flow patterns for Lower Nankoweap Beach..67
39 Hypothetical flow pattern models..........70

LIST OF TABLES

Table		Page
1	General Information on aerial photographs	15
2	General Information on profiles at lower Nankoweap Beach	24
3	Fathometer trace results	31
4	Summary of units used in mapping surficial geology	34
5	Arc Info data for map 4	47
6	Arc Info data for map 2	54
7	Summary of measurements taken on major reattachment bars	55
8	Results of different methods of determining sediment change	66

INTRODUCTION

The Colorado River winds its way through the bedrock gorge of the Grand Canyon for 470km (Figure 1). Within this gorge, the once undammed river is now regulated by Glen Canyon Dam. The dam, completed in 1963, is responsible for changes in the hydrology and geomorphology of the river. This paper discusses the effects of Glen Canyon Dam on an 8.3-km reach in the vicinity of Nankoweap Creek, located 108-km downstream from Glen Canyon Dam.

Dams are constructed for many reasons. One of the most common of which is water storage. In addition, these reservoirs may provide hydroelectric power, flood control, and recreational opportunities. They also trap sediment, change the temperature of water, and alter the natural seasonal flow regime (Hirsh and others, 1990). Glen Canyon Dam is a "cash register" dam. Its sole purpose is to generate power, which is sold to generate income. The dam has the added benefit of a large, scenic artificial lake that attracts thousands of tourists yearly.

Glen Canyon Dam also changes the hydrology of the Colorado River. The pre-dam average annual peak discharge for the Colorado River was typically 2400 m^3/s (Howard and Dolan, 1981), and flow fluctuated depending upon the season. After the gates were closed in March 1963, the flows became regulated, eliminating seasonal variation and reducing average daily peak flows to 850 m^3/s (Schmidt, Brown and Stevens, 1990, written communication). "Spills" from the dam have occasionally resulted in high flows. In 1965, for example, a high flow of 1415m^3/s (Schmidt, Brown and Stevens, 1990, written communication) was discharged and in 1983 a flow of 2750m^3/s was released.

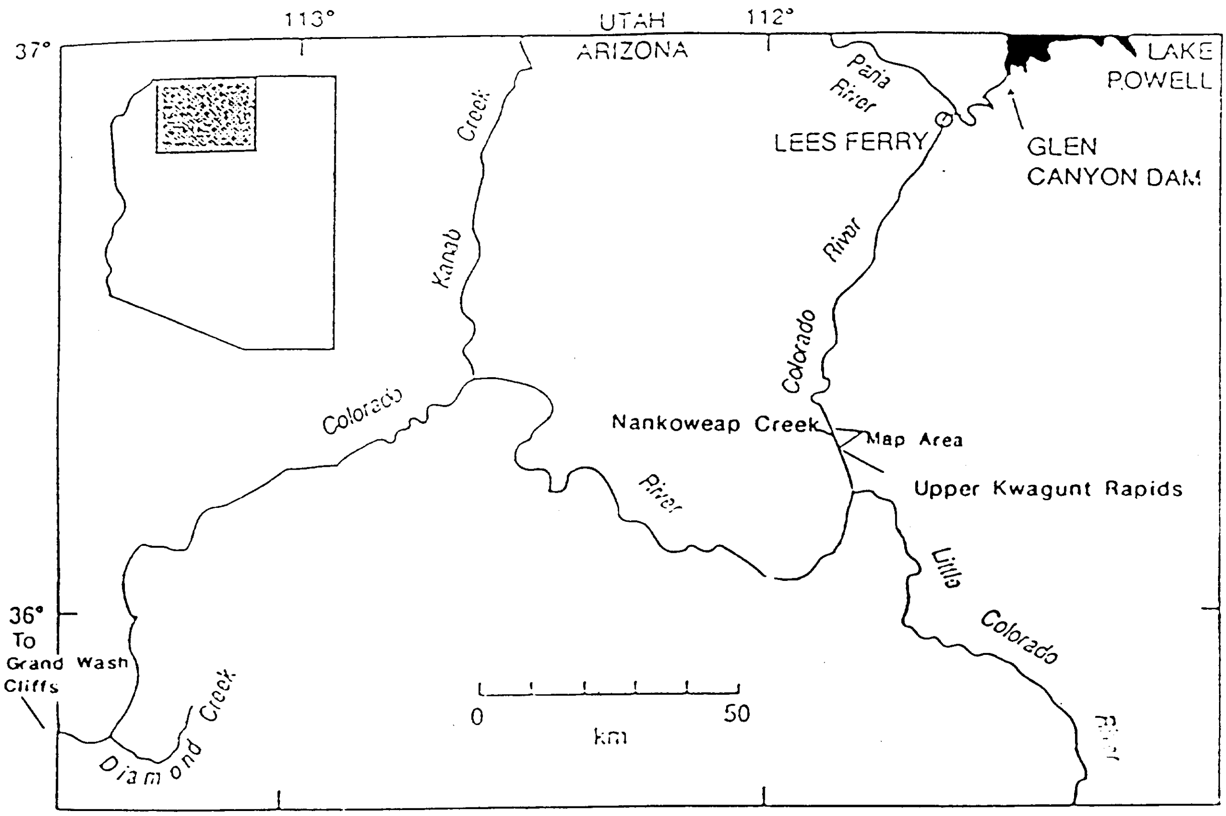


Figure 1.--Map of Study Area. Adapted from Schmidt, 1990.

Large dams like Glen Canyon only allow about 1 percent of upstream transported sediment to continue downstream, trapping the rest behind its concrete walls (Williams and Wolman, 1984). Water released from low elevation in Lake Powell is a brisk 4-6 degrees Celsius year round. The absence of sediment and cold water have driven the native humpback chub to the brink of extinction, while other species have already been eliminated (Howard and Dolan, 1981; Stevens, 1983). The fish, however, are not the only elements being affected in the river corridor. Sand bars, used as campsites by thousands of recreationists, hikers and rafters, feel the effects of the dam.

The purposes of this study were three fold: 1) to describe sediment storage changes in an 8.3-km reach of river, both in terms of bed and bank storage; 2) to determine the relation between bank sediment changes and discharge of the Colorado River, and; 3) to evaluate the channel geometry characteristics of stable and unstable sand bars.

BACKGROUND

Hydrology

There are many reasons to build dams, and regardless of the reason, all dams alter the rivers they regulate. Dams have two basic effects on downstream rivers: 1) they regulate the flow of the river, and 2) they trap sediment. Hydroelectric dams typically operate on a diurnal cycle, producing peak flows in the afternoon and low flows at night (Hirsh et al, 1990). The flows from Glen Canyon Dam fluctuate between lows, ranging anywhere from 30-150 m^3/s and highs from 400-900 m^3/s (Rubin, Schmidt and Moore, 1990). A typical fluctuating flow regime for the month of June is shown in Figure 2. This cycle is further complicated by weekends and holidays when lower flows can persist for several days.

Occasionally, due to a heavy snow melt, an extremely wet year, or operational rules, reservoirs fill to capacity and "spill" their excess water. These spills are flows of high magnitude. In 1983 a discharge of 2750 m^3/s was released by Glen Canyon Dam. The peak flows in the following years (1984-86) were also higher than usual, measuring approximately 1270 m^3/s.

The hydrology of the Colorado River from 1965-90 can be divided into three periods. From 1965-82, there was a fluctuating flow regime with low annual peak discharges. There were no high flows because Lake Powell Reservoir was being filled. During the 1983-86 period, several sustained high flows created a period of fluctuating flow with high annual peak discharges. Between 1987-90 , the dam resumed normal operation with releases similar to the 1965-82 period.

A comparison of flow duration curves is given in Figure 3. Figure 4 shows the number of days certain discharges were equalled or exceeded in each

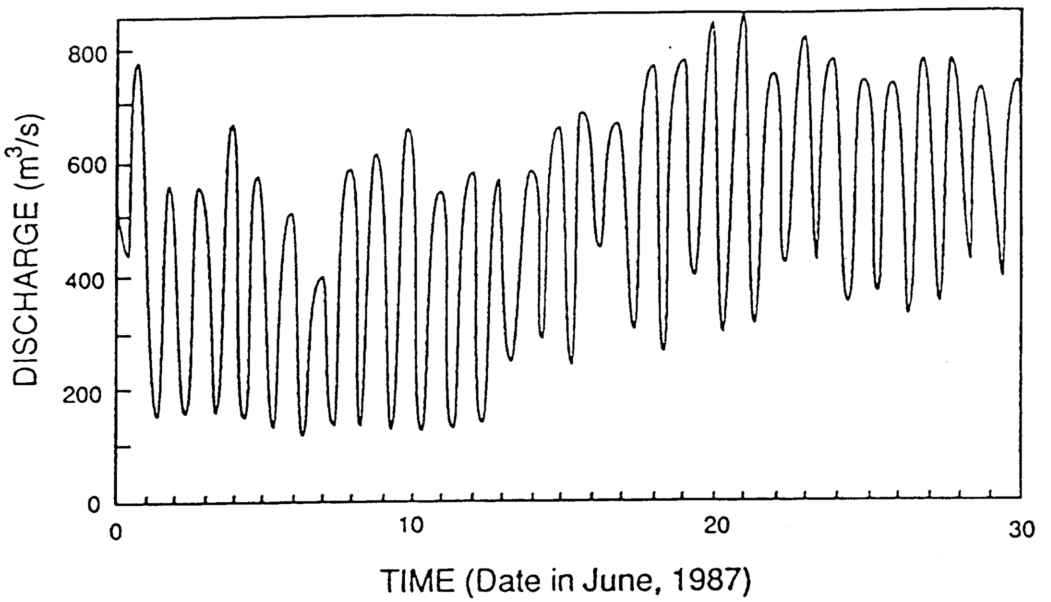


Figure 2.--Hydrograph showing discharge at Lee's Ferry for June, 1987. Discharge fluctuated daily because of releases from Glen Canyon Dam. After Rubin, Schmidt and Moore (1990).

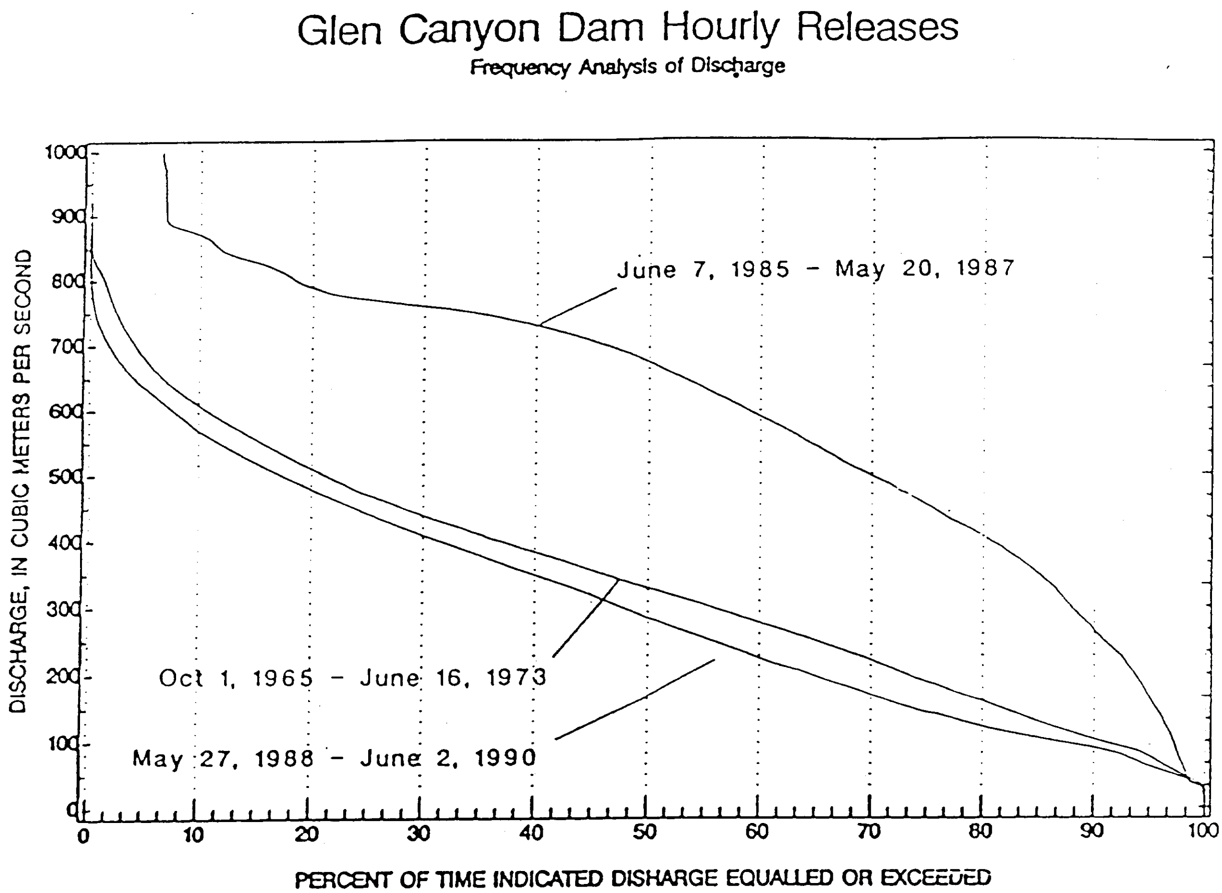


Figure 3.--Flow duration curves of hourly discharge for Colorado River at Glen Canyon Dam for indicated time periods, Data from U. S. Bureau of Reclamation. Plots prepared by W. Vernieu of GCES.

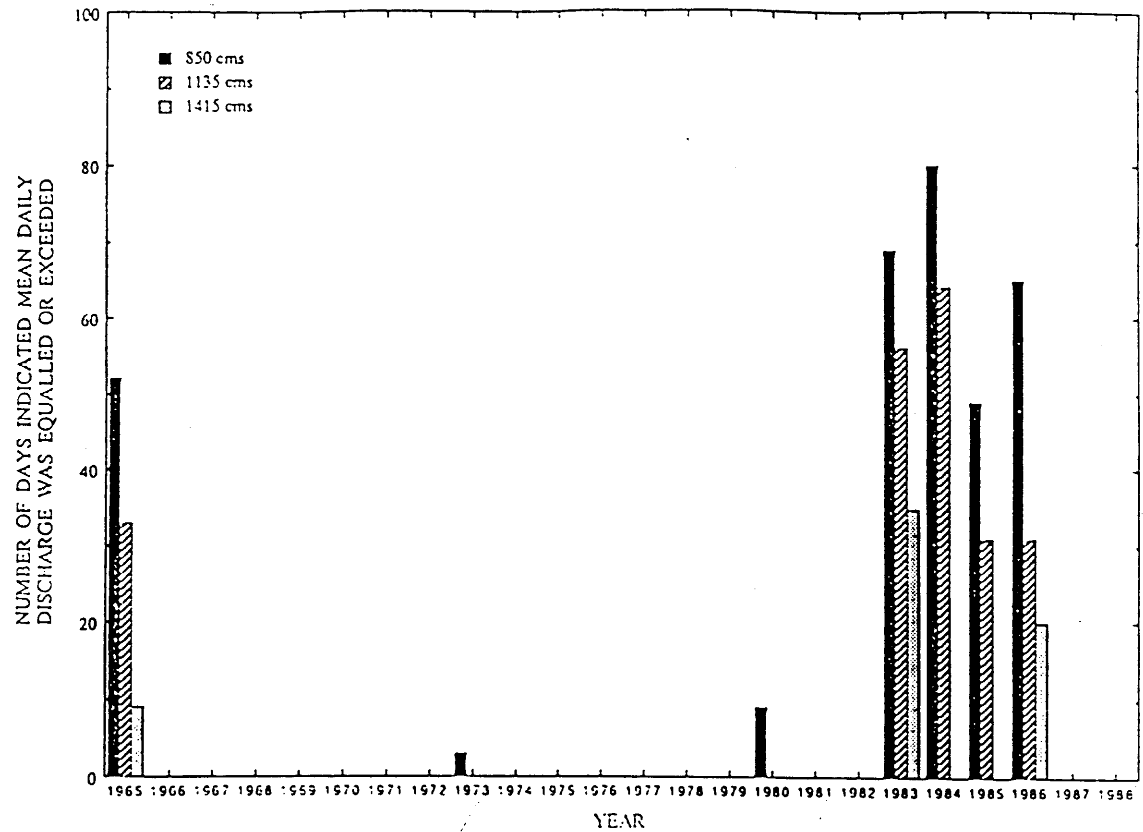


Figure 4.--Bar graphs showing flow conditions for indicated years. Adapted from Schmidt, Brown and Stevens (1991, written communication).

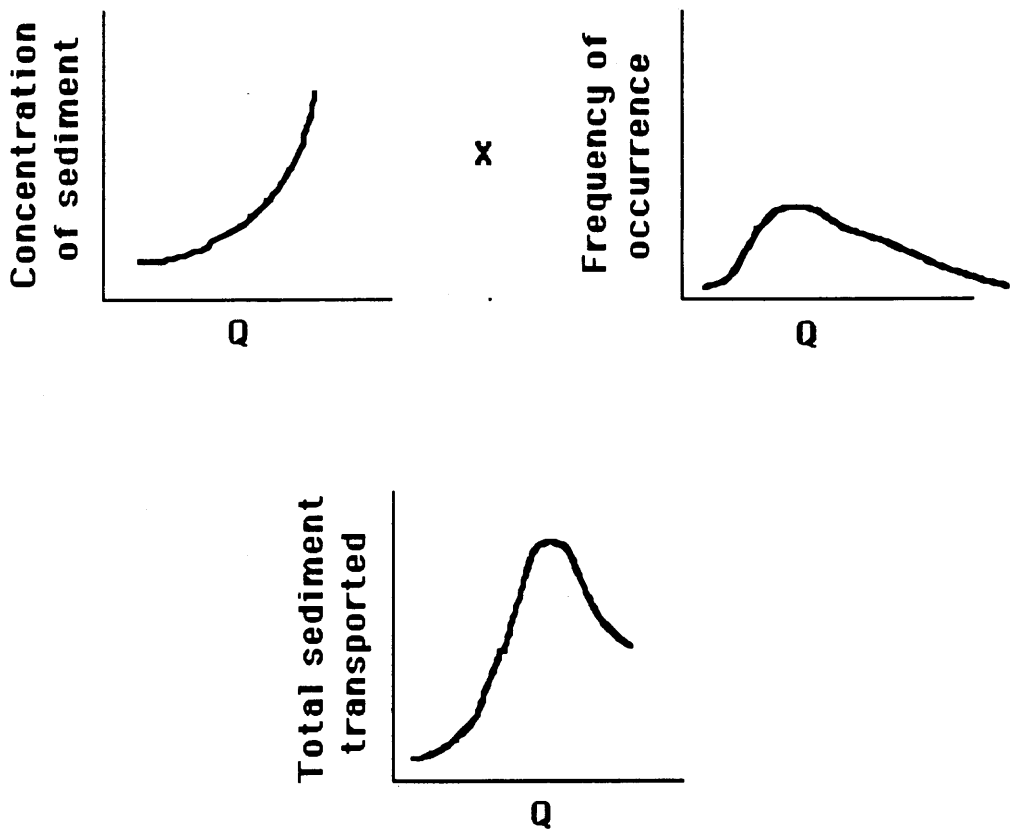
year. The graph shows that from 1966-1982 and 1987-90, flows rarely exceeded 850 m^3/s. During the 1983-86 time period however, flows in excess of 850 m^3/s were common. Powerplant capacity is 890 m^3/s.

Sediment Trapping and Transport

Dams are very effective sediment trapping devices. Measurements directly downstream from large reservoirs like Glen Canyon show that as much as 99 percent of the sediment may be trapped (Williams and Wolman, 1984). According to Williams and Wolman (1984), the sediment yield at Grand Canyon gaging station (150-km downstream from Glen Canyon Dam) was 87 percent lower than after the dam was closed. This number should be higher, because both the Paria River and the Little Colorado River contribute sediment to the system and thus increase the amount of sediment that passes by the gage. Because of trapping, any sediment that is transported out of the system downstream from the dam can only be replaced by sediment influx from tributaries.

Because sediment transport is a function of discharge, the operational regime of dams has a direct influence on sediment transport. By reducing the number of high flows, dams reduce the ability of rivers to transport sediment. Both the capacity (amount of sediment) and the competency (sediment size transported) are reduced (Williams and Wolman, 1984; Howard and Dolan, 1981). The capacity of a stream increases exponentially with discharge, yet flows of high discharge occur less frequently (See Figure 5).

Figure 5.--Curves showing the derivation of the total sediment transport to discharge relation. Q is discharge in m^3/s.



The dashed lines in figure 6 show that the amount of sediment transported by each discharge increment up to a certain point (in this case 90 m^3/s in figure 6a) after which the sediment transported decreases. The solid lines, representing the post dam relation, are much lower than the dashed lines, indicating that less sediment was transported after the construction of Canton Dam. The reasons for this are that the dam has trapped sediment, thus making less available for transport, and increased the frequency of low capacity

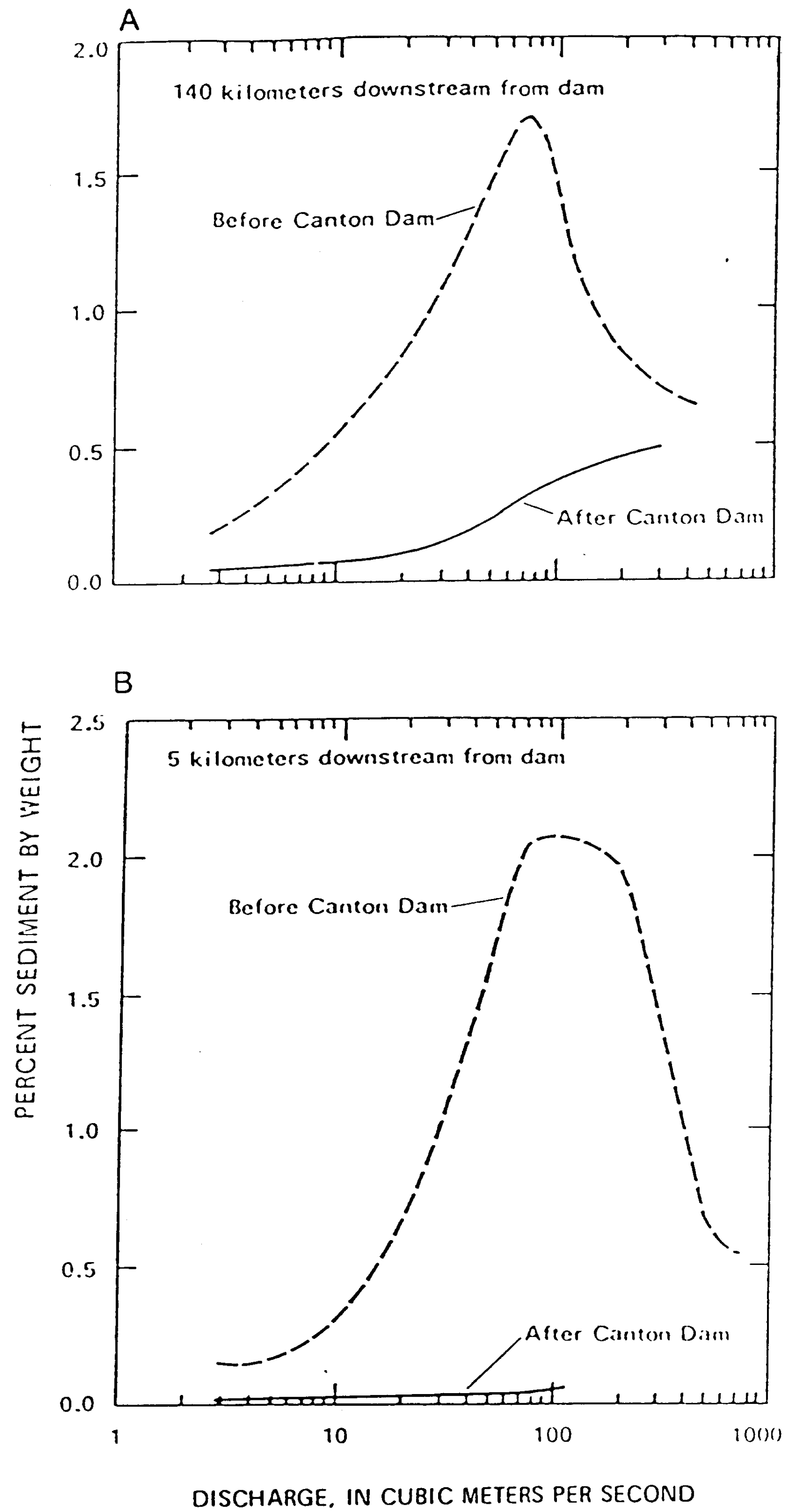


Figure 6.--Suspended-sediment loads (concentrations) transported by various discharges at successive downstream stations before and after closure of Canton Dam, North Canadian River, Oklahoma. Adapted from Williams and Wolman (1984).

discharges while at the same time decreasing the frequency of high capacity discharges and reducing the amount of sediment transported.

The manner in which the reduction in capacity and the trapping of sediment balance out determines how the river corridor will respond to regulation (Williams and Wolman, 1984). In most cases, transport exceeds sediment input and hence net erosion is experienced (Hirsh et al, 1990). Erosion, however, seems to decrease as one moves farther downstream from the dam (Zink, 1989). This is due to the influx of sediment from tributaries and contributions of sediment from upstream banks. Where exactly, downstream from the dam, erosion ceases varies from river to river (Williams and Wolman, 1984).

Schmidt and Grams (1991, written communication) developed a sediment budget for the Colorado River from Lees Ferry to Grand Canyon gage. This relation shows that during periods of fluctuating flow and low mean annual flood (1965-82; 1987-90), the Colorado River has accumulated sediment while during periods of high peak flows, (1983-86) the river has lost sediment. For the Colorado River, then, sediment input exceeds transport during normal dam operations.

Bed and Bank Response to High Flows

With the onset of rising stage in a pre-dam flood, first the bed is scoured and then as the stage increases, banks may be eroded (Leopold, 1969). As the flood passes and stage falls, sand drops out onto the banks, into the eddies, and onto the bed. Because most of the sediment is trapped behind a dam, there is little sediment to replenish that system and as a result, it takes longer for the bed to recover scoured sand. Tributaries supply the only new sediment to regulated rivers. Upstream of the study reach, the Paria River is the only significant sediment source. The high discharge of 1983 greatly increased the capacity of the river. Schmidt and Graf (1990) argued that the high flows eroded sand in narrow reaches.

Channel Characteristics

All rivers are typically made up of a series of riffles (rapids) and pools (Leopold, 1969). In bedrock gorges like the Grand Canyon, tributaries can have flash floods or debris flows and may deliver large boulders to the river. The large boulders make an obstacle that the river must go around, narrowing the width of the channel. Where these debris fans extend into the river, riffles are formed. Virtually every riffle in the Colorado River is a result of a debris flow (Webb et al, 1988), yet recirculation zones can result from any obstruction that forms a constriction (Howard and Dolan, 1981). Above the riffles, the water is backed up forming a pool. Figure 7 shows one pool/riffle sequence.

Constrictions cause two things to happen. Constrictions form pools of slow moving water that deposit sand on margins of the river and on the bed above the constriction. Secondly, downstream of constrictions, separation of flow creates eddies. Sand is deposited in zones of low-velocity flow, such as near a bank or along an eddy fence (See Figure 7). The eddy deposits can be divided into two groups, separation and reattachment bars. These terms are analogous to the flow separation terms. A separation bar is one that is formed near the point of flow separation and reattachment bars are formed near the point of flow reattachment (Schmidt, 1990). Because the points of separation and reattachment vary with discharge, the sand is deposited in a zone which represents the range of all possible points of separation and/or reattachment.

Sediment can also be stored on the channel margins where no or intermittent eddies exist and in the river bed itself. Bed load sediment is

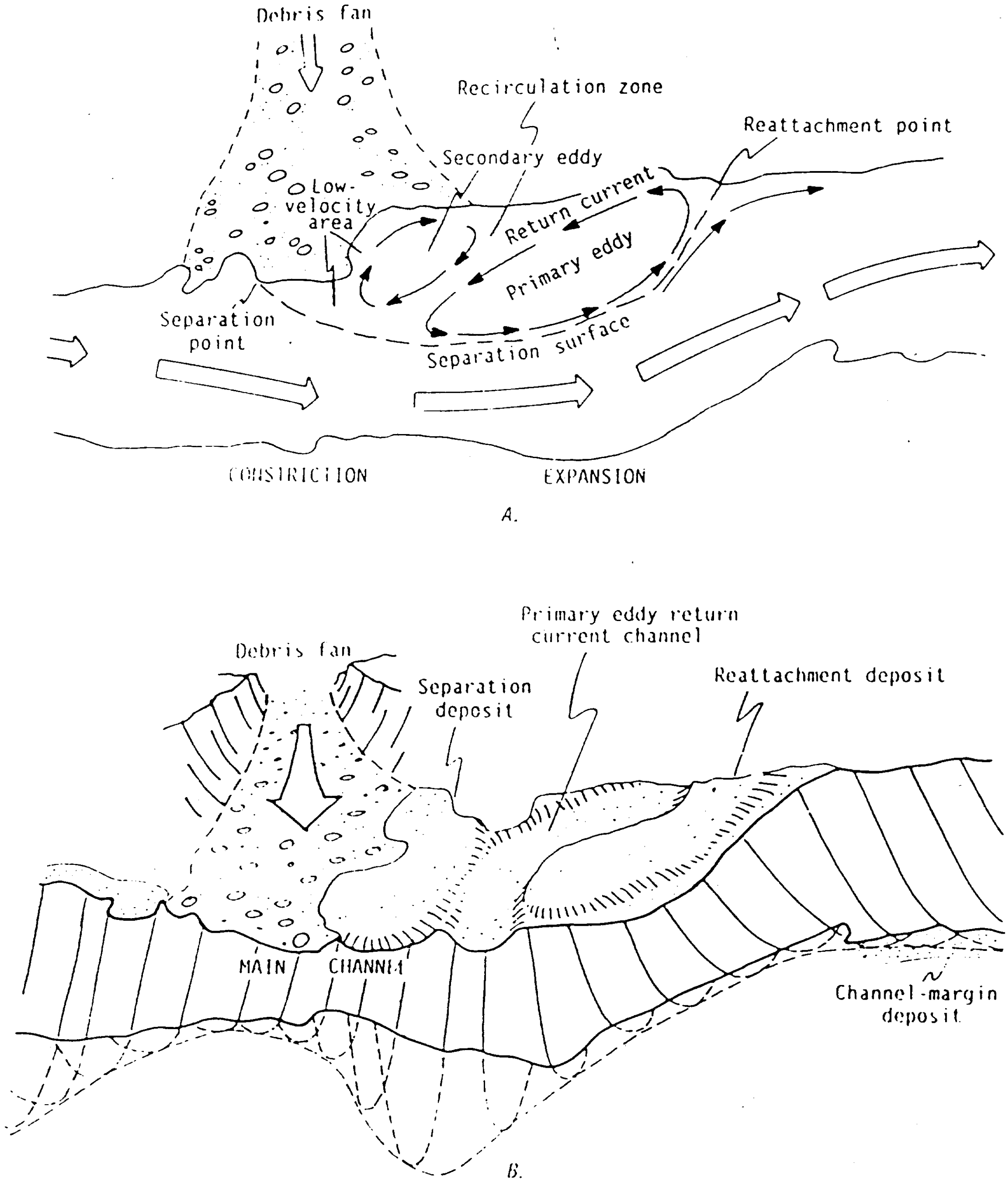


Figure 7.--Flow patterns and configuration of bed deposits in a typical recirculation zone. A, Flow patterns. B, Configuration of Bed deposits. After Schmidt and Graf (1990).

nearly all stored in deep, relatively calm pools, while the primary locations of channel margin deposits are wide calm stretches of river upstream from constrictions. These two areas commonly coincide, though there are many exceptions. Deposition also occurs on the bed, upstream of constrictions, in pools. The water, while moving, is behind a kind of temporary dam. The water above the riffle decelerates and sediment drops out onto the bed. Sediment is also deposited along the banks of this slow moving stretch of river, forming channel margin deposits. The whole pool/riffle sequence is analogous to people leaving a movie theater after the show. People rush to get out the door but are backed up by a constriction (the door). Once past the door, the people speed up and attain a quicker pace.

Bank Stabilization

Due to the flow regulation and the reduction of the mean annual flood, vegetation has flourished on previously open sand deposits. Tamarisk now line the banks of the Colorado. The thick vegetation serves to stabilize banks and to help trap sediment by slowing the current (Williams and Wolman, 1984). Responses like this serve to bring the system to a new state of equilibrium with the established fluctuating flow. However another flow of $2750 m^3/s$ might sweep the beaches clean and eliminate bank stabilization due to vegetation (Schmidt, Brown and Stevens, 1991, written communication). Another way that banks are stabilized is by eroding all of the sand until only cobbles and boulders are left. These rock act as armor, protecting the sites from further erosion. The river bed itself may be protected in a similar fashion if all of the fine sediment is scoured, leaving a coarse bottom. Camp sites mantled by boulders, however, are no longer of recreational use.

METHODS

Surficial Geology

The study area is an 8.3-km reach of the Colorado River in Grand Canyon National Park between river miles 51-56 (Figure 8). Locations along the Colorado River are marked in relation to their distance downstream from Lees Ferry, Arizona, as surveyed by the United States Geological Survey in 1923. In this paper, river mile 52 is noted as RM52 and is located 86.6-km downstream from Lees Ferry and 111.6-km downstream from Glen Canyon Dam. Detailed surficial geology maps were prepared for RM52-56. Using a Bausch and Lomb Stereo Zoom Transfer Scope, aerial photographs for the years 1965, 1973, 1980, 1984, 1985, 1987, 1988, 1989, and 1990 were transferred to overlays on the 1990 GCES topographic base (see Table 1).

Table 1.-- General Information on aerial photographs.

Date	Scale	Agency	Discharge (m^3/s)[1]	Photo Series
5/14/65	1:15000	USGS	792	101-109
6/16/73	1:7200	USGS	210	141-147
7/11/80	1:5000	USBR	767	9.01-10.12
10/22/84	1:3000	USBR	141.5	2.234-3.28
6/7/85	1:5000	USBR	979	2.186-3.14
5/20/87	1:6000	USBR	239	??[2]-1.76
5/27/88	1:4800	USBR	477	45.6-47.12
10/7/89	1:6000	USBR	141.5	34.3-35.14
6/3/90	1:5600	USBR	141.5	33.5-35.14

[1]Determined from discharge records for Lees Ferry, AZ supplied by GCES office in Flagstaff, AZ.

[2]Shadow on photo makes numbers unreadable.

The topographic base was generated by the U. S. Bureau of Reclamation using photogrammetric techniques. The base maps are at a scale of 1:2400 and were taken at a discharge of 141.5 m^3/s on June 3, 1990. By overlaying the maps in ascending order of years, a record of sand bar change over time was generated. The maps were field checked in May 1991, August 1991 and September 1991.

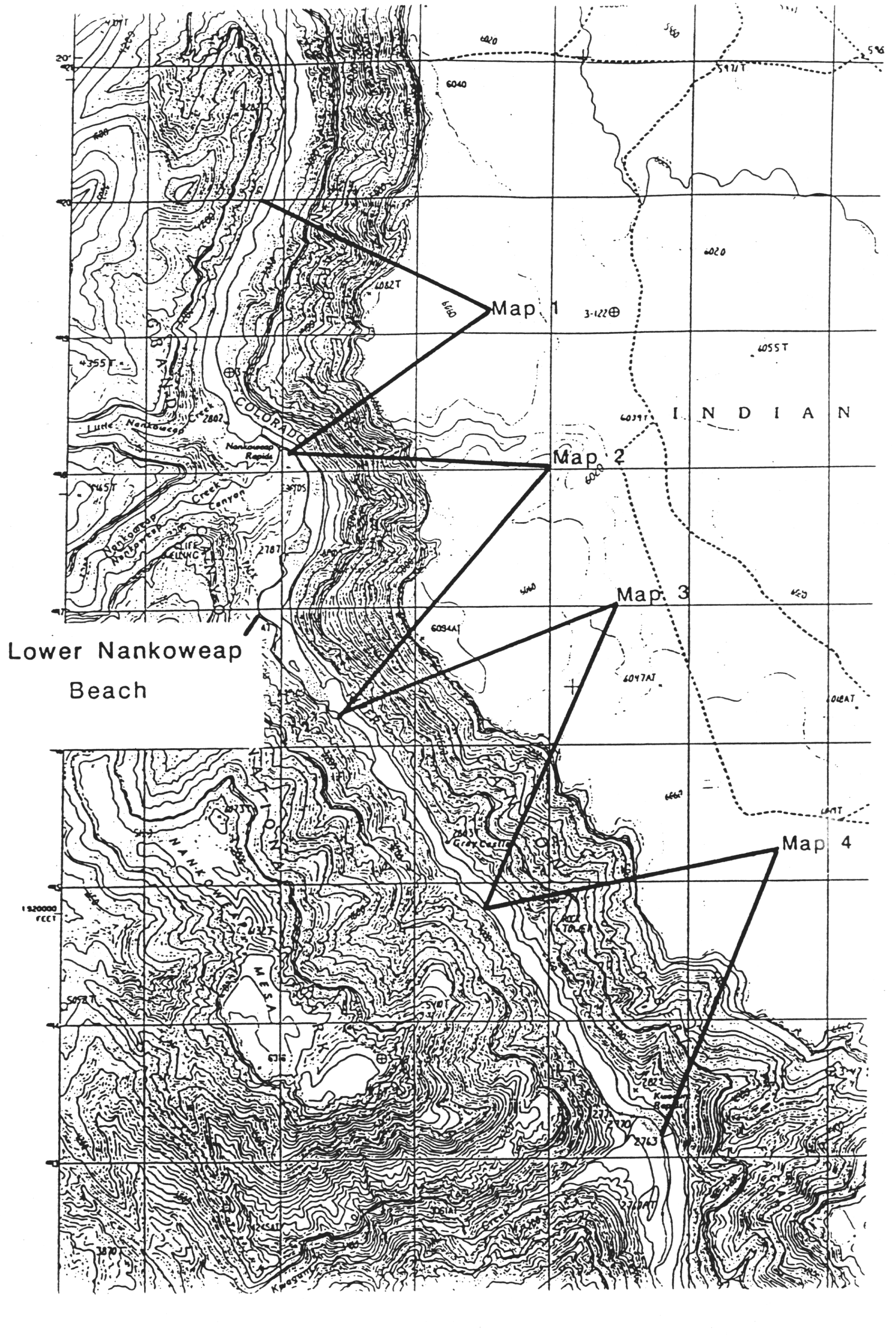


Figure 8.--Fifteen minute topographic map showing areas coverd by GCES maps and the location of Lower Nankoweap Beach.

Final maps were drafted and digitized by the U. S. Bureau of Reclamation GIS Lab, Denver. Maps were edited and converted into an Arc-Info database by the Geographic Information Systems lab, Geography Department, Utah State University (See Appendix 1).

Instantaneous hourly discharge data at Lees Ferry, Arizona, were obtained (W. Vernieu, 1991, Glen Canyon Environmental Studies, written communication). Discharges for the aerial photos were calculated using a stage-wave travel time chart (Appendix 2). From the chart it was determined that it takes approximately 13 hrs for water to reach Kwagunt Rapids, at the downstream end of the study reach. Some of the aerial photographs indicated the time at which they were taken; where times were not indicated, it was assumed photos were taken at noon. Aerial photographs for 1984 and 1990 were taken under steady flow conditions.

Problems in the comparative mapping of aerial photos include: 1) difficulty in distinguishing sand from sand and boulders in some of the 1965 and 1973 photos, 2) inaccuracies in the actual transferring of the aerial photos to the base maps and 3) possible inaccuracies in the base maps themselves.

Sand Bar Stability

Not all sand bars in the Grand Canyon have responded similarly between 1965-90. In an effort to understand why this may be, sand bars in 12 eddies were rated as either "Stable" or "Unstable." Channel geometry measurements were taken of these eddies. The criterion used for distinguishing stable and unstable bars was that if the sand bar disappears and then reappears while looking at maps ordered by discharge, the bar is considered to be unstable (See Figure 9). Because ordering is by discharge and not time, the randomness of behavior shows significant change in sand

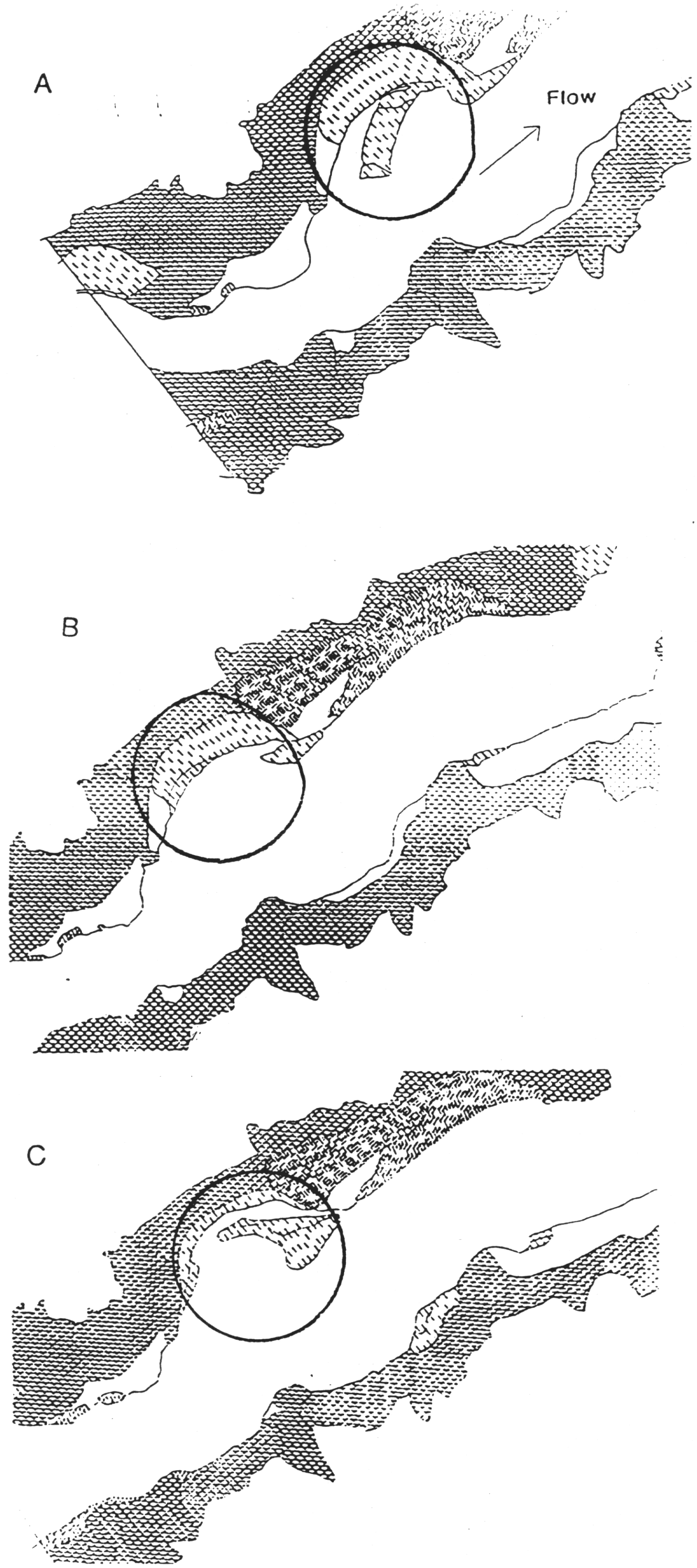


Figure 9.--Maps showing an unstable sand bar. Bar disappears from A to B and then reappears in C. Discharges are: 141.5 m^3/s, 477 m^3/s and 792 m^3/s for A, B, and C respectively. Scale: .7cm = 50 m.

volume in the eddy over time. If the sand bar decreases in area with increasing discharge, it is rated as stable. The channel geometry measurements taken of the associated channel expansion were : 1) constriction width, 2) expansion width, 3) average upstream width, 4) expansion length, and 5) constriction width at the 1985 discharge. According to Schmidt and Graf (1990) constriction width is the narrowest point of the constriction and expansion width is the widest point in the corresponding eddy. The expansion width is measured from the farthest landward point that a reattachment bar ever existed to the opposite side of the river (See Figure 10). Expansion zone length is measured from the narrowest point of the constriction to the downstream-most extent of the expansion. The constriction width at 1985 discharge was measured as the narrowest point of the constriction in 1985. Because the discharge at the time of the 1985 photo was 979 m^3/s, this measurement represents constriction width at moderate discharge. Constriction, expansion and shape ratios were calculated. Schmidt and Graf (1990) described the constriction ratio as the constriction width divided by the average upstream width and the expansion ratio as the expansion width divided by the constriction width. The shape factor is the 1990 constriction width (141.4m^3/s) divided by the 1985 constriction width. The shape factor reflects the geometry of the debris fan creating the constriction. An obstruction with a steep slope will have a shape factor near 1 while a low-slope obstacle, easily overtopped by high flows has a shape factor near 0. The ratios were tabulated and analyzed.

Correlation of Fathometer Traces

Two fathometer traces of the study reach were also examined. The first trace was done by Howard and Dolan in 1973 and the latter was completed by

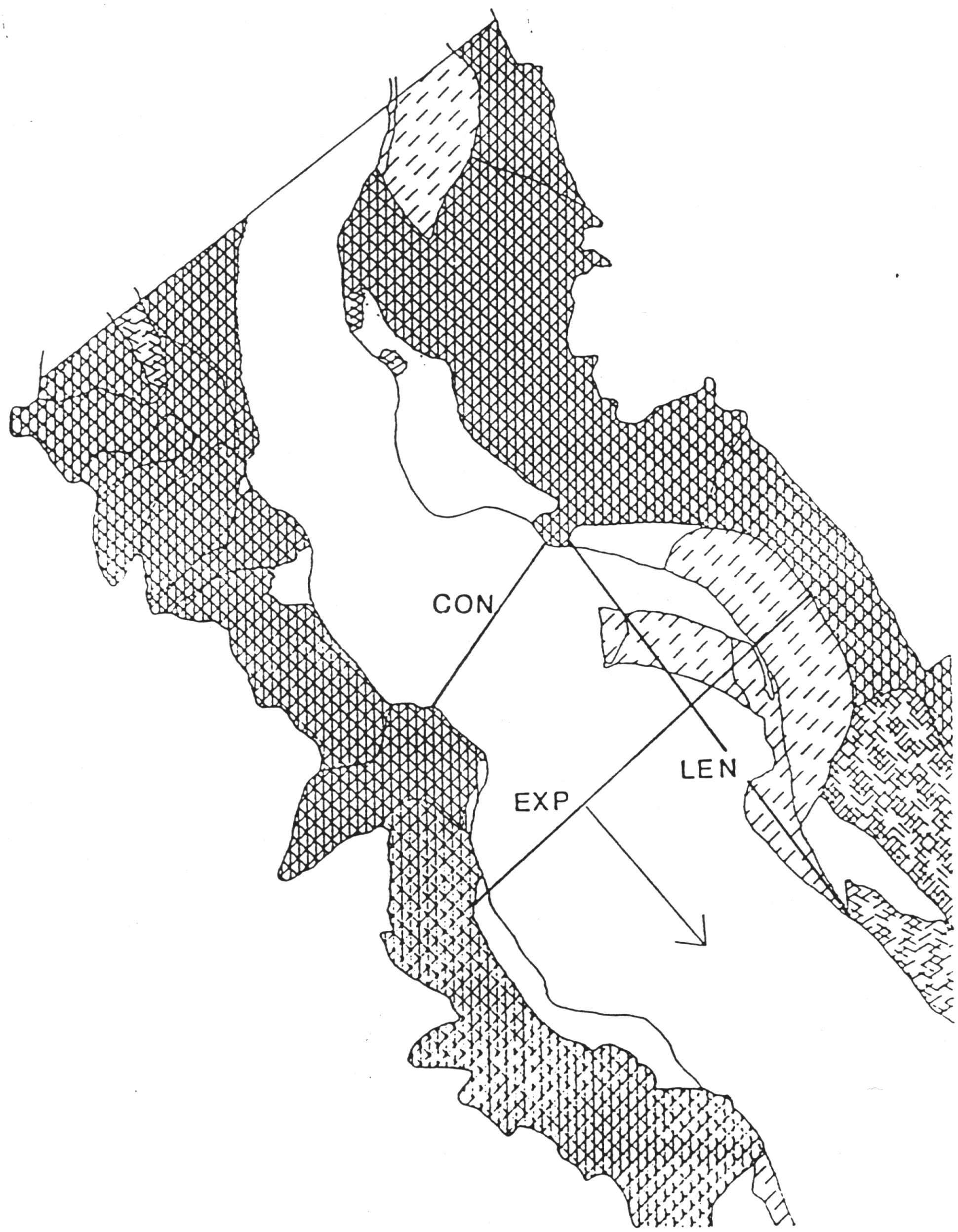


Figure 10.--Map showing how constriction (CON), expansion (EXP) and eddy length (LEN) were measured.

the Bureau of Reclamation in 1984. The method used to compare these traces is similar to that used by Rathburn (1991, written communication). Figure 11 shows both fathometer traces for part of the river. Similar riffle and pool sequences were first identified. The wave-like form from T′ to R′ on the 1973 trace closely follows the 1984 trace from T to R. This is an easy correlation to make as the wave-like forms are similar. Other stretches were not so obvious. For example, the debris fan (DF) just below BB on the 1984 trace doesn't exist on the 1973 trace. There are several possible reasons for this 1) the boat took another course, 2) the boat was moving quickly through the riffle and didn't identify the ledge, 3) net aggradation from 1973 to 1984 has made a ledge and 4) newer, more technologically advanced equipment used in 1984 may have been more sensitive. Choice three, however unlikely, is possible as a high discharge like 1983 may be capable of moving boulder-sized debris downstream of the riffle. A closer examination of the 1973 trace shows the peak 1, followed by another high point 2 and then farther on in the trace another little bump 3. I believe that these correlate to points 1,2, and 3 on the 1984 trace and that due to a combination of different boat courses and boat speeds, the traces look different. In map view (Figure 12), BB' and T' are located just downstream from a cobble bar. Since the stage was .7m higher in 1984 than in 1973 (Rathburn, 1991, written communication) it is unlikely that the boats differed greatly in course.

Once these traces were correlated, a riffle-to-adjacent pool depth measurement was taken (Figure 11). Eight such measurements were collected in all and relative change in elevations were calculated. The figures were analyzed, using Data Desk, and a normal quantile plot generated. Using Minitab, a paired T-test was preformed on the data. Two main assumptions were made to validate this analysis: 1) the boat took the same course in 1973

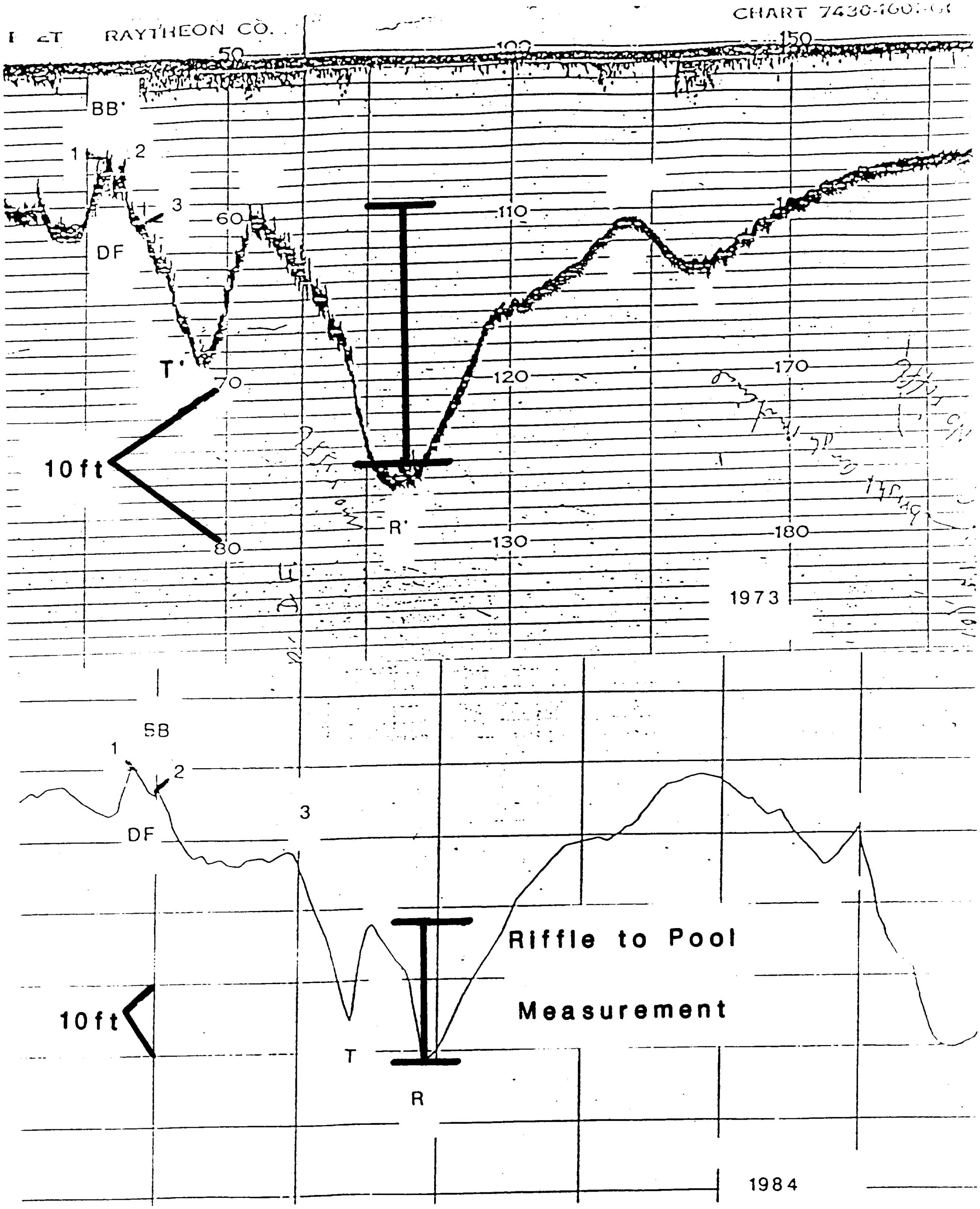


Figure 11.--Fathometer traces for 1973 and 1984.

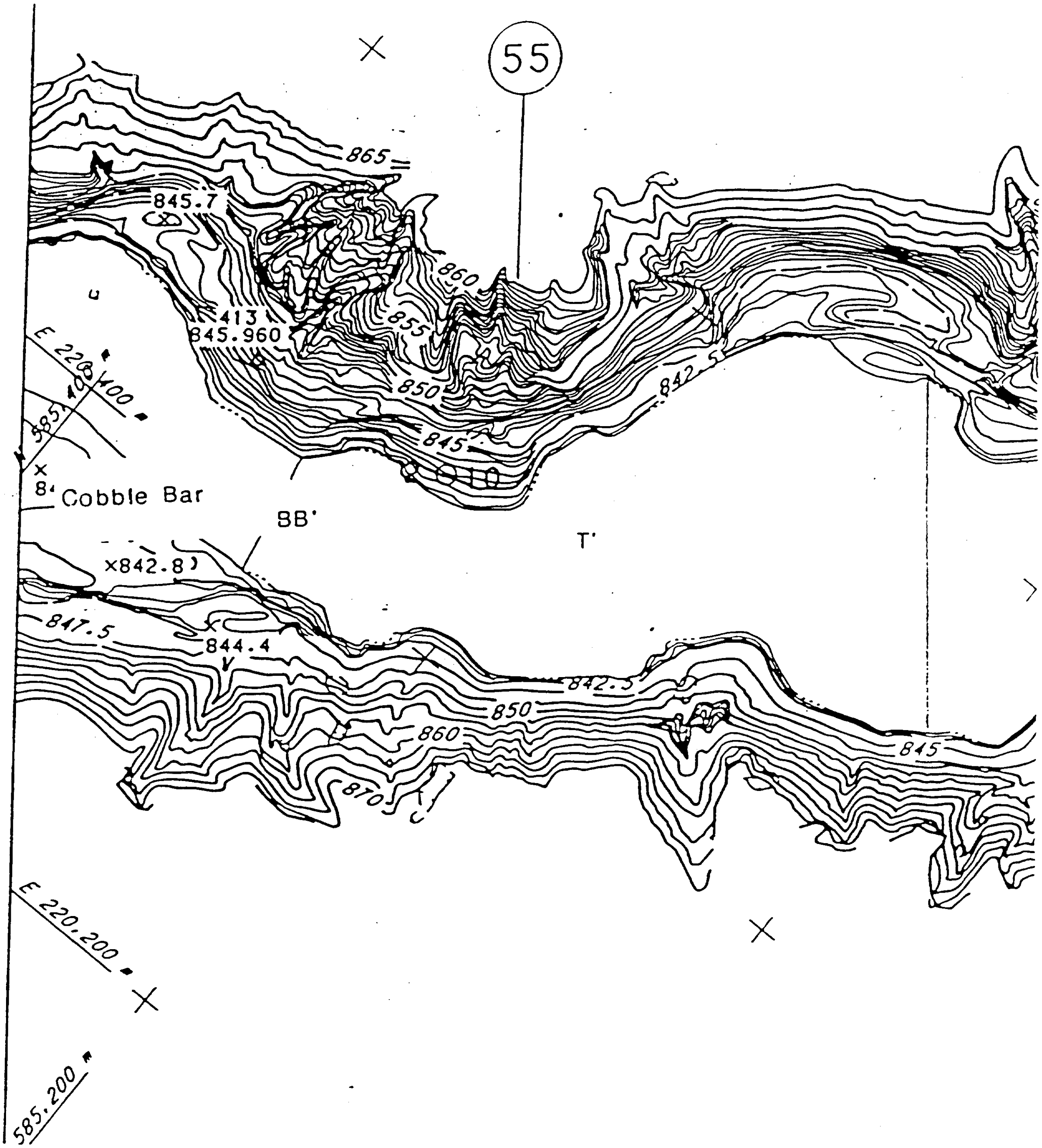


Figure 12.--Map view of 1973 and 1984 fathometer traces shown in figure 11. Scale: 1.7cm = 50m.

as in 1984, thus indicating that the differences in pool depths are actual changes in bed elevation and 2) the riffles stay at the same elevation (i.e. they neither aggrade nor degrade over the eleven year period).

Topographic Change

A historical record of topography exists at Lower Nankoweap camping beach within the study reach. Topographic surveys were done by Howard and Dolan in 1974, and 1975 (written communication), Dolan in 1980 (written communication) and Beus and others in 1983, 1984, 1985, 1986, and 1987 (written communication) at three profiles. (see Figures 13 and 14, see also Table 2).

Table 2.--General Information on Profiles at Lower Nankoweap Beach.

Date	Profile 1	Profile 2	Profile 3
6/23/74	Howard and Dolan	Howard and Dolan	Howard and Dolan
7/10/75	Howard and Dolan	Howard and Dolan	None
6/20/80	Dolan	Dolan	Dolan
7/31/83	None	Beus	None
8/3/84	Beus	Beus	Beus
8/2/85	None	Beus	Beus
7/31/86	None	Beus	None
7/31/87	None	Beus	Beus

All of the survey data was related to a common datum, in this case, Rock 1, for consistency in comparison (See Appendix 3). Campsite historical profiles consisting of overlays of each year were prepared. Possible errors in this analysis include: surveying errors and the loss of 2 bench marks from 1975 to 1980. Profiles were re-established using available data (Beus, 1983, written communication).

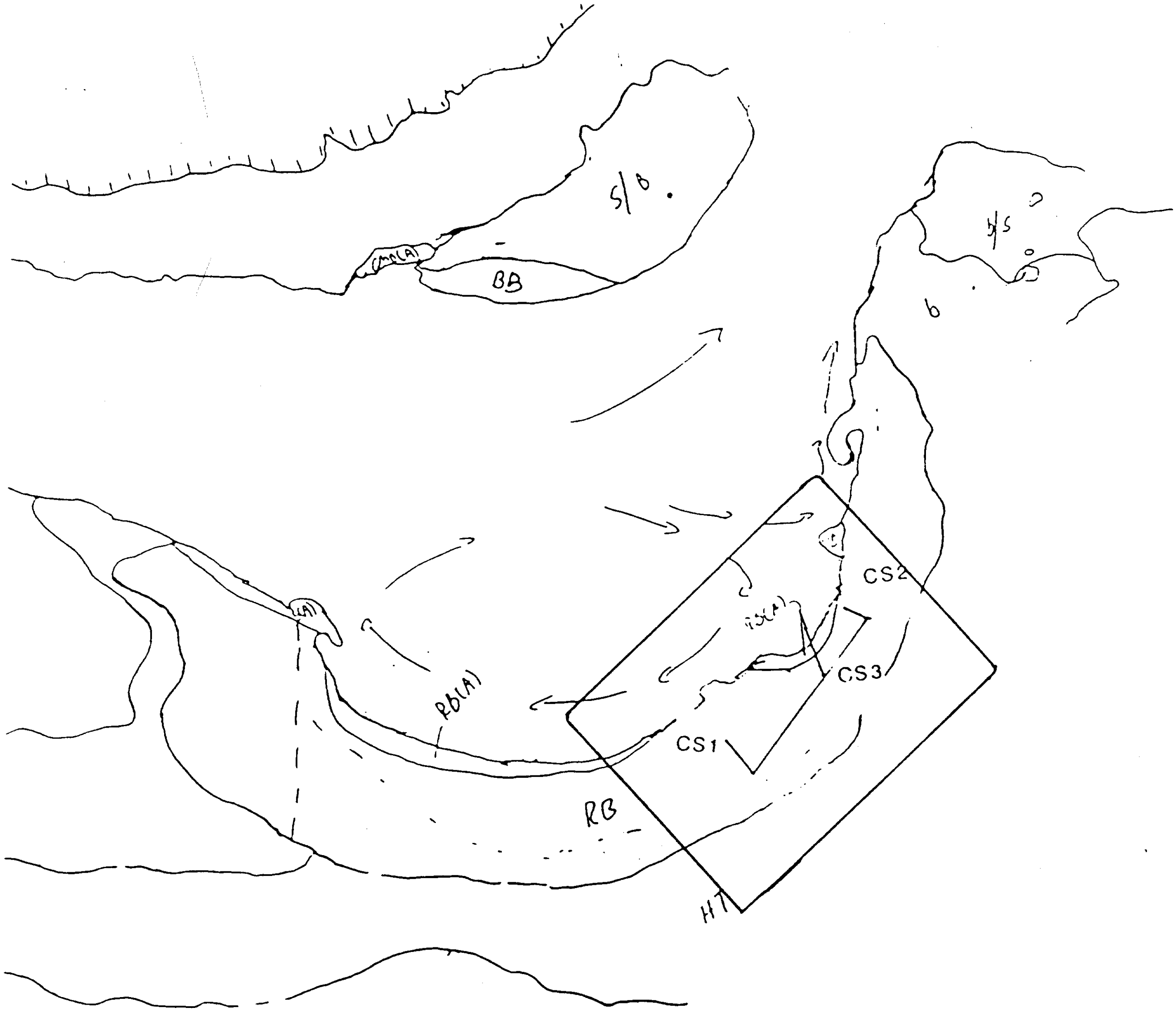


Figure 13.--Map view of three profiles at Lower Nankoweap Beach. Boxed area is shown on Figure 14. Scale is 2.1cm = 50m.

Figure 14.--Map of Lower Nankoweap beach showing locations of three profiles (Howard 1975).

Flow Duration Curves

Flow duration curves using instantaneous hourly releases from Glen Canyon Dam were generated for each of the time periods between aerial photos. Bill Vernieu of Glen Canyon Environmental Studies in Flagstaff, Arizona prepared these plots (See Appendix 4).

RESULTS

Fathometer Traces

The bed of the Colorado River in the vicinity of Nankoweap Rapids is a series of riffles and pools. The riffles (rapids) primarily result from debris fans that emerge from side canyons and create constrictions, while pools are characteristic of wider, deeper areas immediately downstream from debris fans. Within the Nankoweap reach, twelve riffles and eight pools were identified on the fathometer traces. The 1973 trace also reveals channel features such as gravel bars and sand waves. Sand waves, (Figure 15) are commonly found in wide areas of the river. Sand waves are characterized by gentle bed slope and are located near channel margin deposits and large reattachment bars. Cobble bars (also seen in low discharge aerial photographs) occupy wide, shallow reaches (See Figure 16) and are usually found downstream of large debris fans.

Table 3 summarizes the results of the fathometer trace measurements. Note that sequence CC-R is the only riffle and pool pair that shows aggradation. The overall average change in depth is -2.41 meters, indicating overall degradation of the bed from 1973 to 1984. NScores of the Change in depth parameter were calculated and a normal quantile plot was generated (See Figure 17).

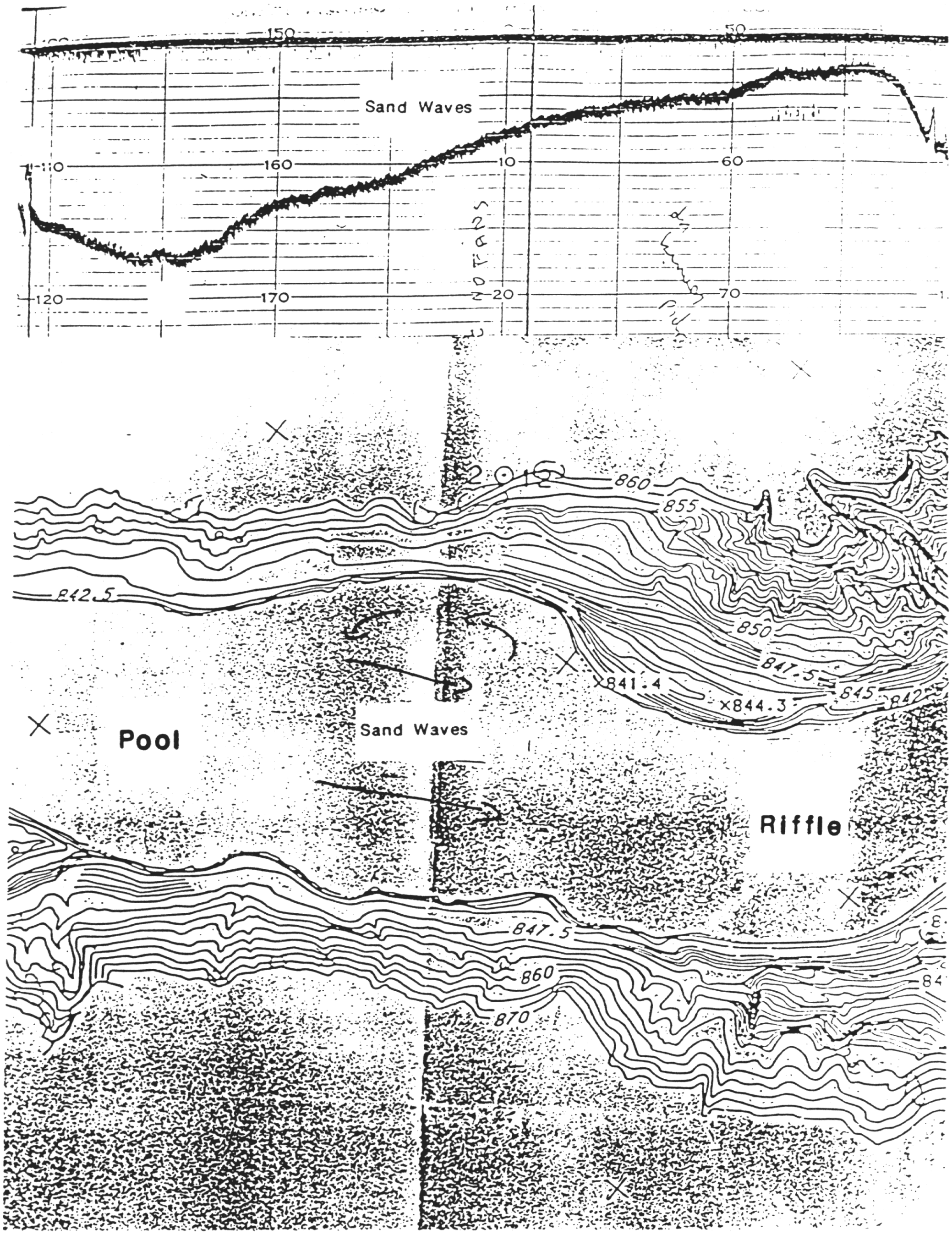


Figure 15.--Sand waves shown on fathometer trace (top) and in map view (bottom) upstream of RM 56. Flow direction is left to right. Map scale is 1.5 cm = 50 m.

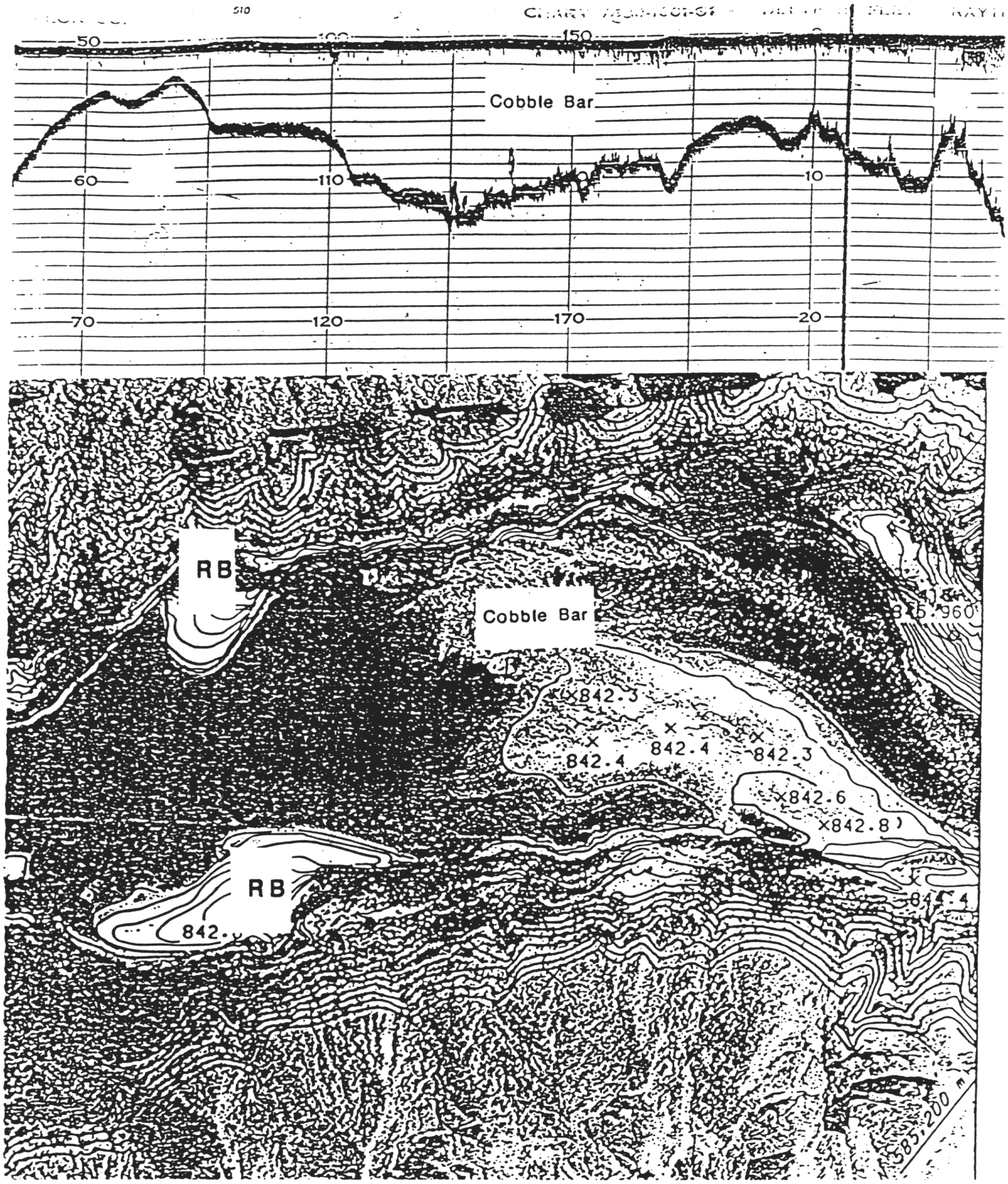


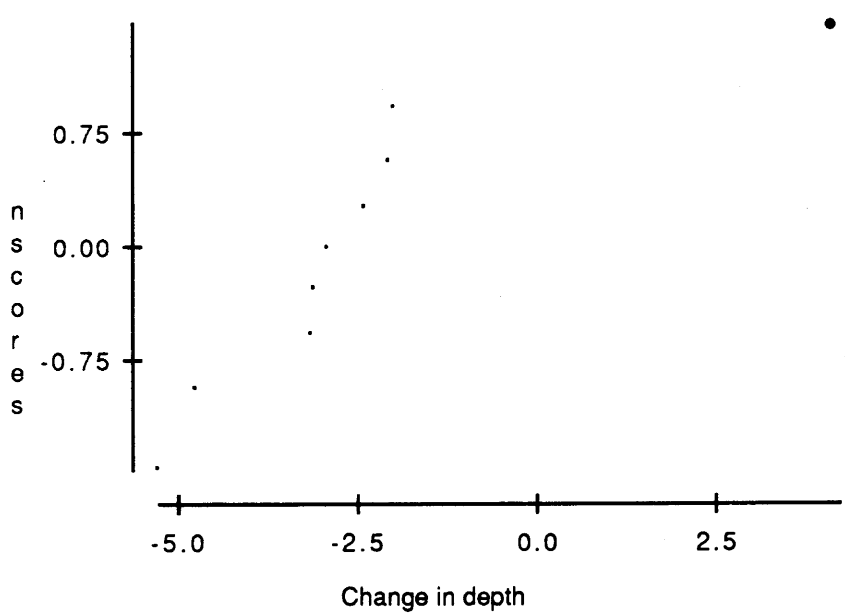
Figure 16.--Cobble bar shown on fathometer trace (top) and in map view (bottom) near RM 55. Flow direction is left to right. Map scale is 1.5cm = 50m.

Table 3.--Fathometer trace results.

Sequence[1]	Relative depth between riffle and adjacent downstream pool. 1973 (m)	1984 (m)	Difference 1973-84(m)
B-C	5.82	11.10	-5.28
A-Z	10.25	13.19	-2.94
X-AA	6.70	8.80	-2.10
BB-T	7.51	10.70	-3.19
CC-R	10.05	5.94	4.11
DD-S	4.36	9.15	-4.79
FF-U	6.80	8.80	-2.00
ZZ-YY	3.04	6.18	-3.14
		Average Change	-2.41

[1]Sequences of riffle and adjacent downstream pool are lettered on the original fathometer traces.

Figure 17.--Normal quantile plot of relative change in depth from 1973 to 1984.



The plot above shows an large circle which is the CC-R sequence, a probable outlier. Before discarding this outlier, plan view maps (Figures 18a

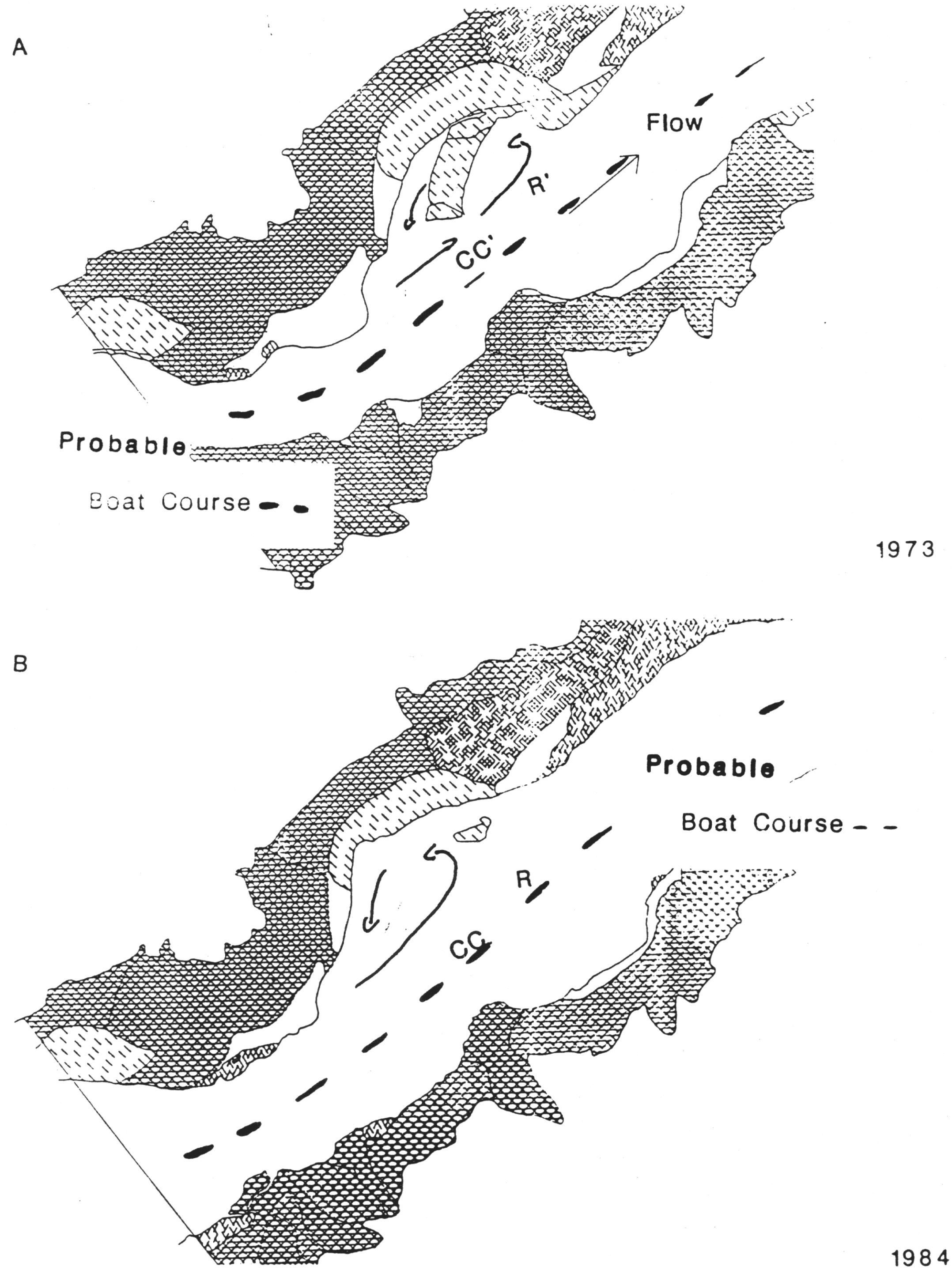


Figure 18.--Hypothetical maps of probable boat course at A) 1973 stage and B) 1984 stage. Flow direction is from left to right. Map scale is 1.1cm = 50m.

and b) were reviewed, they revealed that the area in question is not associated with a boulder bar or other obstruction that differences in stage would uncover, causing the boat to alter course. As a result, the statistical outlier was not discarded. Even with the outlier, though, the plot is fairly regular and so a paired T-Test was performed, yielding a P value of .049. This number is statistically significant at the 95 percent confidence interval, indicating that the change in depth cannot be attributed merely to inherent variation in the data.

The results of the fathometer trace comparison are consistent with that of previous work done by Rathburn (1991, written communication). She reported that pools degraded an average of 3.47m and 1.52m for reaches (RM62.4-64.0) and (RM85.0-87.5) respectively. The average change in the Nankoweap reach(RM 52-56) is similar to these values.

Unit Descriptions

Surficial geologic mapping describes sixteen units. The units were chosen to reflect the types of geomorphology commonly encountered in the canyon. The units can be divided into two broad groups; those deposited by the Colorado River today, and those deposited in some other way (See Table 4).

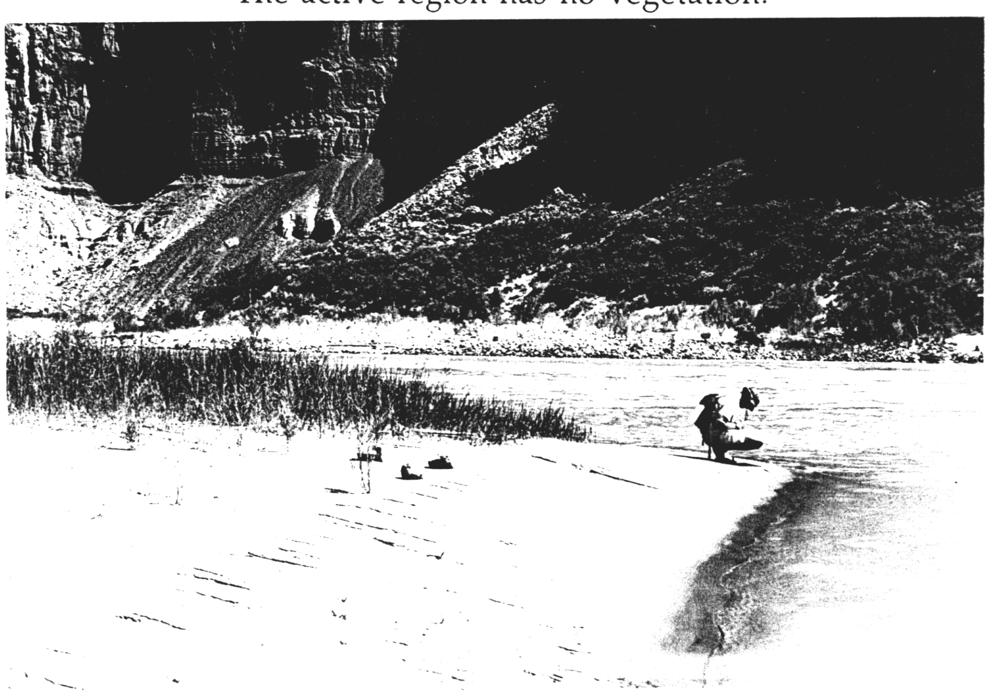
Of the two groups, the former changes the most with time. Within this group further divisions can be made making two subgroups, namely sand deposits associated with eddies and those that are not. The eddy deposits can be classified as either reattachment or separation bars. Reattachment bars (Figure 19a) are fine to coarse-grained sand deposits at least a meter in depth that formed beneath the primary eddy. Separation bars (Figure 19b) are also a fine to coarse-grained sand deposits at least a meter in depth, but they form

Table 4.--Summary of units used in mapping surficial geology.

Unit Name	Symbo	Sediment Size	Sand Thicknes	Vegetation	Notes
Reattachment	1	fine-coarse sand	>1m	Grasses, Tamarix	Reattachment bar
Separation	2	fine-coarse sand	>1m	Grasses, Tamarix	Separation bar
Margin	3	fine-coarse sand	>1m	Grasses, Tamarix	Channel bar
Reattachment Activ	4	fine-coarse sand	>1m	None	Reattachment bar, bare sand
Separation Active	5	fine-coarse sand	>1m	None	Separatoin bar, bare sand
Margin Active	6	fine-coarse sand	>1m	None	Channel bar, bare sand
Debris Fan	7	vfine-boulder	0-.19m	Varies	Debris flow deposit
Talus	8	fine-boulder	0-.19m	Varies	Talus slope or rockfall
Aeolian Sand	9	vfine-coarse san	>1m	Rare(Grasses)	Wind associated deposit
Sand/Boulders	10	fine-boulder	.2-.99m	Grasses	boulders, cobbles in a matrix of sand
Boulder or Cobble Ba	11	cobble-boulder	0-.19m	None	cobbles and boulders, undifferentiat
Separation/Reattach	13	fine-coarse sand	>1m	Maybe	Undifferentiated deposit
Water	99	NA	NA	None	
Submerged Sand	15	NA	NA	None	Sand deposits visible under water
High Terrace	16	vfine-med sand	>1m	cryptogams, Catcla	High terrace (7.5m above river level
				Mesquite, cacti	
Separ/Reatach Activ	17	fine-coarse sand	>1m	None	Undifferentiated deposit, bare sand

Figure 19a.--Active reattachment bar in a small eddy upstream from Lower Nankoweap beach. Note the eddy return channel and cobble bar.

Figure 19b.--Separation bar downstream of Lower Nankoweap beach. The active region has no vegetation.



near the separation point of an eddy. Both of these deposits may be vegetated. In map view, these deposits are separated by an eddy return channel (See Figure 20). Where no eddy return channel exists, the deposit is classified as a separation/reattachment deposit that shares the characteristics of the above deposits with the exception of precise location. The channel margin deposit (Figure 21a), unlike the others, is not associated with an eddy. Instead, it is a fine to coarse-grained sand deposit at least a meter in thickness deposited along the banks of the river commonly in the form of levees. The deposits are commonly heavily vegetated by tamarisk. The margin deposit also acts as a miscellaneous sand deposit category. When it is uncertain whether the deposit is eddy associated or not, it is classified as a margin deposit.

Each of the above units: reattachment, separation, reattachment/separation, and margin has an active unit. The only difference in the standard unit and the active unit is the extent of vegetation. Active units are not vegetated. They represent areas of sand that have been swept clean of vegetation and debris (Figure 21b).

Some miscellaneous categories that result from Colorado River processes are boulder bars, sand/boulder deposits, submerged sand deposits, and water. The category water is self explanatory. Boulder bars (Figures 19a and 22a) are defined as deposits consisting of cobble to boulder-sized sediment with almost no sand (0-.19m) and no vegetation. Sand/boulders on the other hand range from fine to boulder-sized particles (Figure 22b). The unit commonly has cobbles or boulders in a matrix of sand .20-.99m in depth. The sand/boulder unit is often vegetated by grasses. The submerged sand (Figure 23) unit describes sand deposits that are underwater but could be mapped using the air photos. These units are often helpful in determining whether the sand has actually been moved or if it has simply been covered by water.

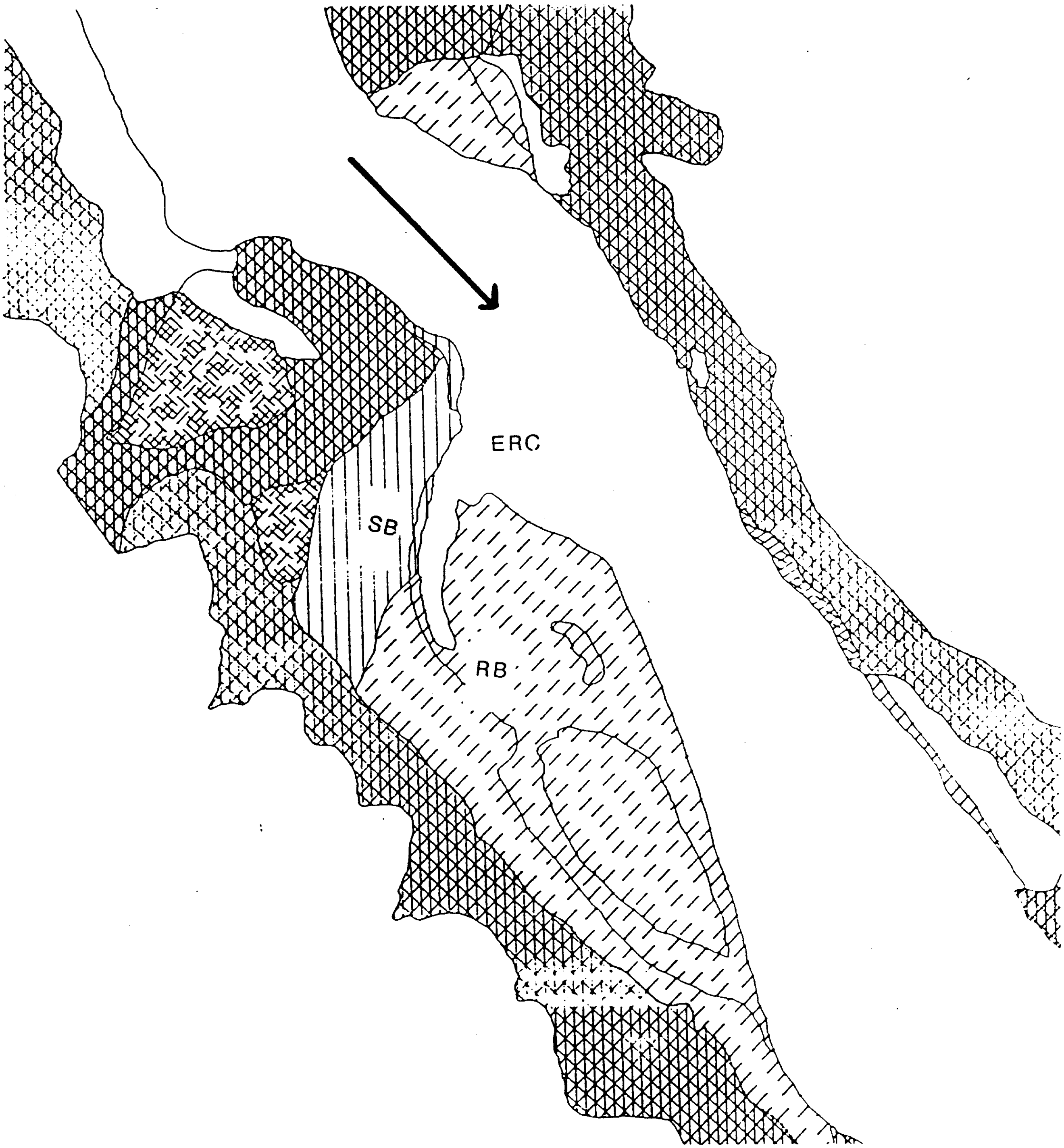


Figure 20.--1990 map of 55 mile marsh. The Eddy Return Channel (ERC) marks the dividing line between Separation Bars (SB) and Reattachment Bars (RB). Flow Direction is upper left to lower right. Scale is 2.1cm = 50m.

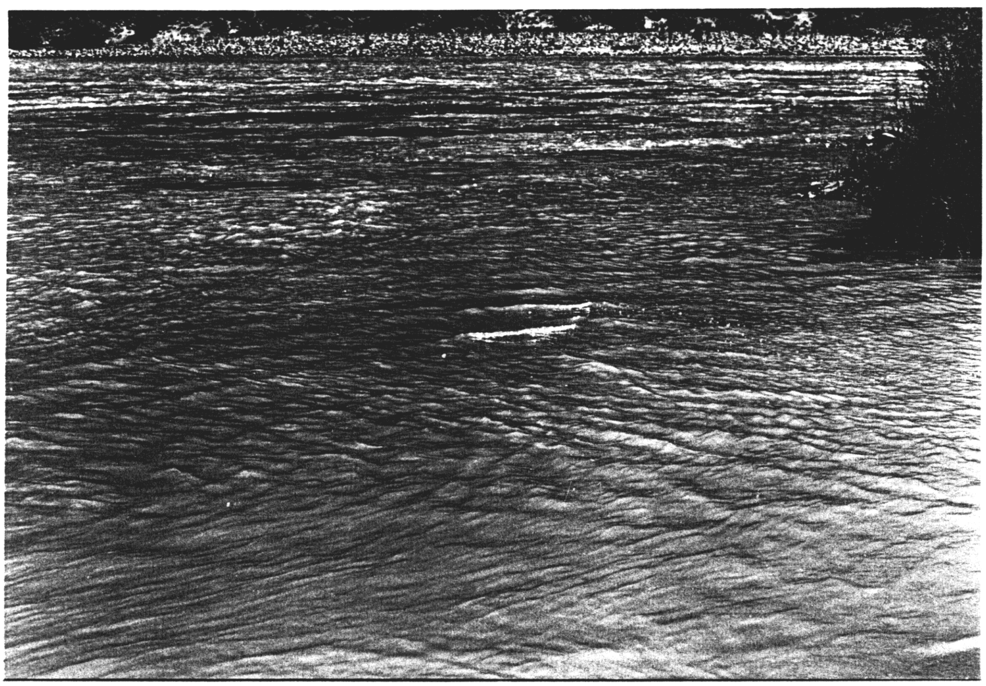
Figure 21a.--Channel margin deposit on river left near RM 51. The unvegetated sand is active. Note the characterisitc berm.

Figure 21b.--View upstream of Fern Glen beach, a large separation bar. The debris line marks the extent of the active unit.

Figure 22a.--Large cobble bar near river mile 55.

Figure 22b.--Sand and boulders near Nankoweap Creek.

Figure 23.--Submerged sand offshore of Lower Nankoweap beach.



There are four map units that are not directly attributed to the Colorado River today, they are: aeolian, high terrace, debris fan, and talus. The aeolian unit represents areas of wind blown sand greater than one meter in depth (Figure 24a). The sand is very fine to coarse-grained and is typically found in dune form with a gentle stoss and steep lee side. The deposit can be vegetated (Figure 24b). High terraces are the result of extremely high flows that because of the dam, are no longer being deposited. The high terraces represent old banks of alluvium that are usually found about 7-8m above river level and are composed of silt to medium sand (Figure 25a and b). The deposits cover talus, but only areas that have a flat plateau like top and have at least a meter of sand are mapped as terraces (Figure 26a). High terraces are always vegetated. Cryptogams, Catclaws, Mesquites and various cacti grow atop these plateaus. The debris fan unit is associated with tributary canyon inputs to the Colorado (Figure 26b). These side canyons will flash and debris flows may develop. The debris flow deposit consists of poorly sorted,(Figure 27a) very fine to boulder sized particles that spread out to a fan shape. The talus unit is a rock fall or talus slope deposit (Figure 27b). The deposit ranges from fine to boulder sized sediment and can be vegetated.

Distribution of Mapping Units

Nearly all of the mapping units mentioned above are found throughout the Colorado Rivers corridor in Grand Canyon. Eddy associated deposits are found where there are constrictions and expansions. Separation bars mantle the downstream side of debris fans while the corresponding reattachment bars form in the eddy downstream of the constriction. Channel margin and high terrace deposits are usually only found in wide reaches of river. While high terraces are found well above river stage (about 7m) channel margin deposits are only a few meters above river level and are

Figure 24a.--Vegetated aeolian dune on the Nankoweap Creek debris fan.

Figure 24b.--Unvegetated aeolian dune on a reattachment bar on river right near RM 54.5.

Figure 25a.--View from old eddy return channel of Lower Nankoweap beach up to high terrace.

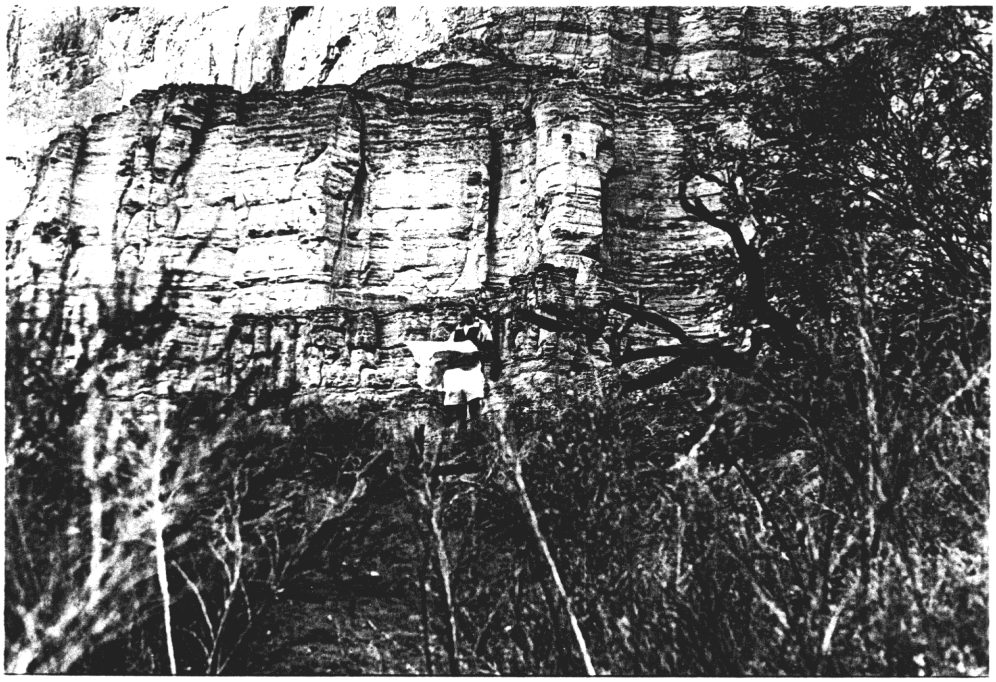


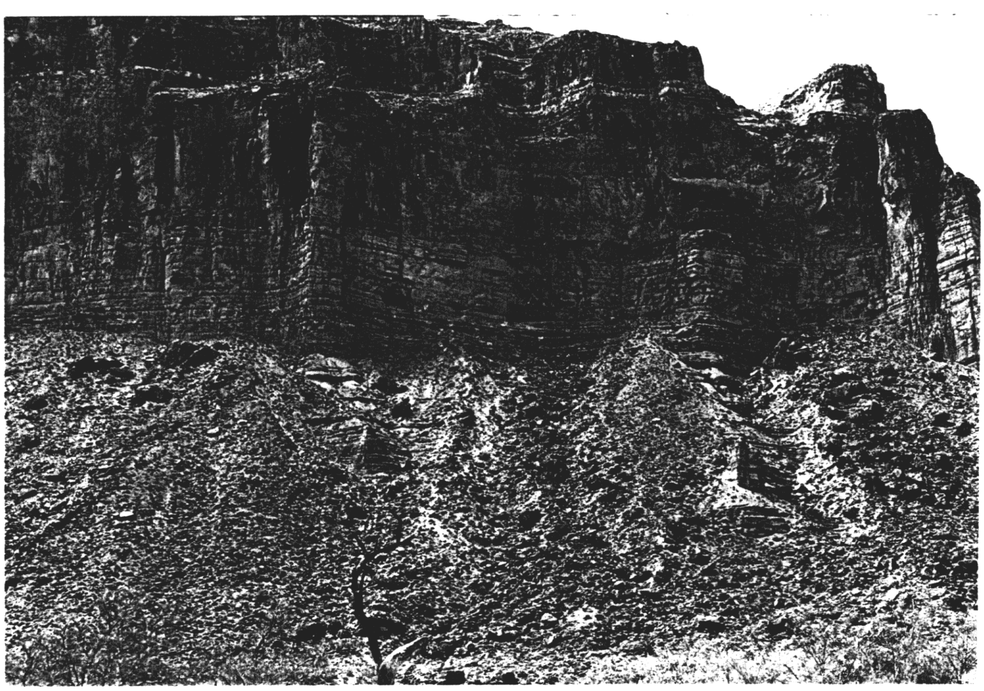
Figure 25b.--View form reattachment bar on river right near RM 54 up to high terrace.

Figure 26a.--"Pancake" flat top of high terrace unit, looking downstream near RM 54.5.

Figure 26b.--Nankoweap Creek debris fan after a flash flood.

Figure 27a.--Debris fan channel in vicinity of furnace flats. Note the poor sorting of sediments.

Figure 27b.--Talus slopes.



inundated at a discharge of 3000 m^3/s. "Active" units of eddy associated deposits and channel margin deposits represent a zone of sand that is regularly inundated and reworked by the river clearing it of vegetation and debris. During periods of normal fluctuating flow the upper elevation of this zone is about 850 m^3/s (Figures 19b, 21a and b). The flood years of 1983-86 created a new active zone which, in most cases, encompassed entire reattachment bars. Aeolian sands are usually found in long, relatively straight sections of river that allow wind a long fetch. Aeolian deposits form on top of other deposits such as talus, reattachment bars and high terraces (Figures 24a and b). Sand/boulders are located almost anywhere that sand deposits are found. Sand/boulder deposits are areas that have had the top layers of sand eroded, exposing large-sized debris. Boulder bars are characteristic of relatively wide, shallow parts of the river immediately downstream of a tributary (Figure 22a). Debris fans are found wherever a side canyon or tributary intersects with the main channel. Talus deposits underlie most of the deposits, forming a foundation upon which high terraces, reattachment bars, and other units form.

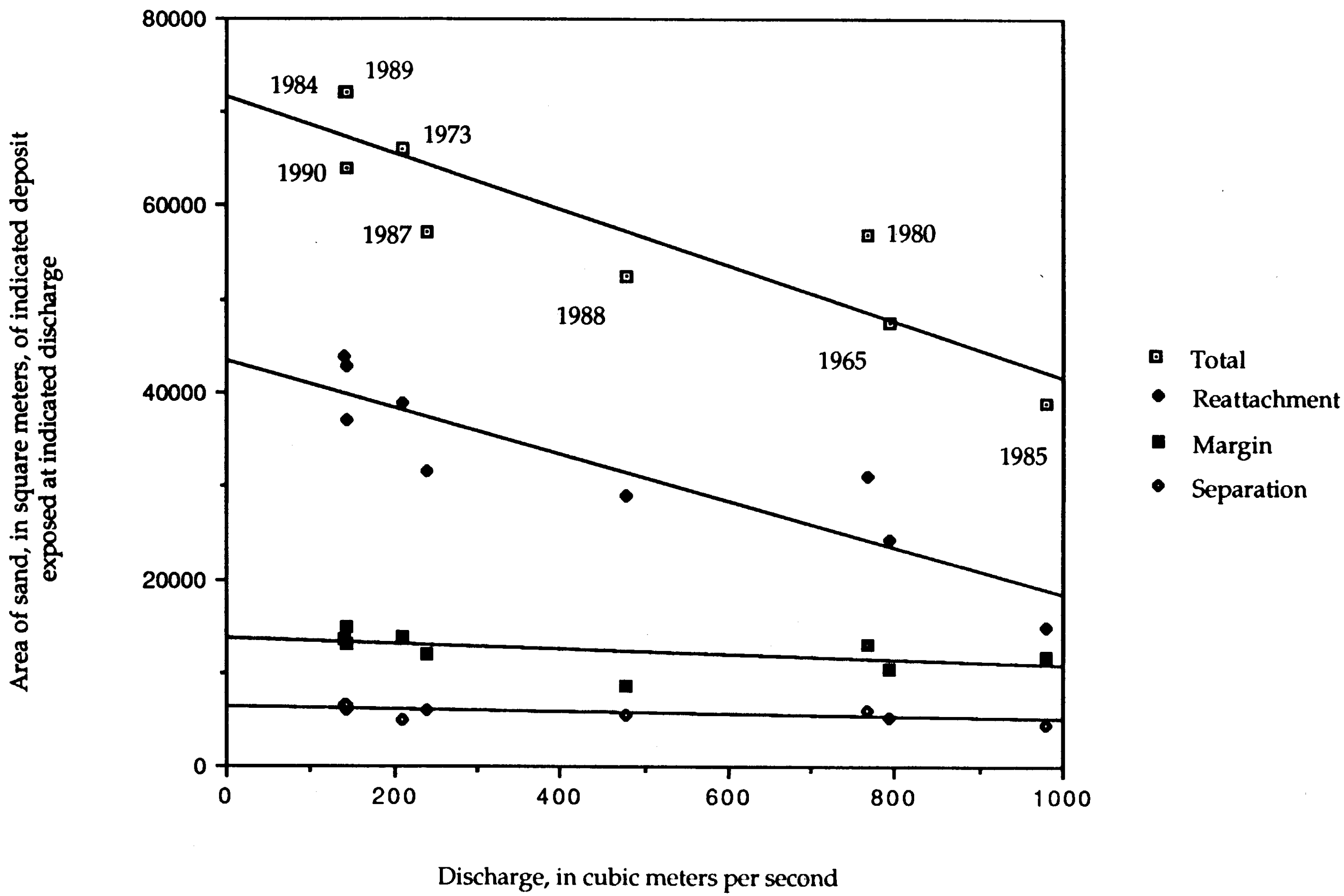
Sand Bar Change

A tabulation of the Arc-Info data compiled for map 4 is shown in Table 5. From these data, plots of time vs area of reattachment bars, separation bars, channel margin deposits and total area of sand were generated (See Figure 28). Note that this plot is uncorrected for changes in stage and as a result, the trends seen are caused by differences in stage not by actual changes in area. To compensate for stage differences, a plot of water area vs discharge was generated (Figure 29). Since there is a good correlation between the two, areas of sand were plotted against discharge (Figure 30). The equations for the

Table 5.--Arc Info data for map 4.

Year	1965	1973	1980	1984	1985	1987	1988	1989	1990
Reattachment area in sq m	13649	28061	30900	21551	13109	15453	16075	20469	20406
Separation	5117	4981	6069	5240	4488	5521	5327	5213	5316
Margin	8294	11799	12564	11968	11000	11579	8242	12920	12067
Ret Active	10730	10904	154	22339	1907	16127	12888	22440	16819
Sep Active	0	69	0	1293	16	495	178	1202	607
Mar Active	2174	2090	381	1629	758	509	388	1973	914
Debris fan	107696	118210	110717	118428	106239	113842	110387	119072	118390
Talus	110728	114765	111849	109543	112377	114620	113907	115784	115390
Aeolian sand	5821	5839	5873	4020	5833	5846	5874	5847	5891
Sand/boulder	11773	15714	15895	19396	15482	18944	18373	21387	20584
Cobble bar	3890	7364	4859	4305	3008	8484	6599	10435	9582
Sep/Ret	7620	8279	6988	7936	7719	7466	9341	7783	7857
Submerged sand	2053	642	1495	1125	4148	114	0	6445	1592
High Terrace	32128	32005	31904	31929	32035	31997	31844	31959	31977
Sep/ret Active	0	0	0	174	0	0	0	236	0
Water	252565	213626	230432	189805	255582	221426	234981	190397	205464
Totals									
Reattachment	24379	38965	31054	43890	15016	31580	28963	42909	37225
Separation	5117	5050	6069	6533	4504	6016	5505	6415	5923
All Eddies	37116	52294	44111	58533	27239	45062	43809	57343	51005
Margins	10468	13889	12945	13597	11758	12088	8630	14893	12981
All sand deposits	47584	66183	57056	72130	38997	57150	52439	72236	63986

Figure 30.--Area of indicated deposits exposed at indicated discharge.



linear regression lines for the total area of all sand deposits and for reattachment bars are:

$$A_t=71{,}538 - 29.848Q \qquad R^2=0.783$$

$$A_r=43{,}482 - 25.034Q \qquad R^2=0.803$$

where A_t is total area of all sand deposits,in square meters, A_r is area of reattachment bars, in square meters, and Q is discharge in cubic meters per second.

Channel margin deposits and separation bars show little correlation ($R^2 < .5$), indicating that these deposits form at too high of an elevation to be affected by the stage differences in the aerial photographs. Because separation and channel margin deposits have steeper slopes than reattachment bars, differences in stage do not greatly affect the area of exposed deposit. Note that for total area of sand, that 1965, 1973, 1980, 1984 and 1989 all plot above the predicted line. This means that for the predicted value there is actually more sand. Conversely, 1985, 1987, 1988, and 1990 all plot below the line, meaning that there is less sand than predicted.

The 1989 residual is uncharacteristically high. The reason for this is that the discharge data is likely to be in error. While 1984, 1989, and 1990 are all listed at 141.5 m^3/s for the Lees Ferry gage, the aerial photos in the study reach show that the stages differ. It is highest in 1990, while 1984 has slightly less water, and 1989 has the least water. The 1984 and 1990 flows must have increased in volume do to tributary contributions, thus accounting for the stage difference. Because of the problems with the 1989 data, it was not included in the residual plot.

The time series residual plot (Figure 31), shows the area of sand predicted minus the actual area of sand. These time series plots are an attempt to describe sand bar change. The linear regression line is only an approximation of the actual curve for the 1965 condition. If we knew what this curve was in 1965, all points would be related to this curve and residuals would give us actual changes in area over time. Because the linear regression line is only an approximation, however, the values of the residuals are meaningless, rather it is the trend in how the residuals change that is of importance. Lines drawn through the points show how the sand bars have changed in area over time. From 1965 to 1982, the total amount of sand was increasing in area. From 1983-86, the total sand was decreasing in area and during the 1987-90 period, the total amount of sand increased in area again. Residuals were not plotted for separation and margin deposits because of the poor line fits. Preliminary analysis of data from map 2 (Table 6) shows the same trends as map 4.

Sand Bar Stability

Twelve eddies were evaluated for stability Of these twelve, four were ranked as unstable. The corresponding channel geometry characteristics (Table 7) were then analyzed to see if unstable bars had anything in common. As seen in the table on the next page, eddy length and constriction ratios vary widely and no sound correlation can be made between instability and eddy length or constriction ratio. The expansion ratios of the unstable eddies, however, are all higher than the corresponding expansion ratios for stable eddies. In addition, unstable eddies exhibit a lower than average shape factor when compared to stable eddies. A plot of expansion ratio vs constriction ratio is shown in Figure 32. The unstable bars are shown as x's.

Table 6.--Arc Info data for Map 2.

Year	1965	1973	1980	1984	1985	1987	1988	1989	1990
Reattachment area in sq m	11179	16651	16590	14811				18301	18725
Separation	4480	5116	5470	7258				5296	5213
Margin	447	3587	3879	0				1469	1623
Ret Active	2552	3089	38	16584				15414	10533
Sep Active	229	557	0	2307				1212	941
Mar Active	2732	914	0	6895				3484	3499
Debris fan	116115	122085	0	122390				121687	122284
Talus	195572	204981	199743	207497				211080	209360
Aeolian sand	14622	17274	15328	14956				15156	15003
Sand/boulder	81109	99896	88573	78442				100878	94577
Cobble bar	15401	24331	15366	66204				50907	55818
Sep/Ret	10110	10228	9126	9545				10310	9590
Submerged sand	4539	0	0	1038				241	250
High Terrace	62184	62476	62396	62356				62095	62513
Sep/ret Active	1106	1626	938	6735				3532	2603
Water	296198	248421	79454	203728				197454	209918
Totals									
Reattachment	13731	19740	16628	31395	0	0	0	33715	29258
Separation	4709	5673	5470	9565	0	0	0	6508	6154
All Eddies	29656	37267	32162	57240	0	0	0	54065	47605
Margins	3179	4501	3879	6895	0	0	0	4953	5122
All sand deposits	32835	41768	36041	64135	0	0	0	59018	52727

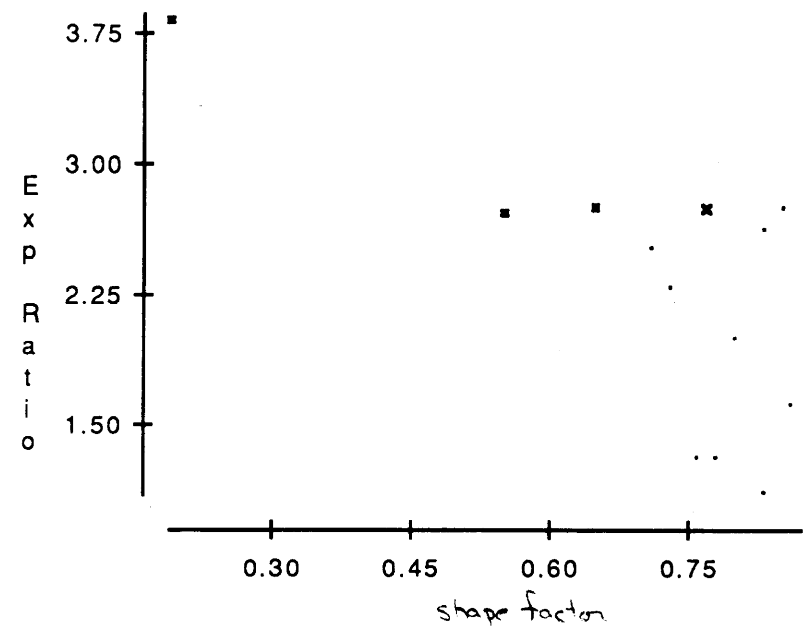
Table 7.--Summary of measurements taken on major reattachment bars.

Eddy*	AUW (m)	CW (m)	EW (m)	CW-85 (m)	Exp Ratio	Con Ration	Shape F	EL (m)	Stability
A	36.28	23.95	47.89	29.75	2.00	0.66	0.80	130.62	Stable
B	36.28	30.84	34.11	37.01	1.11	0.85	0.83	20.32	Stable
C	18.14	17.42	47.89	26.85	2.75	0.96	0.65	101.60	Unstable
D	28.30	21.77	57.33	26.12	2.63	0.77	0.83	90.71	Stable
E	29.03	27.58	36.28	36.28	1.32	0.95	0.76	74.02	Stable
F	39.91	18.14	45.72	25.40	2.52	0.45	0.71	86.36	Stable
H	19.23	15.96	43.54	29.03	2.73	0.83	0.55	97.24	Unstable
I	23.95	12.34	47.17	64.59	3.82	0.52	0.19	68.94	Unstable
J	34.11	32.66	42.82	42.09	1.31	0.96	0.78	37.01	Stable
K	31.20	25.40	58.05	34.83	2.29	0.81	0.73	108.85	Stable
L	34.11	16.69	45.72	21.77	2.74	0.49	0.77	43.54	Unstable
N	30.48	26.85	43.54	31.20	1.62	0.88	0.86	83.45	Stable
O	26.85	21.04	58.05	24.67	2.76	0.78	0.85	117.56	Stable
			Ave	30.69	2.11	0.71	0.67		

Where AUW is average upstream width, CW is constriction width measured on 1990 photos, EW is expansion width, CW- 85 is constriction width measured on 1985 photos, and EL is eddy length.

*Eddies are labeled on the 1990 topographic base maps.

Figure 32.--Expansion ratio vs shape factor for 12 reattachment bars in the Nankoweap reach.



Historical Profiles

Three profiles at Lower Nankoweap Beach have been repeatedly surveyed (Figures 33-35). This particular beach is a very popular campsite for boaters and is always occupied during the commercial season. Comparison of the profiles along with appropriate map view comparisons relate a story of change in sand bar morphology for this beach.

The 1973-1980 time period is one of little change, only slight erosion is seen in the three profiles. Profile 3 shows cutbank retreat in the lower elevations. From 1980-84, profiles 1 and 2 experienced net aggradation while profile 3 shows aggradation of sand below the 99m elevation and degradation of sand above 99m. The formation of an eddy return channel in cross sections one and three, can also be observed. Little insight can be gleaned from looking at the corresponding maps because differences in stage mask any changes. The discharge in 1980 is over three times that of 1973 and hence the meter in stage difference covers up any erosion. Likewise, the extremely low discharge of the 1984 mask the deposition. In 1985, the water level inundated the survey area.

The surveys for cross sections 2 and 3 were continued through 1987. From 1984-97, both profiles show slight net aggradation. The discharge at the time of the 1973 aerial photograph is similar to the 1987 discharge. Comparison of the 1973 and 1987 maps show that the bar has changed shape (Figure 36) in the fourteen year period.

DISCUSSION

Changes in sediment storage from 1965-1990

The total volume of sediment stored in a system can be described by the following equation:

$$SS = BD + BR$$

where SS is total sediment stored, BD is sediment stored on the bed, and BR is sediment stored in the sand bars.

Figure 37 is a time series curve of total sediment storage for the Colorado River between Lees Ferry and Grand Canyon gage from 1963-89. BD, in the equation above, was obtained by comparing fathometer traces. Sediment stored in the sand bars (BR) was determined through comparative mapping (Figure 31) and analysis of historical profiles at Lower Nankoweap beach campsite (Figures 33-35). Total sediment storage (Figure 37) is given in millions of megagrams which implies that SS is a volume. No volumes, however, were determined in this work. As a result, the following will be a qualitative analysis of changes in sediment storage from 1965-1990.

The history of sediment storage can be divided into four time periods. Each of these time periods is characterized by a unique flow regime that the dam was operating under. It is the differences in flow regimes and their juxtaposition in time that dictates how the sediment stored in the system will be affected.

From 1965 to 1982, total area of sand for reach four has increased (Figure 31) and as Figure 37 indicates, the entire system was accumulating sediment. However, all three of the profiles at lower Nankoweap beach campsite showed degradation during the 1965-82 period. Work done by Kyle

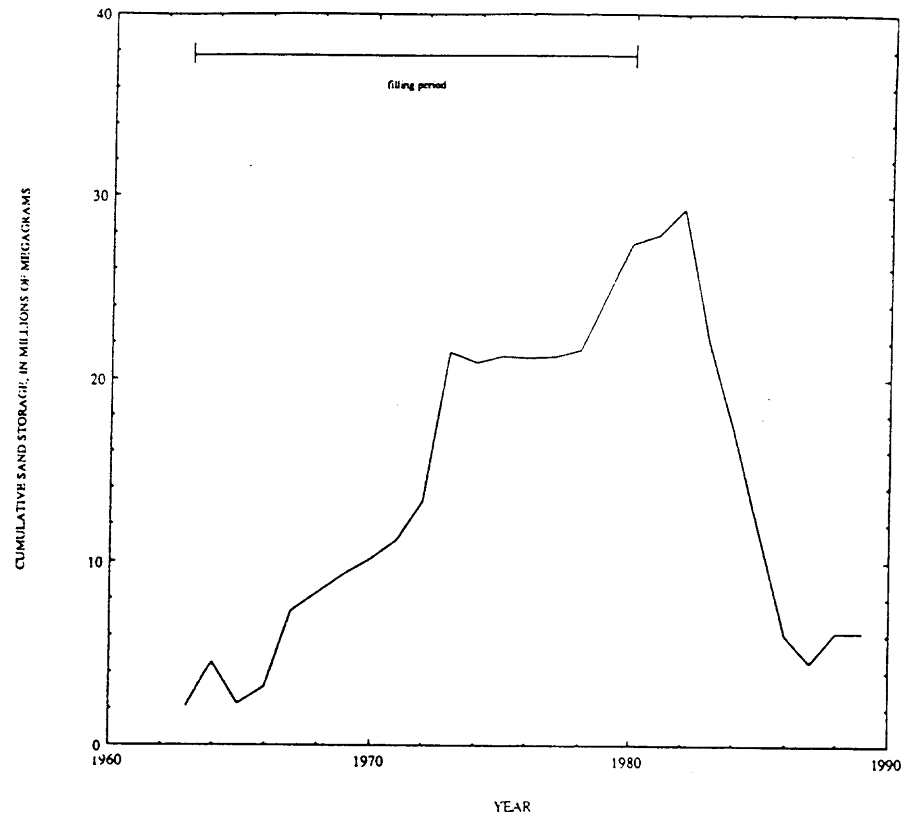


Figure 37.--Cumulative sand storage in Colorado River near Grand Canyon following closure of Glen Canyon Dam. Ordinate values = Colorado + Paria + Little Colorado sediment input - sand transported past Grand Canyon Gage. From Schmidt and Grams (1991).

(1992) shows that many beaches throughout the canyon have also experienced erosion during this time. Flow duration curves (Appendix 4) for this time interval show that the mean annual flood was rarely in excess of power plant discharge (890 m^3/s). Discharge data indicates that this time period was dominated by fluctuating flow. Because the flows were not of great enough magnitude to transport large quantities of sediment, most sediment input was retained in the system.

The 2750m^3/s flow released in 1983, unlike any other flow since the dam had been built, was capable of transporting a great deal of sediment. After the flood, profiles of Lower Nankoweap beach and others in the canyon showed net aggradation. Most of this aggradation occurred at high elevation. During the 1980-84 airphoto interval however, there was a drastic net decrease in overall sand area for the map 4 region. The sediment budget plot by Schmidt and Grams (1991) shows that during this period the sediment that had been accumulating, since the dam was built, was removed. Fathometer trace studies also indicated wide spread scour of the channel bed between the years of 1973 and 1984 (Rathburn, 1991, written communication). Based on this information, it is believed that, the 1983 flood scoured the bed and many eddies in narrow reaches (Schmidt and Graf, 1990). From the historical profiles, it appears that as the flood receded, it deposited this sand high upon reattachment bars in wide reaches (like the study reach) causing the beaches to become steep.

The subsequent flows of 1984-86 were also capable of transporting a significant amount of sediment. However, during this period most profiles show net erosion of high sands (Kyle, 1992) and the area analysis shows continued erosion of the banks. Because these high magnitude flows (1270m^3/s) occurred so soon after the 1983 flood, the system had no time to recover. The bed, after being scoured in excess of two meters, did not have time to sufficiently accumulate sediment for the next flood to remove. As a result, the sediment was taken from the banks of the river. The idea that clear water floods, spaced closely in time, erode existing sand bars is supported by Grams (1991). Grams found that while the dams in Hells Canyon didn't affect the mean annual flood, they did trap sediment. As a result, each year a large clear water flood would occur. Because these clear water floods happened so frequently, the bed had no time to recover and the banks of the channel have consequently been eroded. Erosion rates in Hells Canyon exceed that of Grand Canyon (Grams 1991).

The implications of these findings are that while one flood may seem to be beneficial, by adding sand to campsite beaches, another flood following too closely may not only erase the sand deposited by the first flood, but also cause further erosion to narrow reaches that were eroded by the first flood. To recompense this, sufficient time should be allowed for bed recovery after a flood.

The flow duration curves for the time interval from 1987-90 is similar to that of the 1965-73 interval (Figure 3 and Appendix 4). This indicates that once again the dam was operating under a normal fluctuating flow regime with low annual peak discharge. While lower Nankoweap beach lacks sufficient information for this time period, Kyle (1992) has shown that the high sands have continued to erode and that most profiles have reverted back to the 1973 elevations. The area analysis, in contrast, shows a rate of area increase similar to that of the 1965 to 1982 period. The plot by Schmidt and Grams (Figure 37) shows that, with the advent of low peak annual discharges, the system is likely again accumulating sediment. What appears to be happening is that fluctuating flow gradually moves the 1983 sands from high elevations to lower elevations. In profile view, this is seen as slopes becoming more gentle,while in map view it is seen as bars building out into the channel and increasing in area. Table 8 summarizes the results of the different methods for each of the four time periods.

Table 8.--Results of different methods of determining sediment change.

Time Period	Profiles[1]	Area Analysis	Sediment Budget[2]	Fathometer[3]
1965-82	Degradation	Aggradation	Aggradation	??
1983	Aggradation	Degradation	Degradation	Degradation
1984-86	Degradation	Degradation	Degradation	??
1987-90	Degradation	Aggradation	Aggradation	??

[1]Net change of six beaches analyzed by Kyle and one by Clark.
[2]Budget analysis by Schmidt and Grams (1991, written communication).
[3]Results of analysis by Rathburn and Clark. Only records from 1973 and 1984 were available for analysis.

The table above indicates that the area analysis follows the same trends as the sediment budget analysis, yet the profiles show no good correlation. Therefore, in order to evaluate reach scale changes, we need to consider more than just profiles at a few beaches. Many beaches that have been analyzed are large "campsite" beaches that may be uncharacteristic of other, smaller beaches in a reach.

Change in Morphology of Lower Nankoweap Beach

The surveyed area of Lower Nankoweap beach is a good example of the complex changes that a beach experiences with time. While the entire beach is quite large, the surveyed area represents only a small portion of the beach. The story at Lower Nankoweap is one of change in shape rather than size. Figure 38 shows the 1973 and 1987 maps for the beach. From the maps and the profiles we can see that a sand shift has occurred during the 1984-87

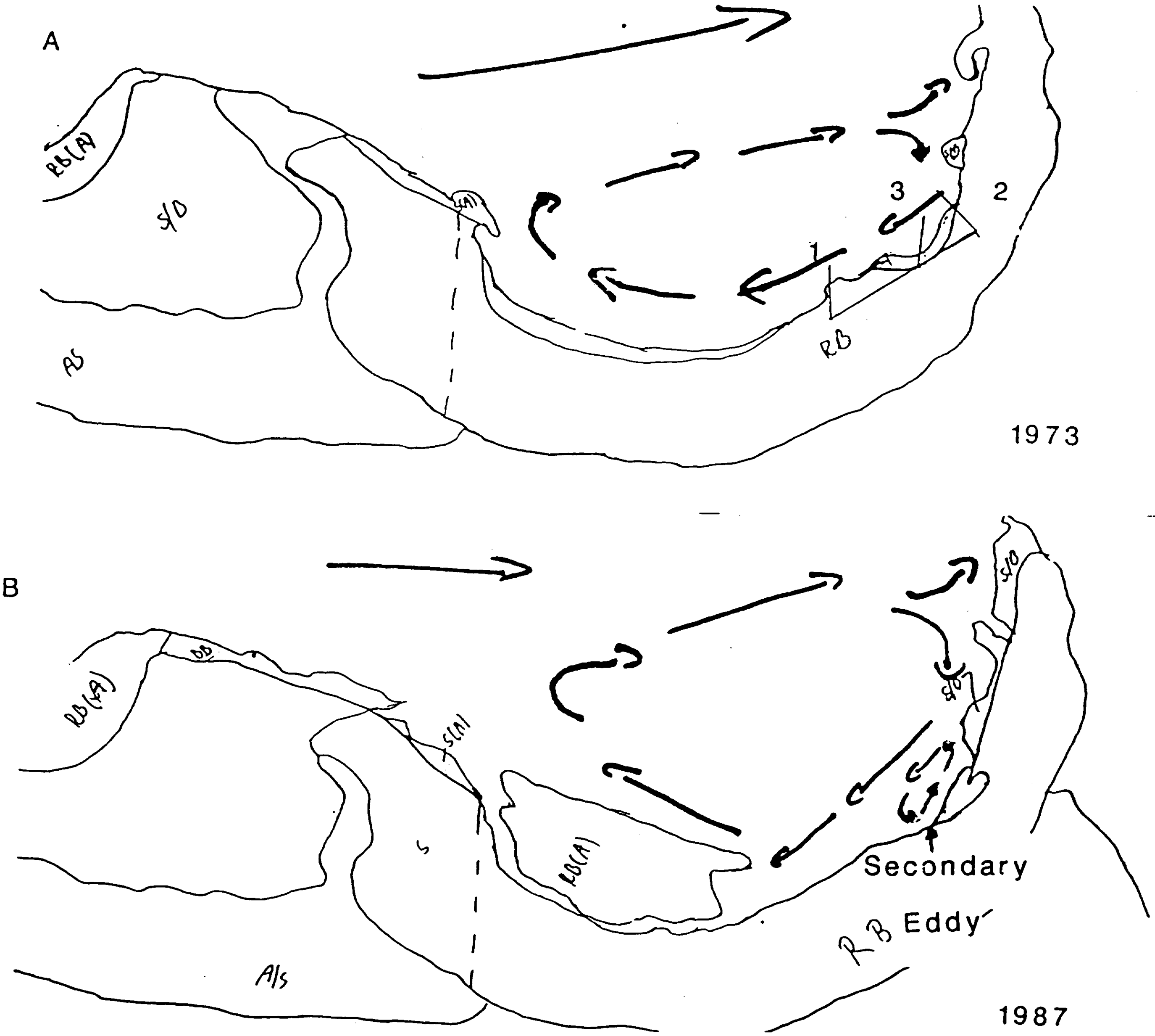


Figure 38.--Maps showing profiles 1, 2, and 3 at Lower Nankoweap beach, for 1973 and 1987 and probable flow patterns. Note the secondary eddy in diagram B.

period. All three profiles (Figures 33-35) experienced degradation from 1973-1980. From 1980-84 cross sections 1 and 2 aggraded. Cross section 3 degraded at high elevations, during this time period, because of the eddy return channel that ran through this profile.

Unlike other beaches in the Grand Canyon, profiles 2 and 3 of Lower Nankoweap, do not show degradation from 1984-87. The aggradation (seen in profiles) and shift in sand (seen in maps) can be attributed to a change in recirculation patterns. Profiles 1 and 3 show that in 1984, there was an eddy return channel. No such channel exists on profile 2. This means that the eddy return channel is located upstream of CS1 and hence the eddy must be moving clockwise. Flow conditions during 1984-87 must have caused a secondary eddy, flowing counter clockwise, to form. Figure 38b shows a probable secondary eddy. The location of the eddy return channel indicates that the water is moving in this direction as well. This eddy is moving even slower than the main eddy and as a result, net deposition occurs here, thus accounting for the aggradation of these two profiles. Lower Nankoweap beach campsite profiles and maps show that flow patterns and areas of deposition and erosion differ with different discharges.

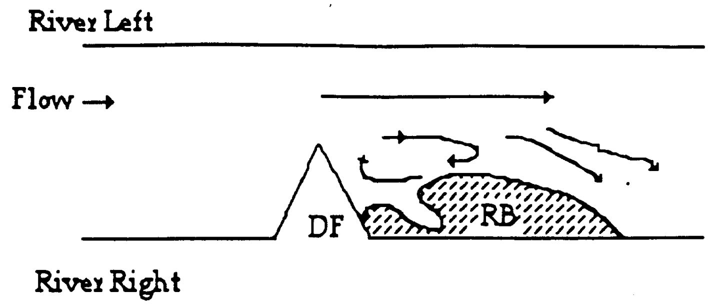
The history of sand bar change at Lower Nankoweap beach shows that individual beaches should not be used to gauge reach scale changes. The main difference in the 1973 and 1987 maps is the large area of sand (labeled RB(A) in Figure 38b) in the eddy that is upstream of the profiles. If one was to only look at profiles, he would miss the most significant change. Moreover, individual beaches may react in the exact opposite fashion as an entire reach and that any large scale assumptions based on the evaluation of just a few beaches may be invalid due to the widely varied characteristics of each beach and the way the eddies that form these beaches react to changes in discharge.

Characteristics of unstable sand bars

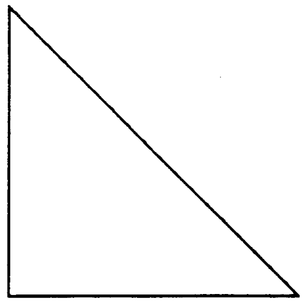
Unstable reattachment bars, in the study reach, are characterized by high expansion ratios and low shape ratios. High expansion ratio means that the constriction width is quite small compared to the expansion width. The low shape ratio indicates that the objects that create the constrictions, in general have a low gradient and are inundated at higher levels of stage. When these obstructions become inundated, the eddy is effectively dissipated, as there is no longer any constriction (Figure 39).

Implications for Dam Operational Strategy

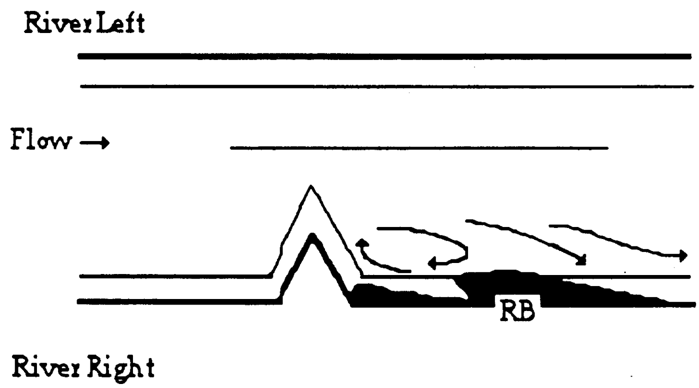
One of the goals of the new operational regime for Glen Canyon Dam is to minimize impact on the sand bars while still being able meet energy demands. Based on the research in this paper, it looks as though periods of fluctuating flow gradually flatten sand bars, causing net erosion while depositing sediment on the bed. After many years of fluctuating flow, the bars may reach a state of stability where little erosion occurs. If this "stable" state is insufficient for the recreational obligations of the beaches then it may be necessary to rebuild the sand bars via a large flow. The sediment budget plot by Schmidt and Grams (unpublished manuscript) can help dictate whether a flood should be released or not. The plot provides us with a record of sediment storage. This relation not only tells us how long it takes the system to recover but it also tells us when the system can afford to support a new flood without it eroding the beaches. This simple relation could make it possible to run the dam efficiently in a way that pacifies all parties involved.



Hypothetical eddy at low discharge. RB is reattachment bar. DF is debris fan. At low discharge, both profiles A and B cause an eddy.

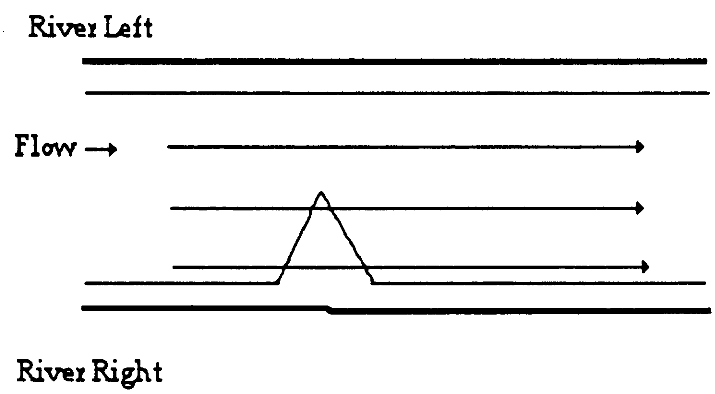


Profile A



Hypothetical flow patterns caused by type A debris fan profile. Discharge is much higher and the water's edge is marked by the thick black line.

Profile B



Hypothetical flow patterns caused by type B debris fan. Discharge is much higher and as a result, the eddy has washed out. Water's edge is marked by thick black line.

Figure 39.--Hypothetical flow models showing how differences in debris fan geometry affect flow patterns.

Future Work

In the midst of a record snowfall year for most of the rockies, I cannot help but wonder if this summer it will again be necessary to spill excess water. The question is if the bed has had enough time to accumulate sediment since the last high flow or not. If there is enough sediment, then net deposition should be experienced. If the bed has not recovered sufficiently, then widespread erosion should be seen throughout the study reach. To further validate the results of the Fathometer trace, I think that it would be beneficial to run another trace before the 1992 thaw. This trace would show if the bed has been accumulating sediment since the last trace (1984). It will also serve as a basis for comparison of another fathometer trace which should be done after the next high flow.

I think that the same surficial geologic mapping and corresponding GIS work should be done for other reaches as well. The results can then be compared with those of the Nankoweap reach and we can get a better understanding of how sediment storage changes with reach width and reach distance downstream from the dam.

CONCLUSIONS

1) So called "campsite" beaches, which are the subject of most topographic resurveying, may not be indicative of reach scale changes.

2) To accurately evaluate reach scale changes, it is necessary to take into account not only topographic profiles within the reach but also, comparative mapping studies, fathometer trace results, and sediment budget analysis.

3) Clear water floods spaced too closely in time have a net erosional effect on the bed and the banks of the reach, regardless of reach width.

4) Unstable sand bars are characterized by low shape ratios and high expansion ratios.

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APPENDIX 1

Surficial geology maps for 1965-1990 (RM52-56)

APPENDIX 2

Stage-wave time travel chart used to calculate travel time of water from Lees Ferry to Kwagunt Rapids

APPENDIX 3

Data used to generate profiles 1,2, and 3 for Lower Nankoweap beach.

APPENDIX 3

Data used to generate profiles 1,2, and 3 for Lower Nankoweap beach.

Cross Section 1

STAT. 6/74	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m	STAT. 6/75	BS or FS m	Dist f	Dist m	Elevation	HI m
Pipe at BS2	1.45			100.11	101.56	7.00	1.63	6.25	1.90	99.89	101.52
1.00	3.86	67.50	20.57	97.70		6.00	2.30	17.17	5.23	99.22	
2.00	3.51	61.25	18.67	98.05		5.00	2.57	29.92	9.12	98.95	
3.00	3.06	48.92	14.91	98.50		4.00	2.82	42.75	13.03	98.70	
4.00	2.80	42.75	13.03	98.76		3.00	3.02	48.92	14.91	98.50	
5.00	2.52	29.92	9.12	99.04		2.00	3.57	61.25	18.67	97.95	
6.00	2.18	17.17	5.23	99.38		1.00	3.98	67.50	20.57	97.54	
7.00	1.67	6.25	1.90	99.89		BS1	2.08			99.44	
BS1	2.12	150.00	45.72	99.44		CS1	1.37			100.15	
BS2	1.45	0.00	0.00	100.11							

Cross Section 1

STAT. 6/80	BS m or FS m	DIST.	DIST. m	ELEV. m	HI m	STAT. 8/84	BS/FS m	DIST. ft	DIST. m	ELEV. m	HI m
BS1(Now R1)	1.34			100.00	101.34	CS1	1.35	0.00	0.00	100.28	101.63
1.00	1.67	6.00	1.83	99.67		1.00	1.87	11.88	3.62	99.76	
2.00	2.03	18.00	5.49	99.31		2.00	2.52	27.63	8.42	99.11	
3.00	2.27	29.00	8.84	99.07		3.00	2.32	39.17	11.94	99.31	
4.00	2.54	41.00	12.50	98.80		4.00	3.28	50.71	15.46	98.35	
5.00	2.81	48.33	14.73	98.53		5.00	3.58	56.58	17.24	98.06	
6.00	2.99	52.33	15.95	98.35		Rock 2	1.92	?		99.71	
7.00	3.84	66.00	20.12	97.50		BS1(Rock1)	1.63			100.00	

Cross Section 2

STAT. 6/74	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m	STAT. 6/75	BS or FS m	Dist f	Dist m	Elevation	HI m
Rock 1	0.90			100.00	100.90	CS2(BS1)	1.46			99.44	100.90
Rock 2	1.17			99.73		White rock	0.90			100.00	
BS1	1.45			99.45		8.00	1.52	6.00	1.83	99.38	
1.00	2.26	24.25	7.39	98.64		7.00	1.62	9.75	2.97	99.28	
2.00	2.52	28.92	8.81	98.38		6.00	1.83	17.75	5.41	99.07	
3.00	2.68	35.42	10.80	98.22		1.00	2.27	24.25	7.39	98.63	
4.00	3.04	38.83	11.83	97.87		2.00	2.51	28.92	8.81	98.39	
5.00	3.16	40.58	12.37	97.74		3.00	2.65	35.42	10.80	98.25	
6.00	1.82	17.75	5.41	99.08		4.00	2.98	38.83	11.83	97.92	
7.00	1.63	9.75	2.97	99.27		5.00	3.12	40.58	12.37	97.78	
8.00	1.52	6.00	1.83	99.38							

Cross Section 2

STAT. 6/80	BS m or FS m	DIST. ft	DIST. m	ELEV. m	HI m	STAT. 6/83	BS/FS m	DIST. ft	DIST.m	ELEV. m	HI m
White Rk(R1)	0.97			100.00		Rock 2	1.52	41.75	12.72	99.44	100.96
HI(BS1)	1.53			99.44	100.97	1.00	1.62	10.75	3.28	99.34	
1.00	1.61	6.00	1.83	99.37		2.00	1.88	13.08	3.99	99.08	
2.00	1.77	11.00	3.35	99.20		3.00	1.92	18.34	5.59	99.04	
3.00	1.87	15.92	4.85	99.10		4.00	1.74	22.17	6.76	99.22	
4.00	2.05	19.75	6.02	98.92		5.00	1.69	25.83	7.87	99.27	
5.00	2.61	29.67	9.04	98.36		HI	1.49	0.00	0.00	99.47	
6.00	2.80	36.67	11.18	98.17							
7.00	3.88	45.67	13.92	97.09							

Cross Section 2

STAT. 8/84	BS/FS m	DIST. ft	DIST. m	ELEV. m	HI m	STAT. 8/2/85	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m
CS2	1.40	0.00	0.00	99.62	101.02	Rock #2	1.42	28.67	8.74	99.73	101.15
1.00	1.54	20.00	6.10	99.48		1.00	1.59	20.50	6.25	99.56	
2.00	1.61	25.67	7.82	99.41		2.00	1.75	28.25	8.61	99.40	
3.00	2.05	31.50	9.60	98.97		3.00	2.02	30.83	9.40	99.13	
4.00	2.43	34.25	10.44	98.59		4.00	2.59	32.67	9.96	98.56	
5.00	2.67	36.00	10.97	98.35		5.00	2.89	36.83	11.23	98.26	
6.00	3.20	38.75	11.81	97.82		6.00	3.34	39.25	11.96	97.81	
Rock 2	1.29	28.67	8.74	99.73							

Cross Section 2

STAT. 7/86	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m	STAT. 7/87	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m
Rock 2	0.98	28.80	8.78	99.73	100.71	Rock 2	1.68			99.44	101.12
HI	1.16	0.00	0.00	99.55		HI	1.50			99.62	
1.00	1.21	11.40	3.47	99.50		1.00	1.56	9.70	2.96	99.56	
2.00	1.17	28.80	8.78	99.54		2.00	1.50	20.00	6.10	99.62	
3.00	2.01	34.00	10.36	98.70		3.00	1.83	29.40	8.96	99.29	
4.00	3.25	42.60	12.98	97.46		4.00	2.42	31.90	9.72	98.70	
						5.00	2.88	37.70	11.49	98.24	

Cross Section 3

STAT. 6/74	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m	STAT. 6/80	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m
BS1	1.527			99.449	100.967	EL Datum	0.93			100	100.93
CS3	1.41			99.566		HI	1.385			99.545	
1	2.278	28.67	8.74	98.698		1	1.594	6	1.83	99.336	
2	2.852	38.08	11.61	98.124		2	1.692	10	3.05	99.238	
3	3.24	40	12.19	97.736		3	1.838	14	4.27	99.092	
4	2.214	25.5	7.77	98.762		4	2.218	22	6.71	98.712	
5	1.883	17.58	5.36	99.093		5	2.427	27.58	8.41	98.503	
6	1.665	9.58	2.92	99.311		6	2.618	31.67	9.65	98.312	
						7	3.695	37.67	11.48	97.235	

Cross Section 3

STAT. 8/84	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m	STAT. 8/2/85	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m
CS3	1.49	0	0.00	99.20	100.691	1	1.63	10.58	3.22	99.66	101.291
1	1.55	9.08	2.77	99.14		2	1.96	18.75	5.71	99.33	
2	1.90	16.08	4.90	98.80		3	2.02	20.5	6.25	99.27	
3	2.01	20.92	6.38	98.68		4	3.28	37.5	11.43	98.01	
4	1.92	25.33	7.72	98.77		HI	1.58			99.71	
5	2.42	31.83	9.70	98.27							
6	3.04	49.08	14.96	97.65							
Rock 2	0.98			99.72							

Cross Section 3

STAT. 8/87	BS or FS m	DIST. ft.	DIST m	ELEV. m	HI m
CS3	1.69			98.91	100.6
BS1	1.16			99.44	
CS3(HI)	1.41			99.19	
1	2.03	19.35	5.90	98.57	
2	2.60	28.1	8.56	98.00	
3	2.83	31.5	9.60	97.77	
4	3.09	32.3	9.84	97.51	
5	3.36	40.7	12.40	97.24	

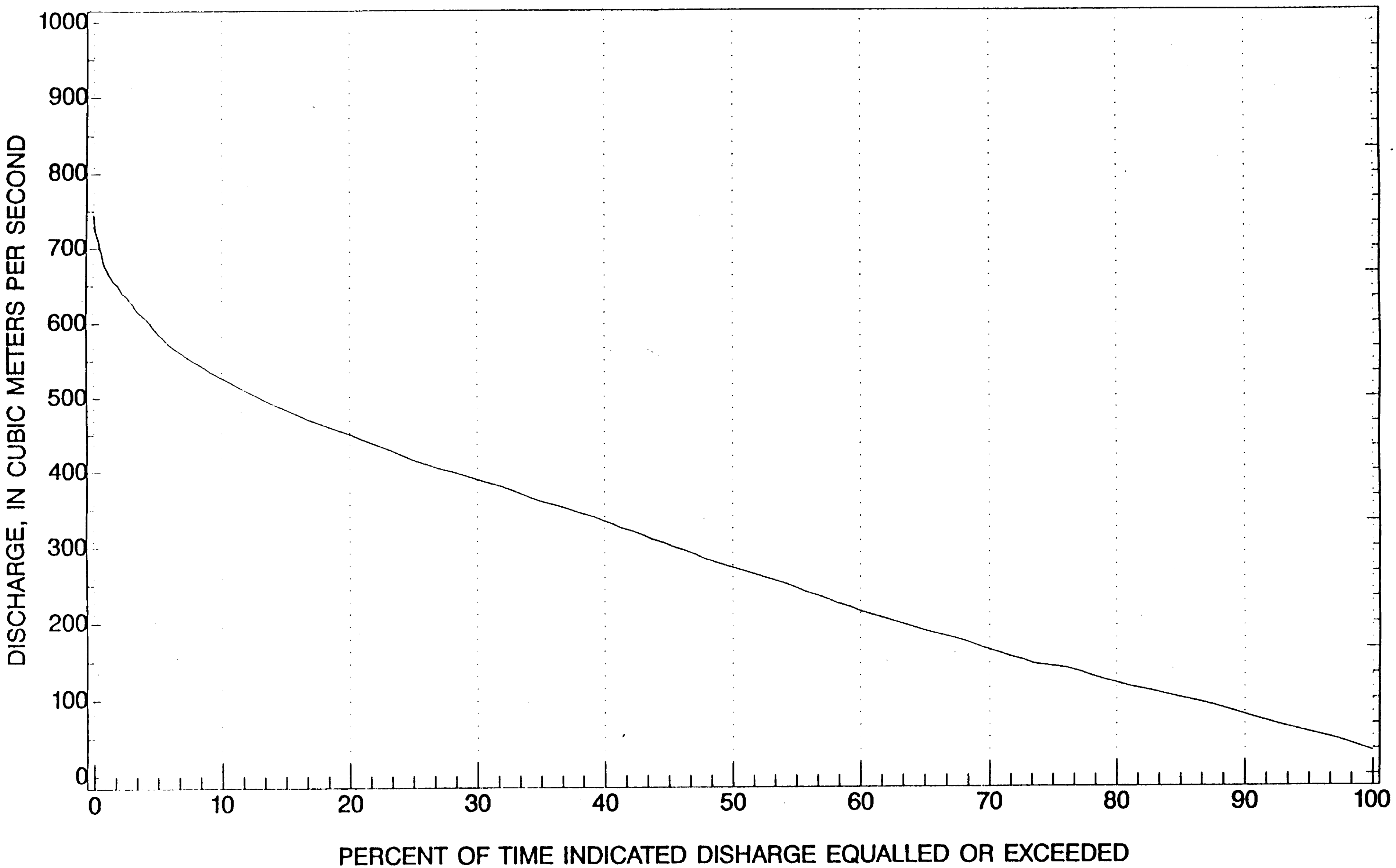
APPENDIX 4

Flow duration curves for time periods between aerial photographs.

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

Oct 7, 1989 – June 9, 1990

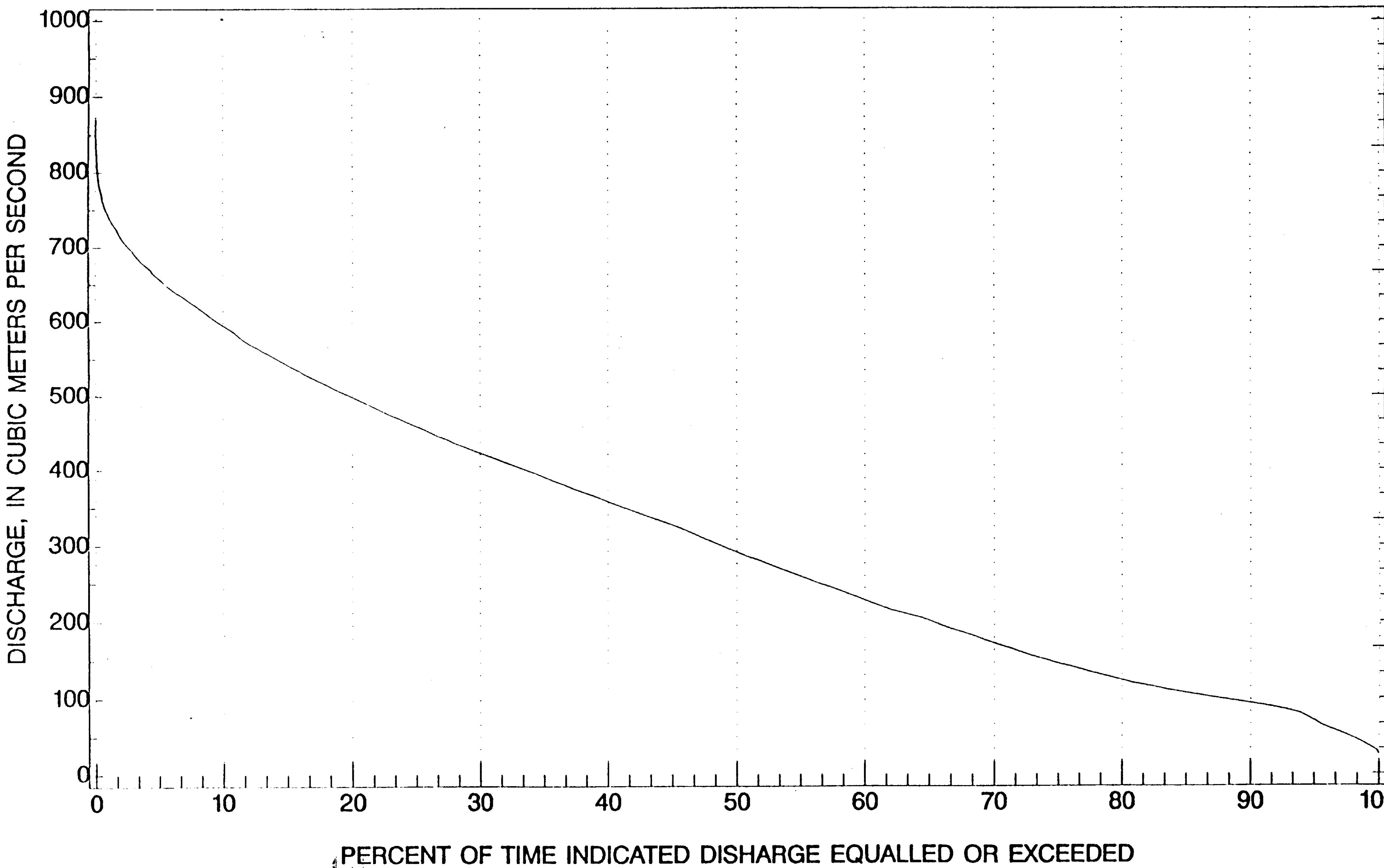


Increments -- 5 cubic meters per second (cfs = cms *35.3)

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

May 27, 1988 – Oct 7, 1989

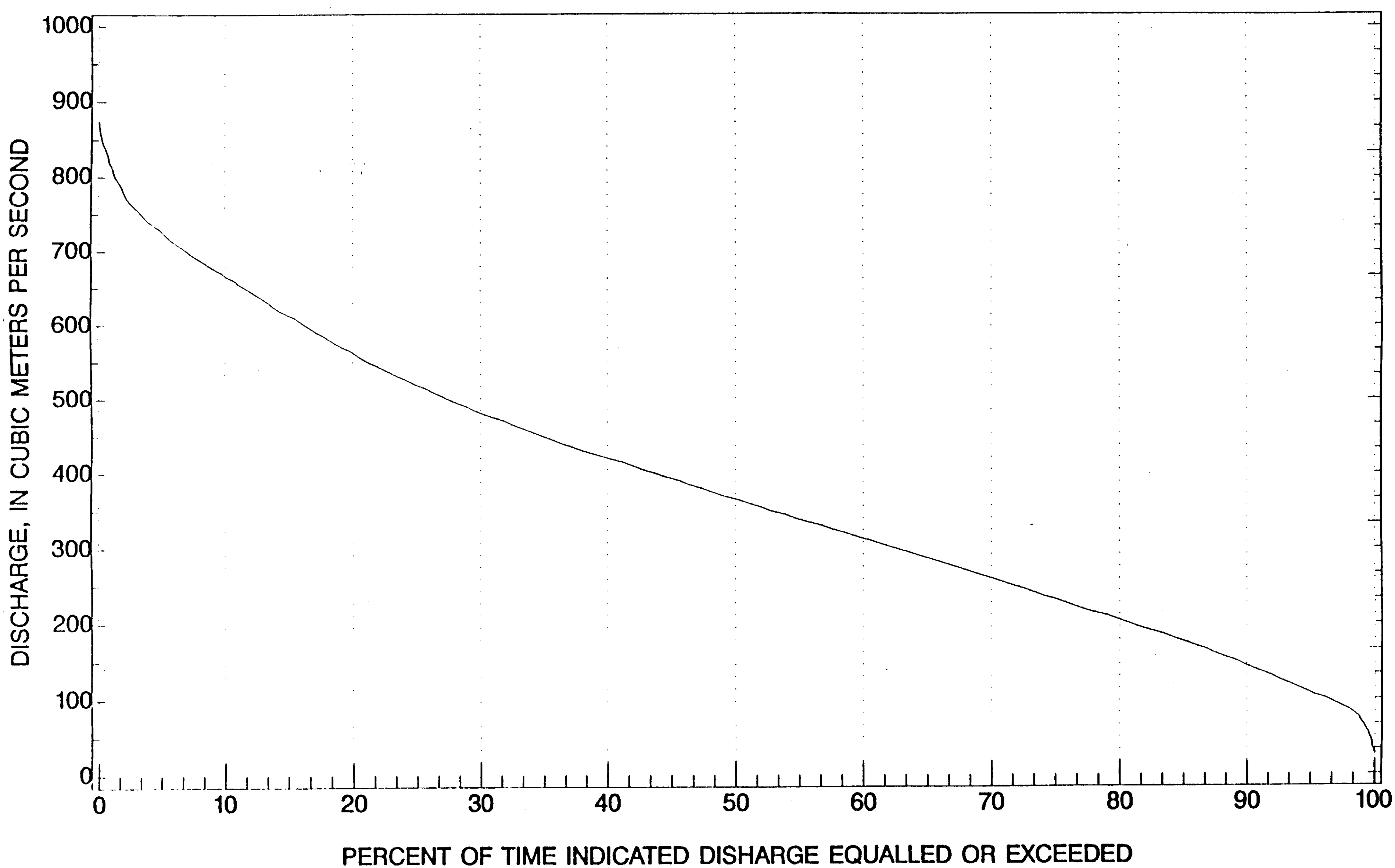


[redacted]

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

May 20, 1987 – May 27, 1988

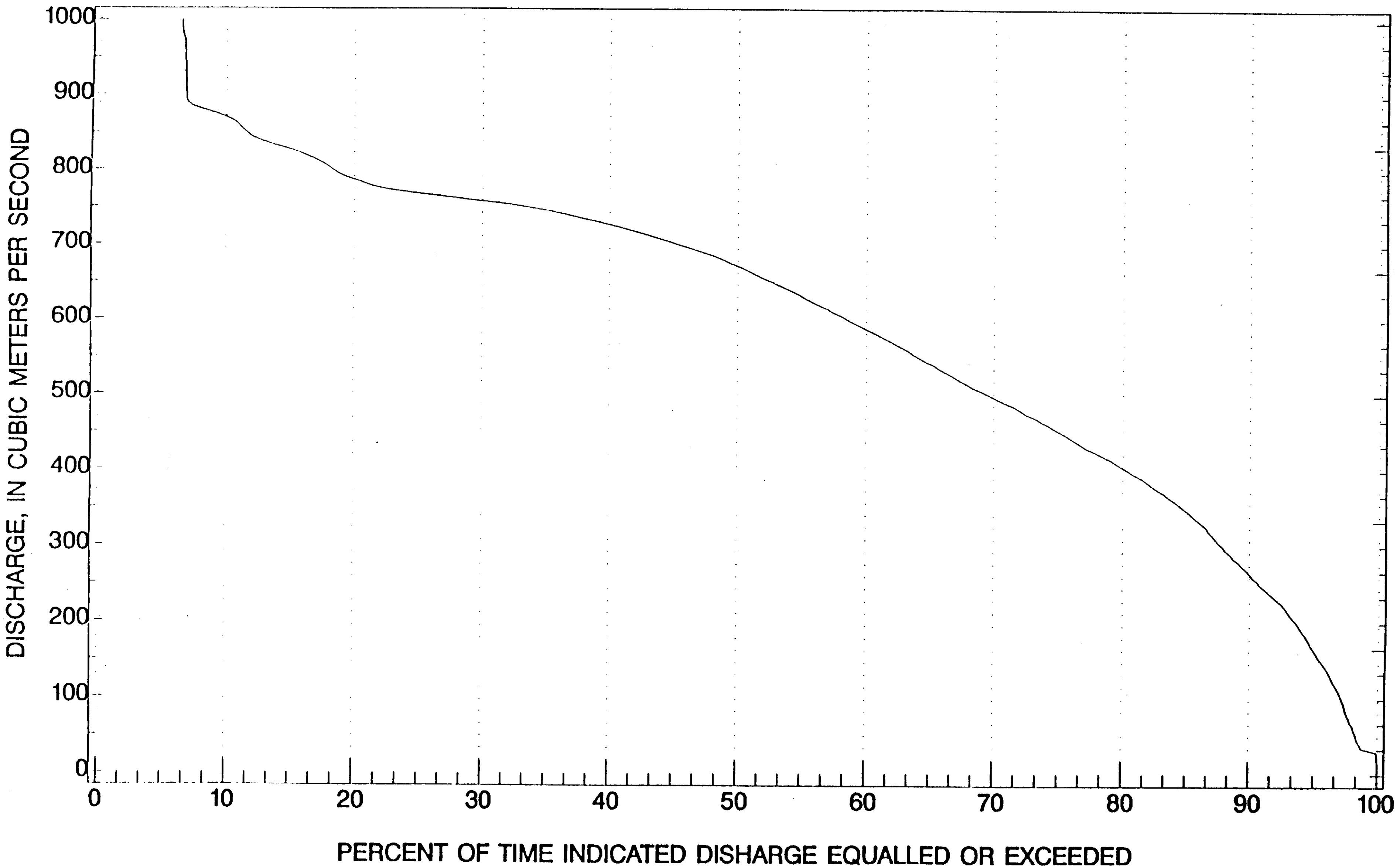


[redacted]rem[redacted]s —[redacted]cubi[redacted]ete[redacted]per [redacted]nd [redacted] = [redacted] *3[redacted]

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

June 7, 1985 – May 20, 1987

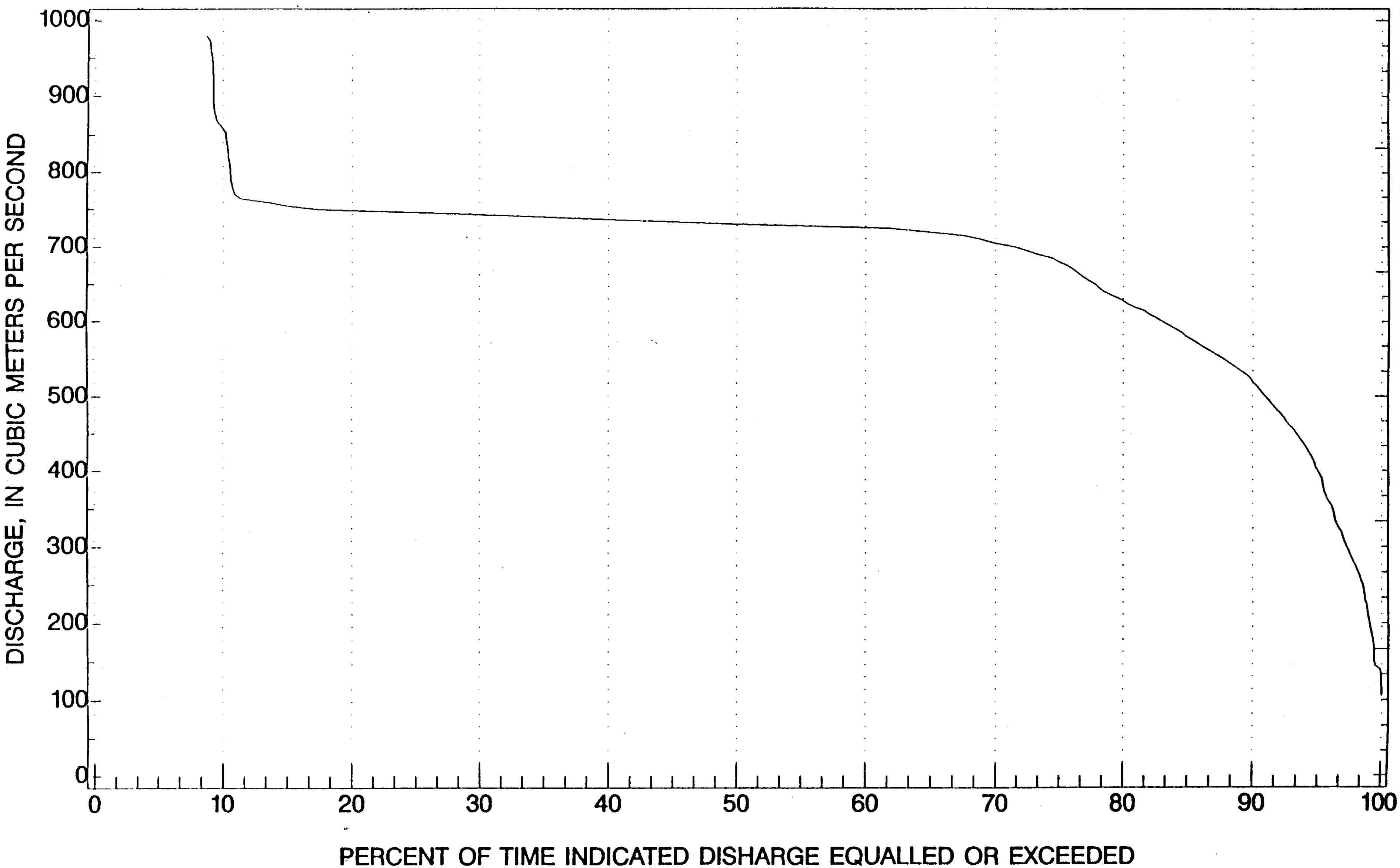


[redacted]

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

Oct 21, 1984 – June 7, 1985

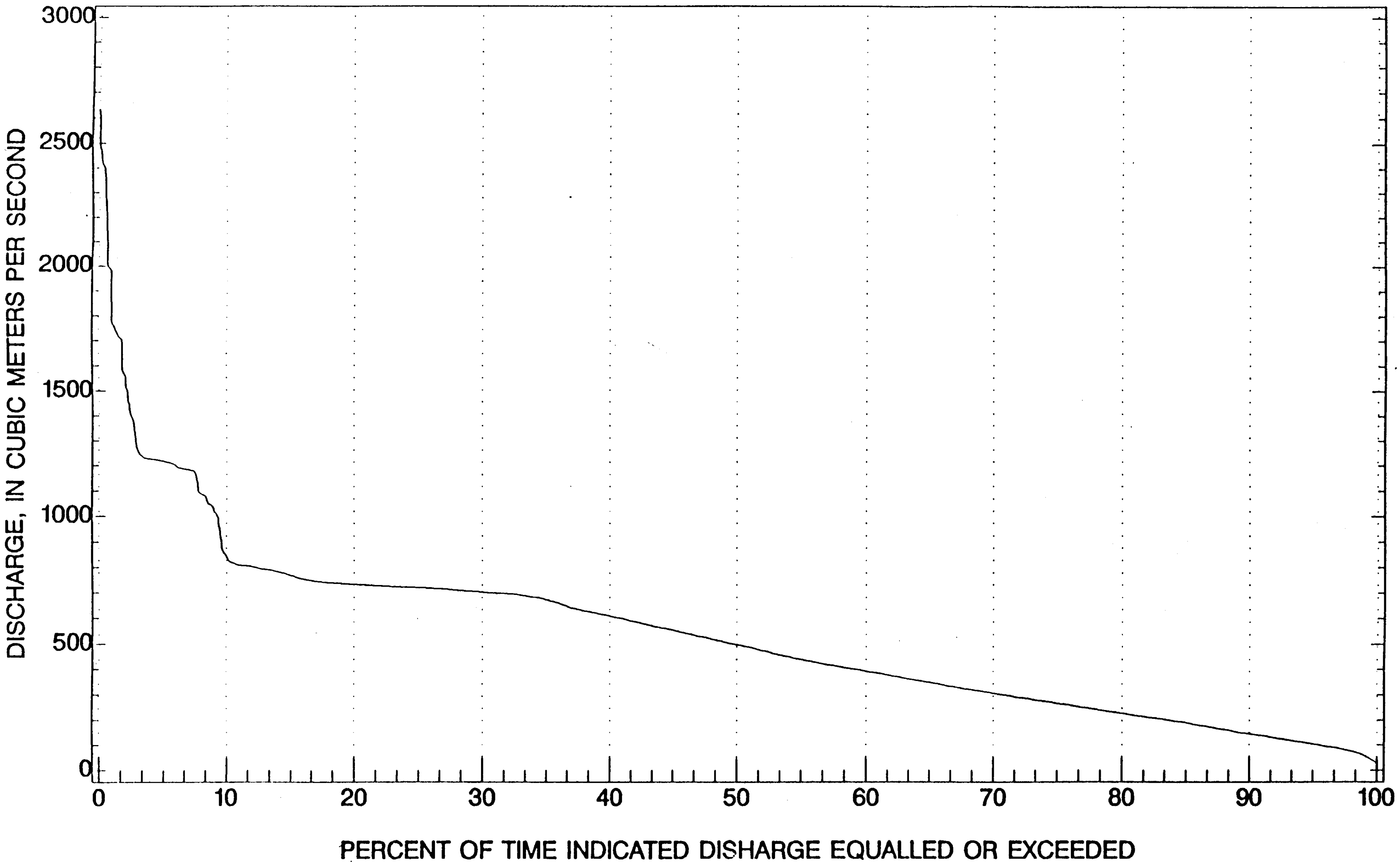


[redacted]

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

July 11, 1980 – Oct 21, 1984

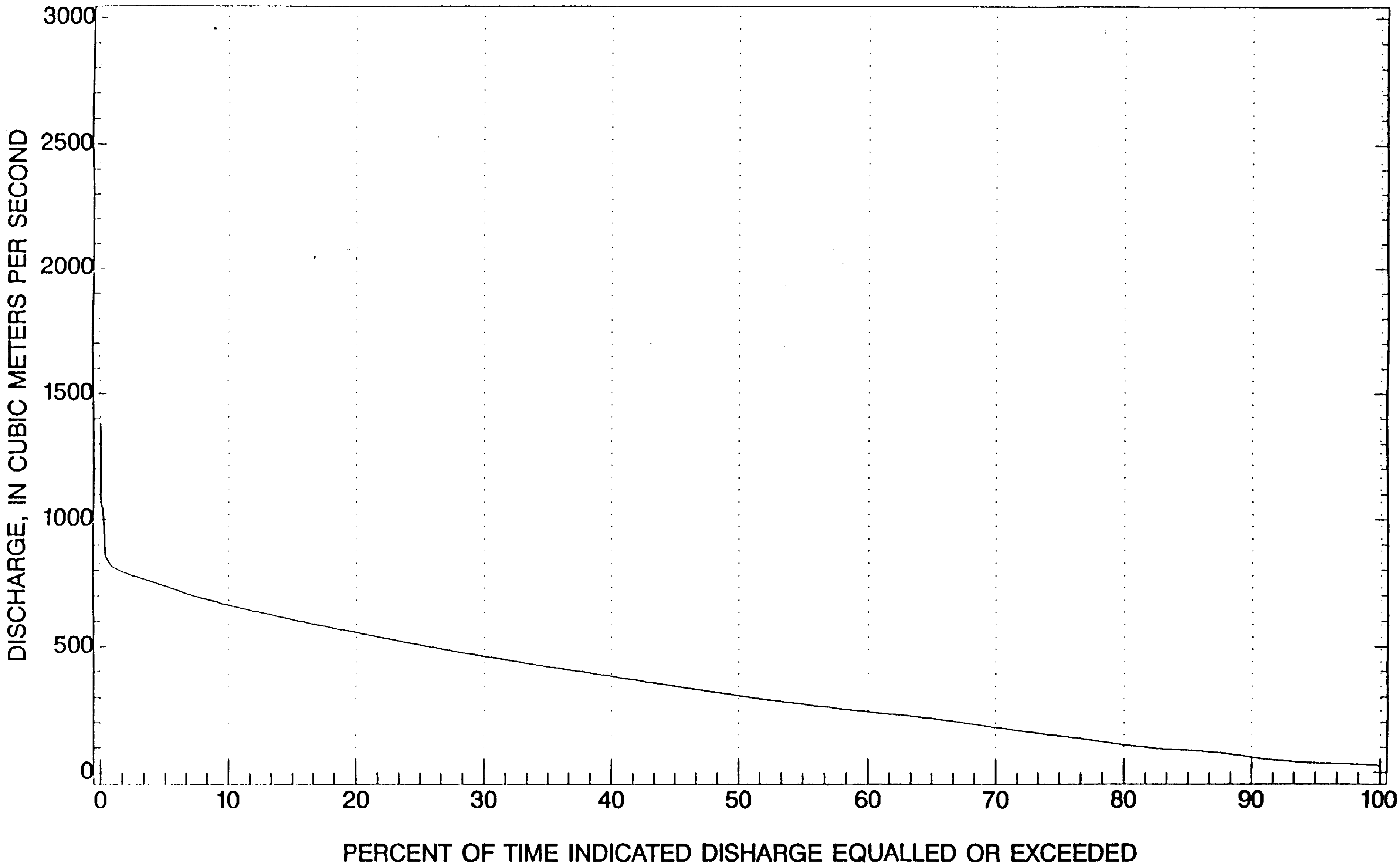


[redacted]ren[redacted]s –[redacted]cubi[redacted]ete[redacted]er [redacted]nd[redacted] = [redacted]s *[redacted]

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

June 16, 1973 – July 11, 1980

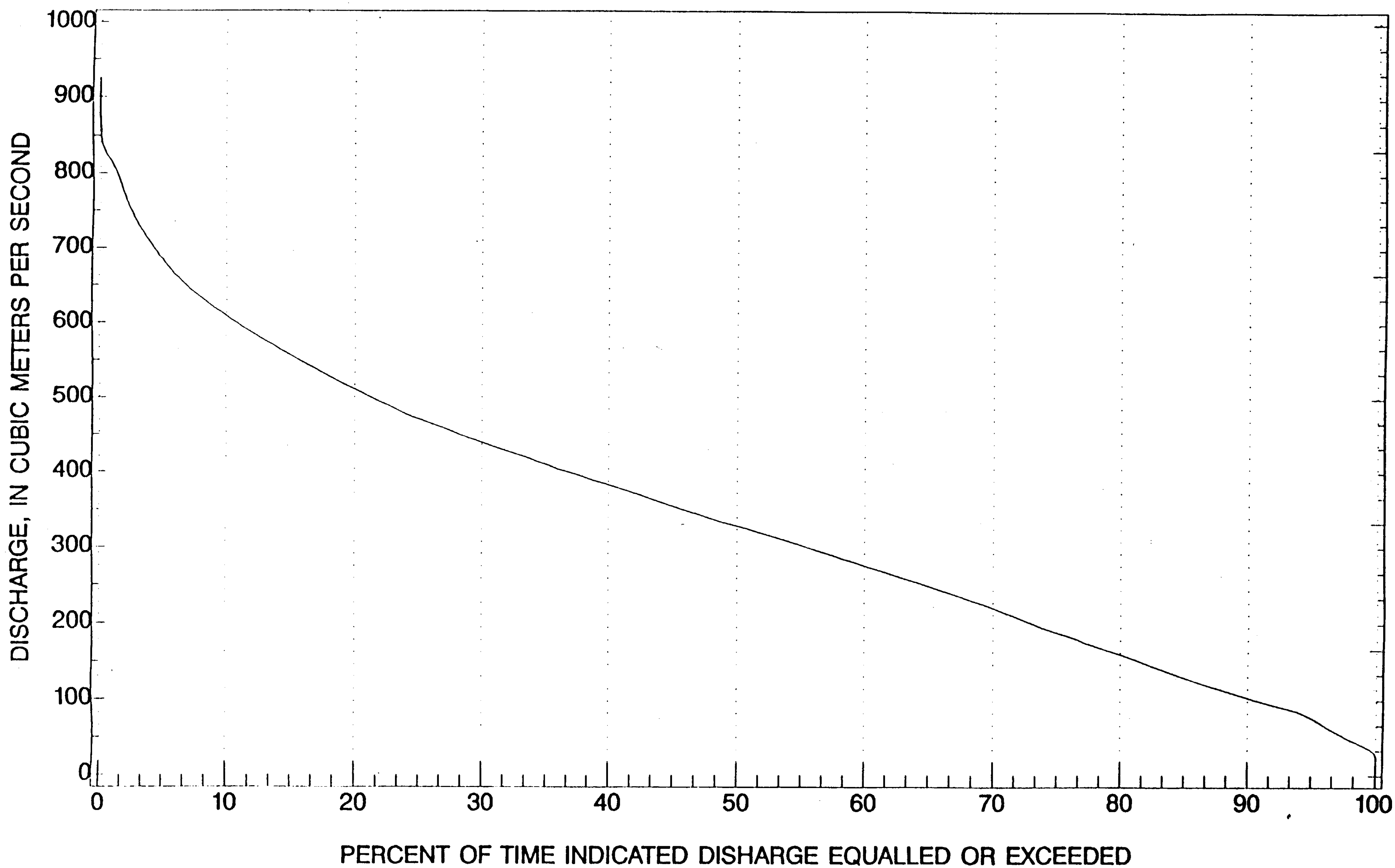


Increments — 5 cubic meters per second (cfs = cms *35.3)

Glen Canyon Dam Hourly Releases

Frequency Analysis of Discharge

Oct 1, 1965 – June 16, 1973



Increments -- 5 cubic meters per second (cfs = cms *35.3)