CHANGES IN THE FLUVIAL DEPOSITS OF THE COLORADO RIVER IN THE GRAND CANYON CAUSED BY GLEN CANYON DAM

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INTRODUCTION

Most of the sediment formerly carried by the Colorado River through Grand Canyon National Park is now being trapped in Lake Powell, the reservoir of the Glen Canyon Dam. As a result, sandy river terraces, or "beaches" deposited by the turbid pre-dam Colorado are being eroded. These beaches are used as campsites by float trips, and form the most diverse and densely populated natural communities within the canyon; therefore their erosion is of concern to the National Park Service. Although local examples of pronounced erosion can be cited by experienced river guides, a quantitative appraisal of the rate and pattern of change is needed.

Our studies of post-dam changes in the fluvial deposits of the Colorado River include an evaluation of the first ten years of shorefront changes by the use of aerial photography. Because the method has inherent limitations that will be discussed more fully, we have also initiated a field program of surveyed baselines which will be resurveyed at intervals of a few years. The procedures and limitations of these studies will be outlined first, followed by a presentation of results. For a general discussion of the nature of the changes in the fluvial regime caused by Glen Canyon Dam, the reader is referred to papers by Dolan et al. (1974) and by Dolan et al. (this volume).

AERIAL PHOTOGRAPHIC MAPPING

In June, 1973 aerial photography at a scale of 1:7,000 was flown along the 240 miles of the Colorado River from Lee's Ferry to Lake Mead. Photo coverage of portions of the river are also available for the period 1959-66 at scales ranging from 1:10,000 to 1:37,000. When compared to this earlier photography, the 1973 coverage provides an excellent record of about 8 years of changes in shoreline position. Unfortunately, the mapping of these changes is complicated because the river discharge varied between and during the photo flights. Higher river stage is associated with greater river width, but the width-stage relationship depends upon shoreline gradient, which on the sand beaches varies from two degrees to angle-of-repose slopes, about 35 degress. If ignored, the stage differences cause apparent erosion or deposition. For example, if the 1973 discharge was less than the discharge during the pre-dam photo flight, an apparent deposition would be superimposed upon the actual changes. The amount of apparent deposition would depend upon the beach gradient, being larger for lesser gradients.

Therefore, to use measurements made from aerial photographs, variations in discharge must be compensated for. Along about one-third of the 240 miles between Lees Ferry and Lake Mead two or more sets of pre-dam photography were available which spanned the discharge range during the 1973 flight (specifically, miles 0-21, 29-55, 129-150, and 155-177). Shorelines for the pre- and post-dam photography were superimposed at a common scale, as illustrated by Figure 1, showing shorelines mapped between miles 52 and 53 in the Nankoweap Rapids area. A *predicted* pre-dam shoreline for the same discharge as the 1973 photo coverage was drawn by interpolation between the pre-dam shorelines. When compared with the *actual* 1973 shoreline, the predicted pre-dam shoreline indicates total lateral erosion or deposition (Figure 2). Errors and biases that can affect the results include:

1. Errors in registration of shorelines or in drawing of shorelines from the photography. These include cases where overhanging cliffs obscure the shoreline or where the land-water interface is misplaced due to mistaking damp sand for submerged sand or shallow bars for subaerial sand.

2. The discharges assumed for the various sets of photography may be somewhat in error. This is particularly true for the 1973 flight, because discharges released by the dam vary widely during a daily cycle, and the flow must be routed downstream (Figure 3). The exact time of day that the photos were flown is uncertain, and a time of error of two or more hours can lead to 3 or 4 meters of apparent lateral erosion or deposition.

Some of the sandy beaches and tributary fans often slope at an angle of only a few degress. Small errors in estimates of water level on a low-gradient shorefront can lead to large values of apparent erosion and deposition. Fortunately, the pre-dam deposits of cobble bars are also low-gradient, and they are essentially immobile under the low post-dam flows, so where they are present they can provide a partial check against misinterpretation of discharge. For example, a slight amount of deposition is indicated on a cobble bar just below the word "Rapids" in Figure 2. The most likely explanation is a slight underestimation of the discharge at the time of the 1973 flight, for this area is in a section of river that was experiencing a rapid change of stage during the flight (Figure 3). If this error were accounted for, the amount of post-dam deposition on the tributary fan (below the arrow in Figure 2) would be reduced while the estimated extent of erosion in the stippled areas would be increased.

3. The shoreline position under pre-dam conditions was not constant, varying in response to deposition during the turbid summer floods and erosion during the clearer spring meltwater floods. Shoreline positions for higher pre-dam flows sometimes extend farther riverward than those for lower flows (for example, a small area on the right-hand bank near the downstream end of Figure 1). However, the amount of pre-dam variation appears to be small when compared to post-dam changes.

A final problem associated with using aerial photography is that the result is only a two-dimensional record of beach changes. Modifications that occur above normal high water, such as addition or removal of sand and silt by overbank flooding, by wind action, or by human activity occur largely in the vertical dimension and cannot be evaluated by this method.

BENCHMARK SURVEYS

The baseline and profile surveys complement the photo sampling in that the profiles provide

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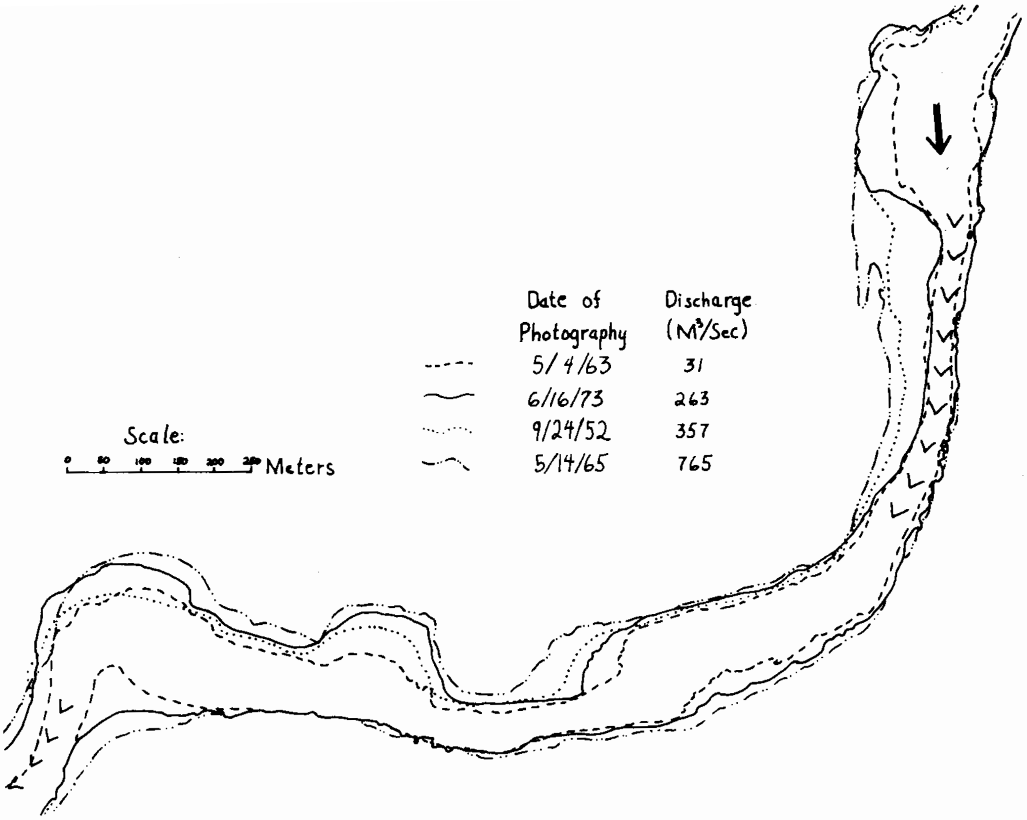

FIGURE 1. Shoreline of the Colorado River between miles 52 and 53 as mapped from various sets of pre- and post-dam aerial photography.

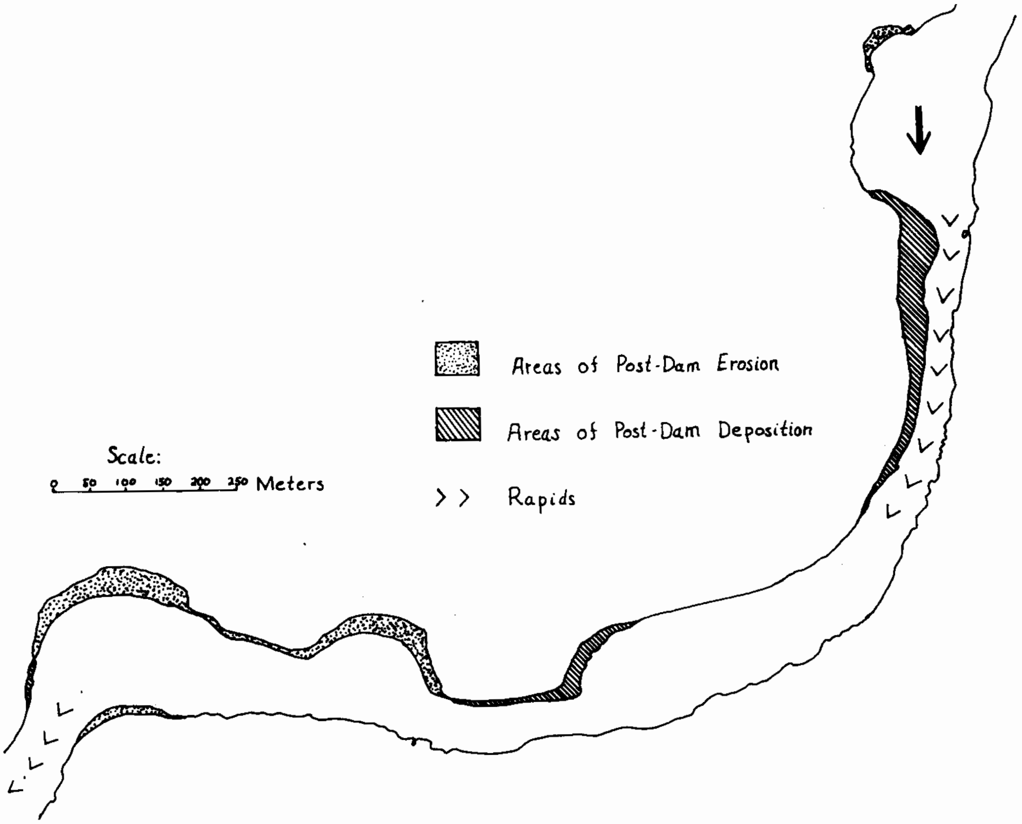

FIGURE 2. Post-dam erosion and deposition between miles 52 and 53, from aerial photographic interpretation.

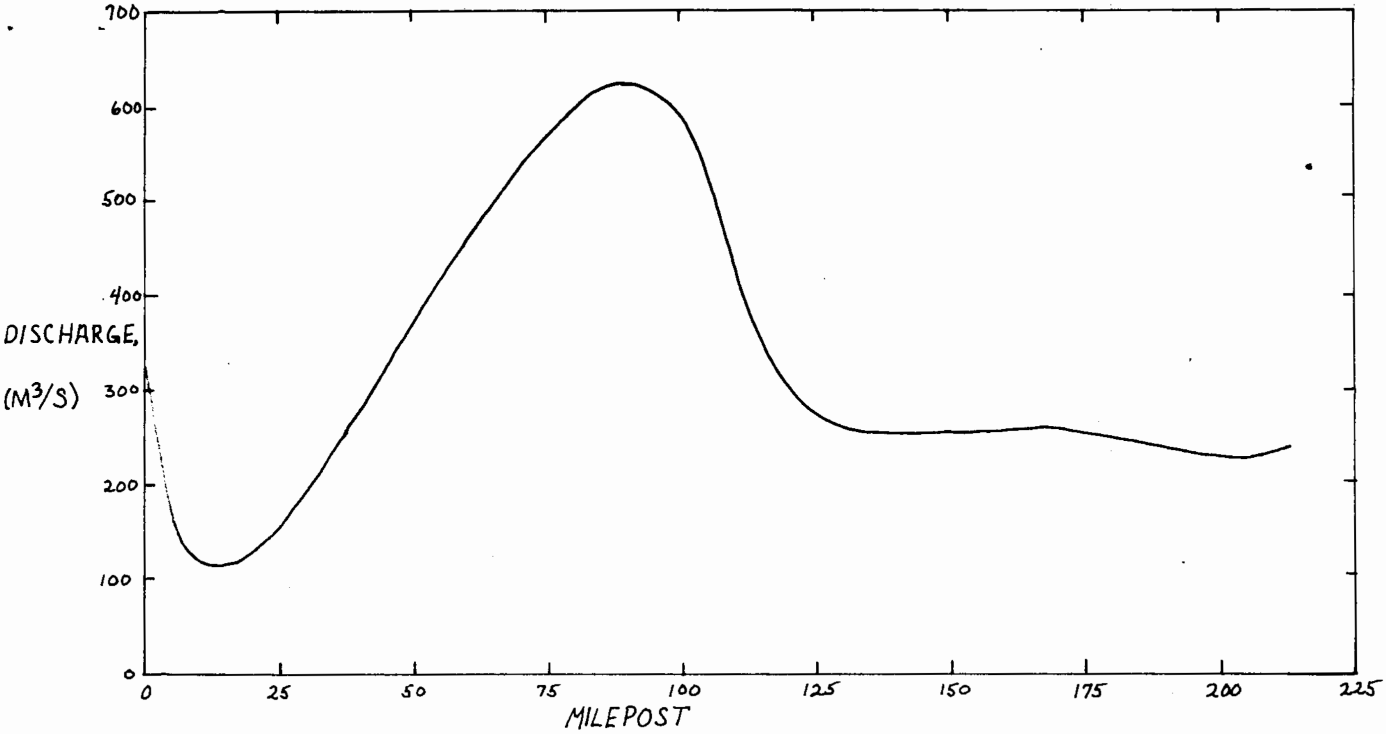

FIGURE 3. Discharge of the Colorado River in the Grand Canyon for noon, July 19, 1973. Pattern of discharges is found by downstream routing of releases from Glen Canyon Dam, taking into account the variation of velocity with discharge.

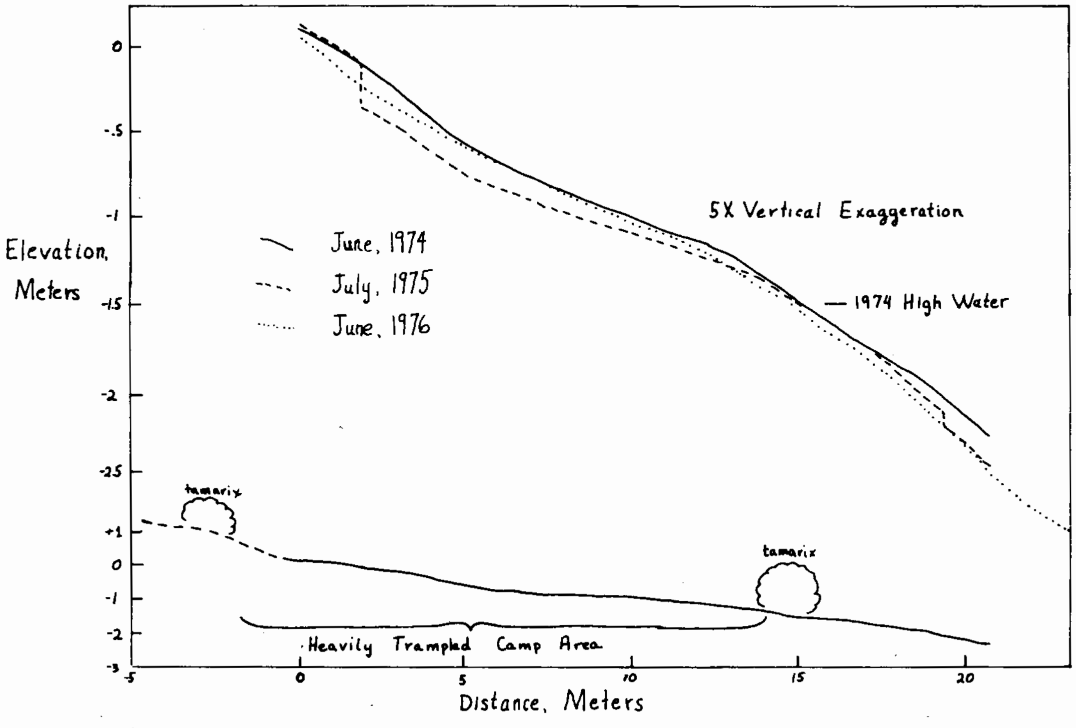

FIGURE 4. Surveyed profiles across beach at Nankoweap campsite, mile 53, showing changes occurring during two resurveys. Lower cross-section to scale, while upper has 5X exaggeration. Arbitrary elevation datum.

a record of changes in elevation through time on both the subaerial beach and the zone periodically submerged. During two float trips made in the summers of 1974 and 1975, 20 baseline sites at campable beaches were established with a total of 38 surveyed profiles. The sites were selected to yield a diverse sampling of beaches as regards morphology, vegetation density, and human impact. The one to three profiles at each campsite run perpendicular to the shorefront, and were chosen to sample the different types of shorefront morphology and vegetation pattern at each campsite. Documentation of the baseline, elevation datum, and profiles is sufficient that a resurvey could be accomplished by persons who did not participate in the original survey. Figure 4 shows a profile at Nankoweap beach, mile 53.0, first surveyed in 1974 and resurveyed in 1975 and 1976. The marked erosion on the portions of the beach above present high water is unusual, having resulted from concentrated runoff during a heavy thunderstorm.

The survey method of assessment of beach changes offers several advantages. The impact of specific events, such as floods, can be determined soon after the event. The surveyed profiles are also more accurate than aerial photographic comparisons, and they are not affected by variations in water level at the time of resurvey. However, there are obvious disadvantages. Information about beach changes is limited to a small number of locations scattered along more than 200 miles of river. The profiles are, like the photographic comparisons, two-dimensional, that is, the vertical and cross-beach dimensions. However, at each survey site the profiles were established at places where the shape of the beach varied little along the shore.

The analysis of systematic erosion and deposition will require observations made over a period of time proportional to the rate of changes. Measurements on the survey sites will have to extend over a period of years to give an accurate picture of the rate and direction of systematic changes.

RESULTS

The sediments found on the terraces can be classified according to age as pre- or post-dam. They may also be divided by agent of deposition into flood deposits, eolian sands, or sands reworked by the river below present normal high water. Similarly, the sediments can also be distinguished by grain size into cohesive silts, which are dominantly silt with a small percentage of clay, silt-sand, with about 30% silt content, and sands, with negligible silt (Figure 5). Several generalities can be made about these deposits:

1. Pre- and post-dam flood terraces are unusually silt-sand.
2. Predam eolian deposits are but little coarser than the flood terraces from which they were derived.
3. Pre-dam cohesive silt was deposited by summer floods and runoff, and it seldom extends more than a few feet above present high water levels. Because of the abundance of water and the fine substrate, they have been covered by a dense vegetative growth.
4. Post-dam beach deposits, reworked by small waves and current, are dominantly sand, with noticeable silt content only along the wide, quiet sections of the river. These deposits are well sorted, and they are the source for most of the post-dam eolian deposits.

Fine-grained deposits below the present high water are being reworked by the river. The rate of response depends upon grain size. Because of the heavy vegetation cover and clay content, the cohesive silts are being cut back more slowly than the sands, forming steep banks with exposed roots (Table 1), which, however, give the *appearance* of rapid erosion.

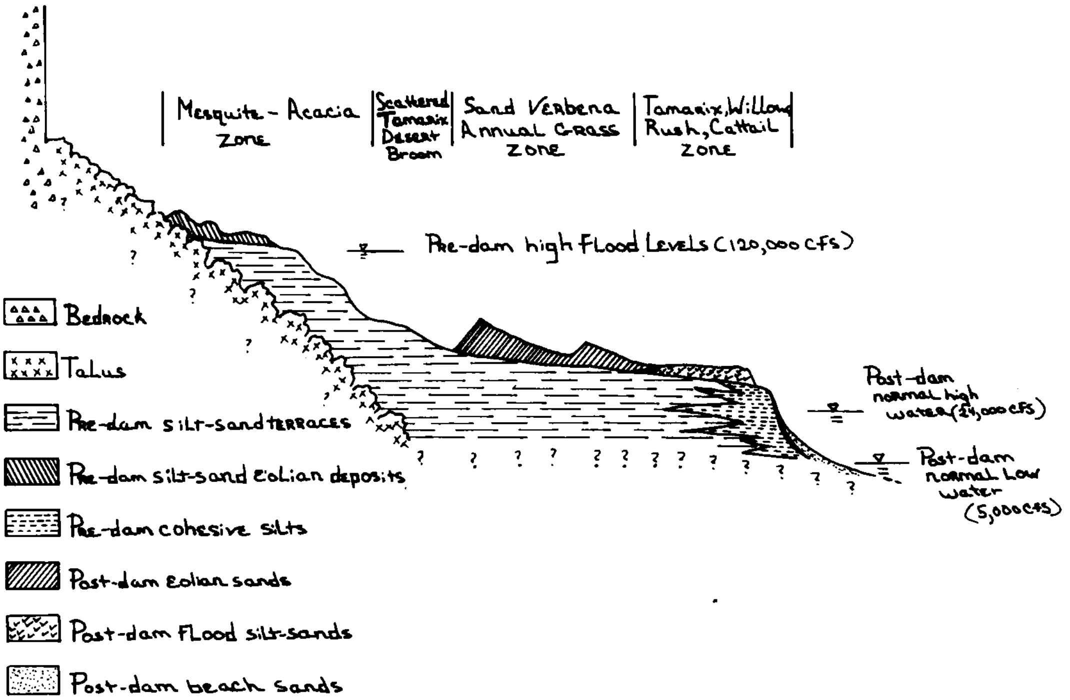

FIGURE 5. Cross-section across typical beach, showing terrace deposits, water level variations, and vegetation zonation.

TABLE 1. Summary of changes to fine-grained fluvial deposits measured by resurvey of base-line profiles.

A. Maximum Changes

Beach Location (mile)	Cross-Section Identification Number	Interval Between Resurveys (years)	Location on Beach 1)	Dominant Grain Size of Beach	Average Gradient	2) Maximum Lateral Change (meters)	Maximum Vertical Change (meters)
L19.5	1	2	Beach Face	Silt-sand	.091	-4.9	-.85
L19.5	2	2	Beach Face	Silt-sand	.190	-4.0	-.98
L34.7	1	1	Beach Face	Sand	.040	-4.3	+0.73
L34.7	2	1	Beach Face	Sand	.160	0	0
R53.0	1	2	Beach Face	Silt-sand	.152	-1.3	-.24
R53.0	1	2	Camp Area	Sand	.125	-0.9	-.12
R53.0	2	2	Beach Face	Cohesive silt	.200	0	0
R72.2	1	1	Beach Face	Sand	.124	-4.0	-.79
R72.2	2	1	Beach Face	Cohesive silt	.73	0	0
R151.6	1	1	Beach Face	Cohesive silt	.40	+0.7	+.15
R151.6	2	1	Beach Face	Silt-sand	.133	-1.8	-.55
L208.8	1	2	Beach Face	Cohesive silt	.244	-0.8	-.18
L208.8	2	2	Beach Face	Cohesive silt	.400	0	0

B. Average Rates of Change of Beach Face

Dominant Grain Size	Average Gradient	Average Vertical 3) Change (meters/yr)	Average Lateral 4,5) Change (meters/yr)	Number of Profiles in Sample
Cohesive silt	.39	0	0	5
Silt-sand	.14	-.16	-1.19	4
Sand	.11	-.10	-.67	3

Explanation:

1) Beach Face: Portion of profile below present high water.
Camp Area: Portion of profile no longer inundated. Note: Changes in camp areas are not listed if amount of change recorded is less than expected survey errors.

2) Maximum change observed on resurveyed profile. Zeros are entered if change is less than expected magnitude of survey errors.

3) Calculated by dividing the total areal change of portion of profile below high water by 1) the lateral extent of the profile, and by 2) the number of years between resurveys. Figures quoted are averaged over all profiles.

4) Calculated as above but divided by the vertical extent of the the profile.

5) Zeros indicate average changes less than probable resurvey errors.

Pre-dam flood terraces and post-dam deposits of sand and silt-sand are more easily entrained by present-day flows. The changes measured over one or two years at seven profiles in this coarser-grained sediment (Table 1) are variable, with an average rate of lateral backcutting of about 0.9 meters per year, and a range from 4.9 meters per year of erosion to deposition of 0.7 meters per year. Similarly, the aerial photographic analysis (Table 2) shows rates of erosion exceeding 10 meters per year at a few sites and a few areas that have expanded through deposition. The average rate of erosion of fine-grained shorelines was measured to be 0.3 meters per year. About 16 percent of the mapped sandy terraces were eroding at an average rate exceeding 2 meters per year, while only 6 percent underwent an quivalent rate of deposition (Table 2). Despite possible inaccuracy and bias in these figures, the management implications are clear: severe lateral erosion by the river sufficient to affect camping activities over the next few years will be localized occurrences, and that over the long run, measured in decades, the slow progress of erosion will gradually reduce the number of sandy beaches.

The pre-dam terrace deposits above present-day high water have been modified by three natural processes, eolian transport, rainfall, runoff, and vegetation. Eolian sand movement occurs mostly where vegetation is sparse and the local winds are strong. Under such conditions, rates of vertical erosion or deposition may exceed a meter per year. Rainfall and associated runoff also erode the pre-dam terraces on a localized basis by both sheetflow and gullying. Many terraces are a thin mantle deposited by pre-dam floods on tributary alluvial fans. During a major flash flood the tributary stream can cause wide-scale erosion of the fine-grained mantle.

The one- to two-year resurveys of 13 profiles (Table 1) indicated only one instance where the average amount of vertical erosion above the present high water exceeded the probable survey errors (about 3 cms). This was at the Nankoweap beach shown in Figure 4, due to local gullying during an intense thunderstorm. Since many of these profiles pass through heavily used campsites, the measurements suggest that the combined effects of natural and man-induced erosional processes above high water is slow on the average. However, many paths on steep slopes are inset more than 0.5 meters below adjacent vegetated slopes, indicating erosion rates up to 10 cm per year on steep slopes with high rates of human traffic. Because of the low average rate of vertical erosion, few campsites will become usable due to exposure of the underlying coarse substrate during the next decade.

The absence of large floods since Glen Canyon Dam has resulted in a decreased competency of the post-dam river. Because almost all of the major rapids have resulted from deposition of coarse debris brought by the flooding of tributary canyons, the smaller post-dam river may be forced into a gradient as much as twice its pre-dam value if a major side-canyon flood occurs. However, in order for the river to be so narrowed and steepened, the tributary must flood. The aerial photographic study indicates that 27% of

TABLE 2. Post-dam shoreline changes of the Colorado River, 1965-73, using aerial photography.

Mile[1]	Average Channel Width (meters)	Average Shoreline Change (meters)		No. of Fine-Grained Shoreline with Given Maximum Changes						No. of Fan Deltas with Given Maximum Changes			
		Fan Deltas	Fine Alluvium	--[2]	-[3]	0[4]	+[5]	++[6]	Total Cases	0	+	++	Total Cases
0.5	138.5	0	+5.68	1	1	1	1	2	6	0	0	0	0
2.1	101.5	+0.08	-4.61	3	1	5	4	0	13	7	1	0	8
3.6	74.5	0	-4.38	2	3	3	4	0	12	3	0	0	3
4.6	98.5	0	+0.63	1	1	4	2	1	9	4	0	0	4
6.0	88.0	+6.70	+2.64	2	0	2	0	0	4	3	1	2	6
7.2	97.0	+1.06	+1.15	0	3	1	3	0	7	2	2	0	4
8.7	78.5	+1.51	+0.92	1	1	4	3	2	11	4	1	0	5
10.0	62.5	0	-0.26	1	1	8	2	0	12	1	0	0	1
11.3	57.0	+2.62	-0.44	0	3	6	1	0	10	2	1	1	4
12.8	41.5	+0.64	-1.29	1	1	4	2	0	8	3	2	0	5
14.2	46.0	+0.75	0	0	0	3	0	0	3	2	1	0	3
15.4	57.5	0	-0.52	1	2	4	1	1	9	5	0	0	5
16.7	66.5	+2.82	+0.57	1	1	4	1	2	9	1	1	3	5
18.0	59.0	+2.12	+0.94	0	1	7	0	1	9	2	4	0	6
19.4	59.5	+1.86	+3.41	0	3	7	5	3	18	4	3	1	8
20.5	54.0	+14.12	+2.20	0	0	5	2	0	7	0	0	1	1
29.9	64.0	+0.48	+0.33	0	1	3	1	1	6	6	1	0	7
31.2	65.0	0	-3.57	1	6	4	3	0	14	9	0	0	9
33.0	65.0	+0.29	-1.54	1	3	9	1	0	14	4	1	0	5
34.4	80.5	+1.20	-6.09	3	6	0	1	0	10	2	1	1	4
35.5	70.5	+0.38	-5.01	4	3	6	0	0	13	4	2	0	6
36.9	78.5	+5.07	-2.88	3	2	6	0	0	11	2	0	1	3
38.1	83.5	+2.78	-2.15	2	4	5	2	1	14	1	2	1	4
39.7	85.0	+1.49	-5.51	4	1	6	0	1	12	2	1	0	3
40.9	88.5	+1.49	-1.26	3	2	3	0	2	10	1	1	0	2
42.2	94.5	0	-2.50	0	3	1	1	0	5	1	0	0	1
43.8	81.0	+5.52	-4.00	8	2	2	2	2	16	3	1	1	5
45.3	95.5	+2.83	-6.16	4	0	7	1	0	12	1	0	1	2
46.7	104.5	+0.92	-9.05	5	0	6	1	1	13	5	0	1	6
48.1	102.0	+1.23	-5.00	5	1	9	0	0	15	5	0	1	6
49.5	110.0	0	-7.08	3	1	6	0	0	10	5	0	0	5
50.7	93.5	0	-8.42	4	0	5	1	0	10	3	0	0	3
52.5	113.5	+2.82	-1.41	4	2	3	0	1	10	2	1	1	4
129.5	50.0	+6.84	+2.38	0	0	5	0	1	6	0	1	2	3
130.8	58.0	0	-2.10	4	4	2	3	1	14	4	0	0	4
132.2	49.0	+0.16	-9.17	1	8	6	2	0	17	5	1	0	6
133.5	60.5	+0.43	-4.95	2	5	4	1	0	12	8	1	0	9
135.0	48.0	+1.44	-4.60	3	6	3	2	0	14	4	2	0	6
136.4	48.0	0	-4.37	2	3	10	1	0	16	5	0	0	5
137.7	63.0	+0.07	-1.48	2	5	7	0	0	14	6	1	0	7
139.4	56.5	+1.27	-4.39	2	2	7	0	0	11	3	2	0	5
140.5	51.0	0	-4.01	1	5	4	0	0	10	9	0	0	9
142.0	55.5	0	0	0	2	0	1	0	3	0	0	0	0
143.4	56.0	+14.87	-3.61	0	1	0	1	0	2	1	0	1	2
155.8	42.8	+2.13	0	0	0	5	0	0	5	3	1	0	4
157.3	45.0	+1.78	-3.08	1	0	4	0	0	5	4	1	1	6
158.8	44.0	+1.77	0	0	0	7	0	0	7	3	1	0	4
160.4	48.5	0	+2.45	0	0	9	0	1	10	2	0	0	2
161.5	50.5	+2.15	+0.19	0	0	8	0	0	8	1	1	0	2
163.2	54.5	+1.43	-0.84	1	1	4	1	0	7	6	0	1	7
164.8	63.5	+2.57	+0.21	0	0	17	1	0	18	1	1	0	2
166.5	65.5	0	+0.42	0	1	13	1	1	16	3	0	0	3
167.7	76.5	+2.41	-2.89	3	1	14	0	1	19	2	0	1	3
169.4	68.0	0	0	0	0	7	0	0	7	1	0	0	1
170.8	65.0	+2.12	+2.72	2	0	3	0	3	8	1	0	1	2
172.3	72.5	+0.42	-4.54	4	2	10	1	0	17	1	1	0	2
173.5	68.0	+3.08	+2.23	1	4	6	1	2	14	6	0	2	8
175.1	69.5	+1.33	-2.97	1	0	8	4	4	17	3	1	0	3
176.4	81.5	0	-3.52	2	3	6	0	1	12	1	0	0	1
Averages:	68.9	+0.22	-0.31										
			Totals:	100	112	318	65	36	631	181	43	25	249
		Percent of Totals:		16	18	50	10	6	100	73	17	10	100

Explanation:

1) Center of 1.5 mile segment of river.
2) Maximum lateral erosion of fine-grained shoreline segment greater than 15 meters in 8 years.
3) Maximum lateral change between 0 and 15 meters of erosion.
4) No change.
5) Maximum lateral change between 0 and 15 meters of deposition.
6) Greater than 15 meters of deposition.

tributary fans in the study sites have built outward, but narrowing of the river by more than 15 meters has occurred on only 10% of the fans (Table 2). Catastrophic narrowing and steepening of rapids is very uncommon, the most notable example being the creation of a major rapid at Crystal Creek (mile 98.2) in the mid 1960's.

Constriction of the river by tributary floods may make the rapids impassable to float trips and can raise the level of the water by several feet a mile or more upstream. Such major floods are rare and unpredictable in specific occurrence, and even their frequency is uncertain. Human adjustment to any such major flood will have to be done on an after-the-fact basis, but the likelihood of a flood of sufficient magnitude to create an impassable river over the next few decades seems remote.

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