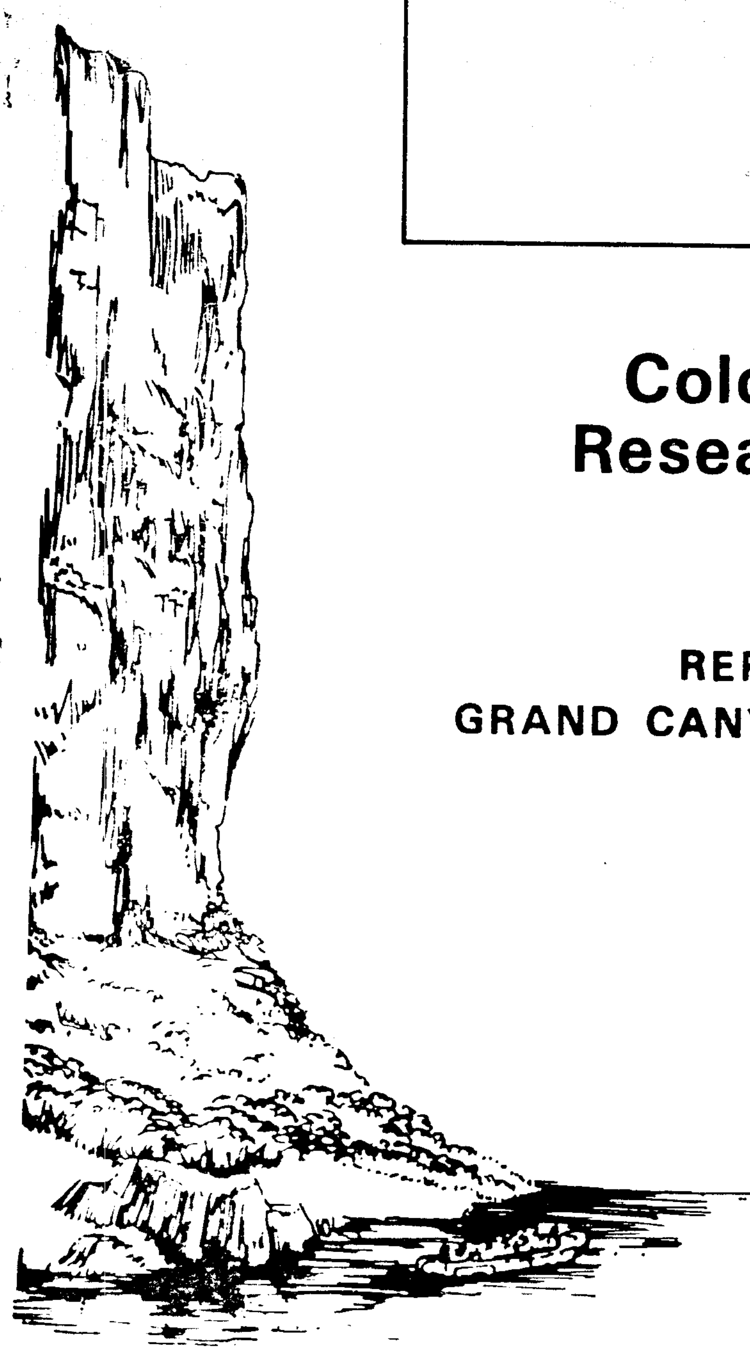

Colorado River Research Program

REPORT SERIES
GRAND CANYON NATIONAL PARK

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Department of the Interior
National Park Service

ALTERATIONS OF TERRACE DEPOSITS AND BEACHES OF THE COLORADO RIVER IN GRAND CANYON

Alan D. Howard and Robert Dolan

Colorado River Research Program Final Report

Technical Report No. 7

Grand Canyon National Park
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Contribution Number 36

ALTERATIONS OF TERRACE DEPOSITS AND BEACHES OF THE COLORADO RIVER IN THE GRAND CANYON CAUSED BY GLEN CANYON DAM AND BY CAMPING ACTIVITIES DURING RIVER FLOAT TRIPS:

SUMMARY, MANAGEMENT IMPLICATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH AND MONITORING

FINAL RESEARCH REPORT

July 1, 1976

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University of Virginia Grand Canyon Study

Technical Report No. 2

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ABSTRACT

The National Park Service faces several difficult issues concerning the management of float trips down the Colorado River of the Grand Canyon. The demand for float trips has increased dramatically since the early 1960's while concurrently, irreversible changes are occurring to the alluvial deposits along the river as a result of regulation of the river flow by the Glen Canyon Dam. The questions of primary importance are: 1) in what manner and how rapidly are the alluvial deposits adjusting to the new river regime, and 2) is the increased use of the river contributing to the irreversible degradation of the system.

Prior to 1963 the Colorado River was little affected by man. The river's regime was characterized by spring floods from snowmelt and periods of heavy suspended sediment loads during summer runoff. Regulation of the river by the Glen Canyon Dam has reduced peak flows resulting in sediment-free water most of the year. The responses to this change have been assessed by field surveys and by photogrammetric analyses.

Silt and sand were deposited in slack water by predam floods, particularly in back eddies below the rapids. Our measurements indicate that the postdam regime is scouring these sand banks. Many terraces above present high water have been altered by wind, side-canyon runoff, and human impact. The result is a gradual diminishing of the number of sandy terraces suitable for camping.

Human use along the Colorado River is limited, for the most part, to the relic, pre-dam fluvial deposits colloquially called "beaches." With the new river regime these deposits are positioned well above the present high-water stage (27,000 cfs), so they are not replenished periodically as they were prior to construction of the dam in 1963. The dominant natural process is therefore eolian.

The float-trip passengers use the river beaches for hiking, camping, and for lunch stops. At the most desirable sites between thirty and forty people camp on the beaches each night over a four to five month season. Human impact includes incorporation of camp-site litter, burial of chemically treated waste, and the direct stress associated with people walking on the vegetation and unstable sedimentary deposits.

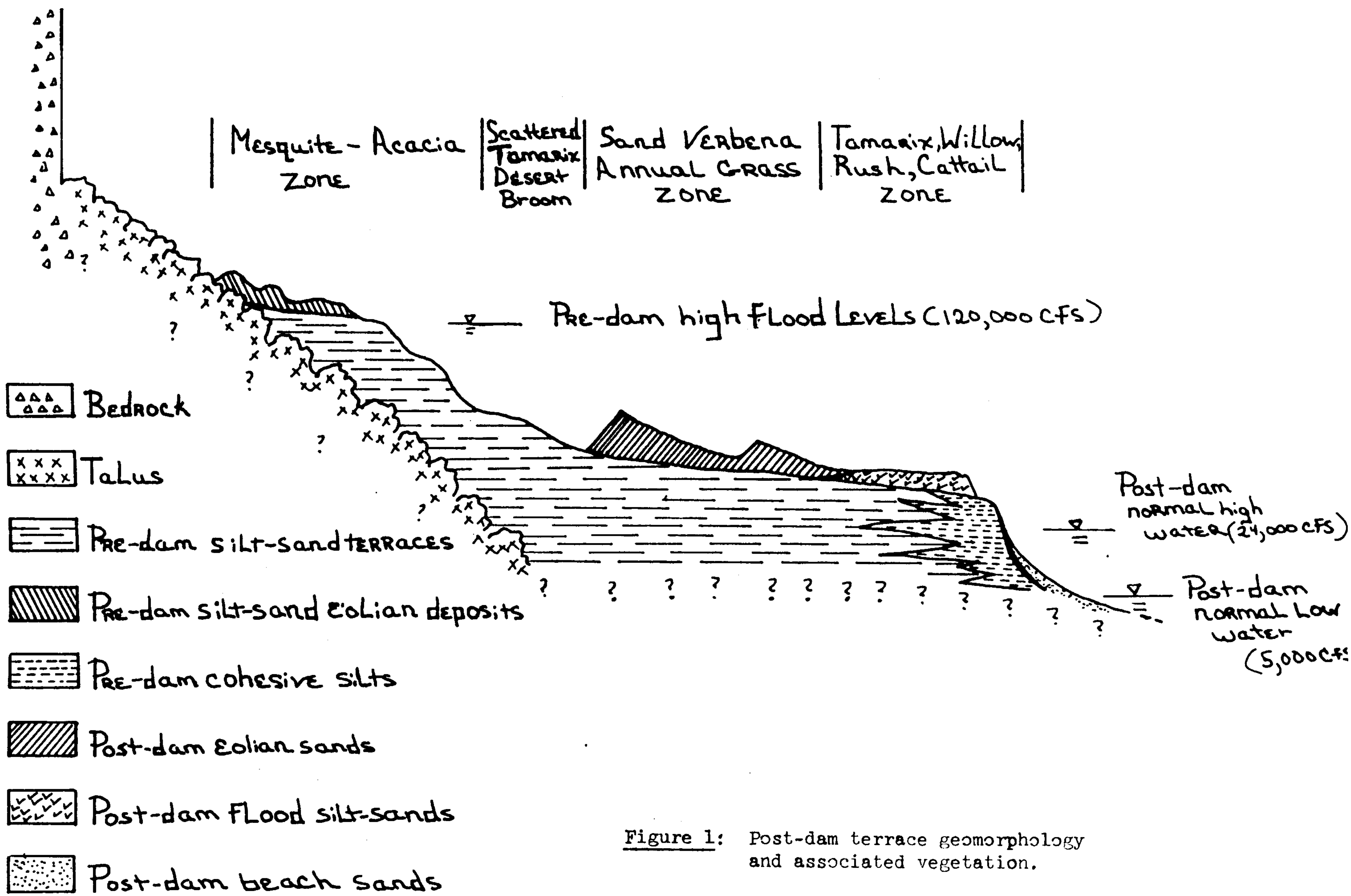


Figure 1: Post-dam terrace geomorphology and associated vegetation.

FOREWORD

Since the completion of Glen Canyon Dam in 1963 reductions in peak flood stages of the Colorado River and entrapment of the sediment it carries from upstream have resulted in major changes in morphology and vegetation patterns along the river. These changes are continuing today.

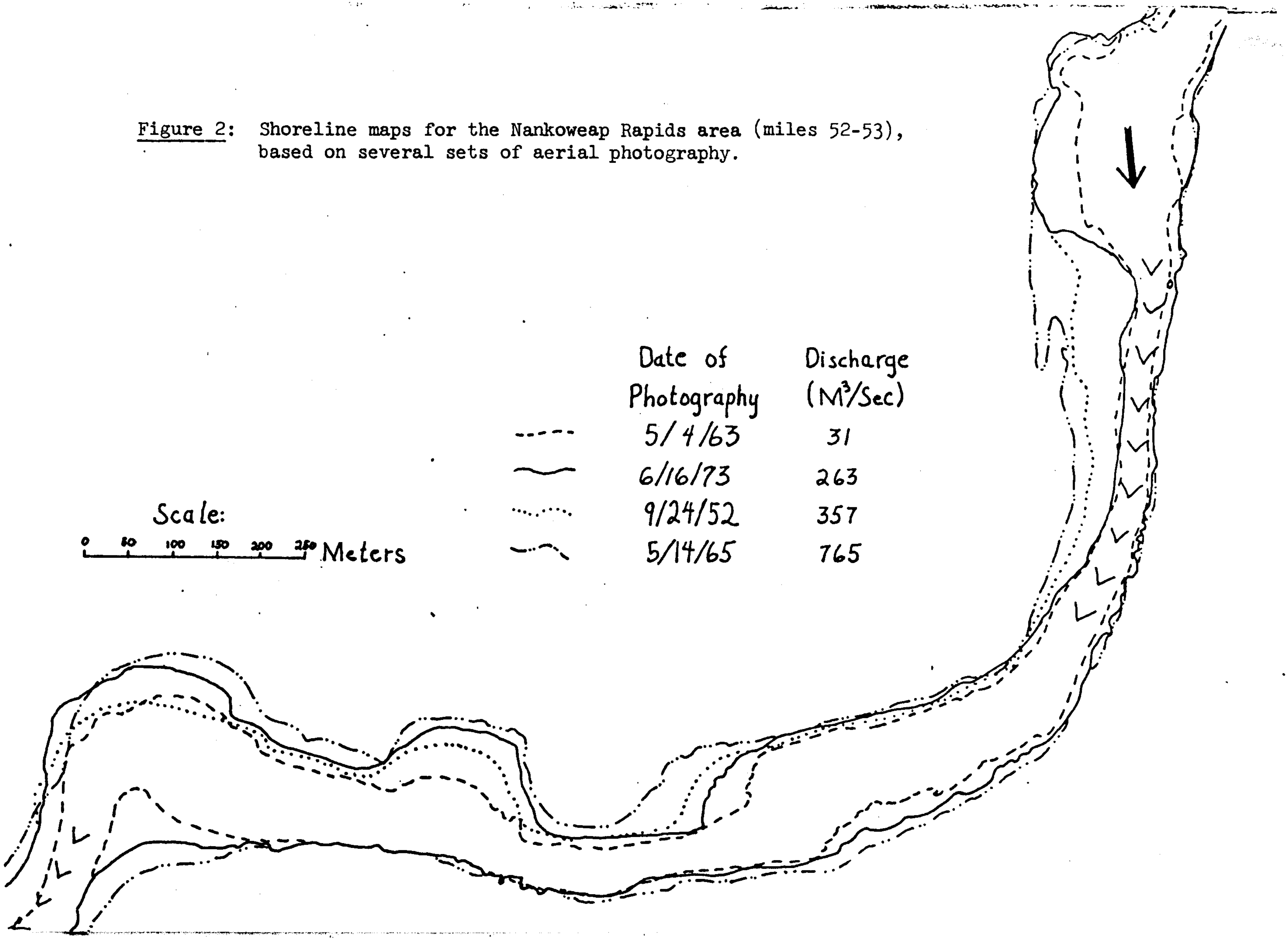
A second form of environmental impact is the result of a rapid increase in visitor use during the past ten years; 15,000 visitors per year now pass through the canyon. Their impact is concentrated on approximately 150 large sandy terraces distributed along the river. These beaches, as they are termed colloquially, are used for sightseeing, picnicking, and overnight stops. The management problem is complex, for the human impact is superimposed upon the changes caused by the dam. Our investigation is designed to answer questions about the physical changes to the fluvial terraces and changes in vegetation produced both by the dam and by visitor use. We have developed several approaches to answer these questions and to provide a data base for monitoring future trends:

1) Study sites have been established at camping beaches between Lee's Ferry (River Mile 0) and Diamond Creek (River Mile 225). Twenty of these sites, with 39 surveyed profiles, were established in 1974 and 1975. In 1975 and 1976 twelve of the 30 profiles were resurveyed to provide quantitative data on lateral erosion and deposition by wind, and vegetation changes (Fig. 1). Procedures, presentation of basic data, and an analysis of errors inherent in these methods are summarized in our Technical Reports Nos. 1 and 3.

2) In 1973 aerial photography at a scale of 1:7000 was flown along the Colorado River from Lee's Ferry to Lake Mead. When compared to similar photography flown in 1965, the 1973 photography provides an excellent record of eight years of changes in the geomorphology and vegetation since the regulation of the river. Photo coverage of portions of the canyon are also available for the period 1959-1966 at scales ranging from 1:20,000 to 1:37,000.

   We have used this photography to quantify two types of changes: lateral erosion and deposition of terrace deposits and the build-up of tributary fans. This mapping is complicated because water levels

Figure 2: Shoreline maps for the Nankoweap Rapids area (miles 52-53), based on several sets of aerial photography.



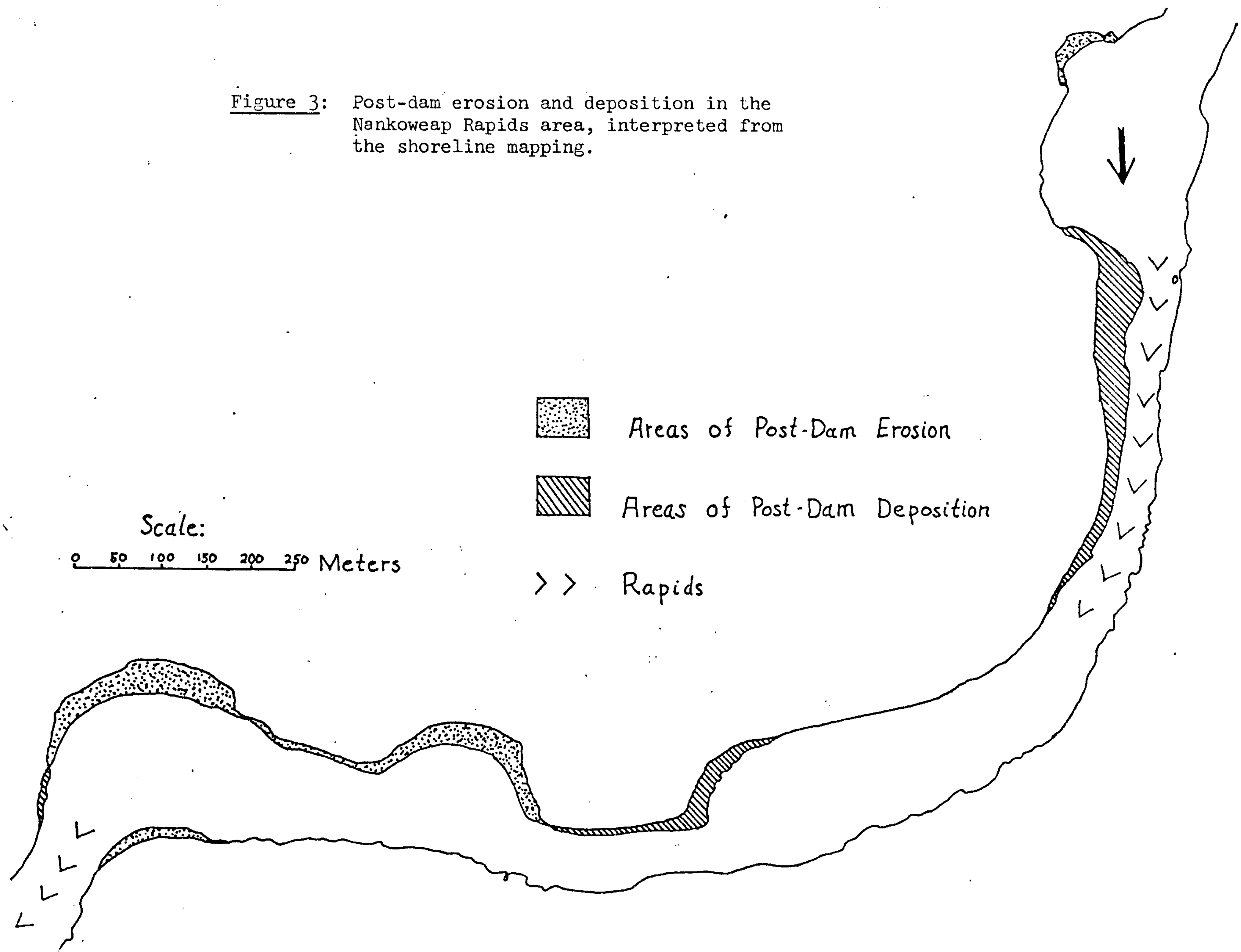


Figure 3: Post-dam erosion and deposition in the Nankoweap Rapids area, interpreted from the shoreline mapping.

varied during the course of the photo flights. If ignored, the differences cause apparent erosion and/or deposition. For the rapidly varying discharges of the post-1965 flights, it has been necessary to route the water releases from the dam to determine discharge at each point along the river. Furthermore, we were limited in our mapping to portions of the canyon where pre-dam photography was available for both lower and higher discharges than those of the 1973 flight (Figs. 2 and 3). These criteria limited us to detailed shoreline comparison of 40 percent of the river (miles 0-21 29-55, 129-150, and 155-177). In addition, the photography permitted comparison of vegetation patterns before and after the dam, and to relate these patterns to the geomorphic changes occurring since the dam. The complete results of our aerial photographic studies will be presented in Technical Report No. 5.

3) In order to understand the changes that have resulted from Glen Canyon Dam, we have summarized existing data on the hydrology and sediment budget of the Colorado River before and after Glen Canyon Dam (partially reported in Dolan, Howard and Gallenson, 1974).

   Our current field studies include investigation of the geomorphic and vegetational setting of the fluvial deposits. More specifically, this includes analysis of the sediment budget of the river, the investigation of the relationship between the slope and grain size of beach deposits and the intensity of current, determination of the relationship between flood hydrology and vegetational response through tree-ring analysis, determination of the relationship between river depth, width, and grain size of the channel bed (Technical Report No. 4).

4) Detailed mapping of the vegetation, geomorphology, and patterns of human impact was conducted at seven beaches along the river (19-mile, Nankoweap, Cardenas, Unkar, Blacktail, National, and Granite Park) during the summer of 1976. This mapping study will form part of the data bank for future monitoring of human impact and the continuing evolution of the beaches as a result of Glen Canyon Dam (Technical Report No. 6).

Assistance in mapping of shoreline changes was provided by Stan Dunford-Jackson and Brian Culhane. Trinkle Jones assisted with photographic work.

Alan D. Howard, Robert Dolan

SUMMARY OF RESEARCH RESULTS

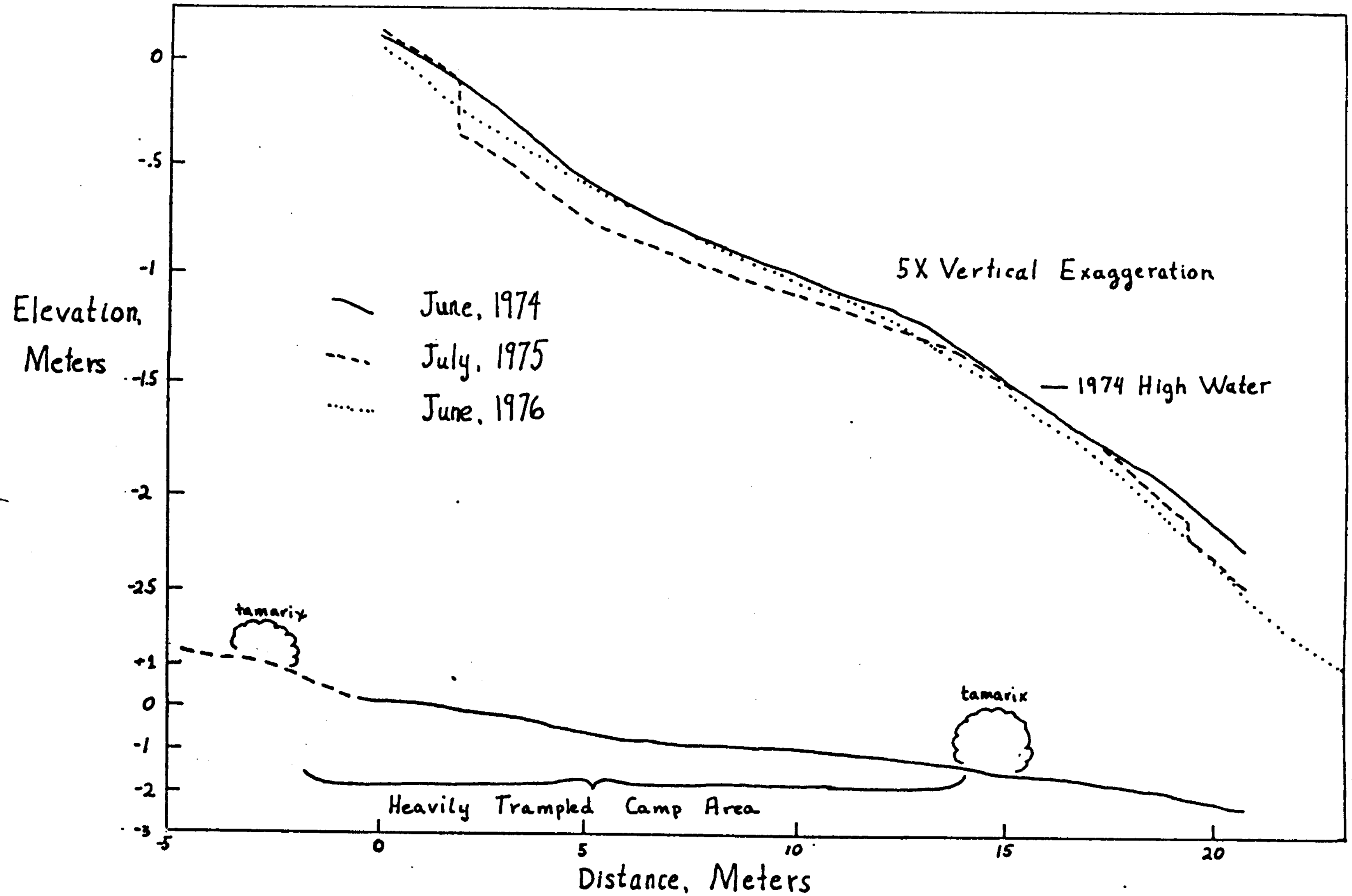


Figure 4: Profile across beach at the Nankoweap campsite, Mile 53.0, showing changes occurring over a two-year period. The July, 1975, profile above the high-water level follows a narrow runoff channel scoured during a July, 1975 rainstorm. Downslope and lateral movement of sand, aided by foot traffic, had largely refilled this channel to about the 1974 level by June, 1976. Note the consistent erosion below present high water.

SUMMARY OF RESEARCH RESULTS

The following discussion is presented in two sections; the first deals with evolutionary changes to the terrace deposits following river regulation by Glen Canyon Dam and the second is on the human impact to these terraces.

Changes in fine-grained deposits measured by baseline resurvey and aerial photography techniques can be quantified in several ways. The aerial photographic technique yields a measure of the lateral change in shoreline position (Fig. 3). The baseline surveys yield comparative profiles of the beach surface (Fig. 4). Changes between resurveys can be expressed as areal changes, or linearly as vertical or lateral erosion or deposition. The relative vertical (Δz) and lateral (Δx) changes depend upon the surface gradient:

$$\frac{\Delta z}{\Delta x} = \text{Tan}\ \theta$$

where θ is the angle of inclination of the surface from the horizontal. On the portions of the profiles below the present high water mark the amount of lateral erosion or deposition is the most convenient statistic, because it is equivalent to the aerial photographic measurements. Above high water on the campsites the vertical change is more revealing, because the surface gradient is generally very low.

Impact of Glen Canyon Dam

The impact of the regulated flows from Lake Powell may be divided into changes in river bank morphology below the present high-water level and modifications of pre-dam flood terraces that are now above high water level. Discussion will be concentrated on the fine-grained (sand-size or smaller) flood terraces which are both the most dynamic of the fluvial deposit and the most frequent sites used for camping. Cobble bars and tributary fan deposits are relatively inhospitable for camping, and are much more stable under the present river regime.

The sediments found on the terraces can be classified according to age (pre- or post-dam), agent of deposition (floods, eolian action, or fluvial reworking in the zone below present normal high water), and grain size (cohesive silts, dominantly silt with a small percentage of clay;

Table 1: Classification of fine-grained deposits.

Age of Deposit	Depositional Agent	Grain Size
Pre-Dam	Spring Flood Terrace	Silt-Sand
	Eolian	
	Summer Flood Terrace	Cohesive Silt
Post-Dam	Flood Terrace	Silt-Sand
	Eolian	Sand
	Beach Deposits	

silt-sand, with about 30 percent silt content; and sands with negligible silt). Table 1 lists associations between these classifications, and Figure 4 illustrates their spatial relationships. Several generalities can be made about these deposits, and their response to different stresses:

1) Pre- and post-dam flood terraces are usually silt-sand.

2) Pre-dam eolian deposits are but little coarser than the flood terraces from which they are derived.

3) Pre-dam cohesive silt was deposited by summer floods and runoff. These deposits seldom extend more than a few feet above present high water levels, and because of the abundance of water and the fine substrate, they have been covered by a dense vegetative growth since the dam.

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 are the predominant source for post-dam eolian deposits.

Fine-grained deposits below the present high water are being reworked by the river. The rate of response of these sediments depends upon grain size. Cohesive silts are being slowly cut back, forming steep, vegetated banks with numerous exposed roots which give the appearance of rapid erosion. The slow rate of erosion is due to the heavy vegetation cover and the cohesion of the silts (Table 2B). However, unlike the coarser deposits, the fine silts and clays, once eroded, stay in suspension and are carried all the way to Lake Mead.

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 are variable, but they show rates of lateral erosion averaging about 0.9 meters per year (Table 2B). Since the measurements were made at commonly used campsites, human impact contributes to this figure.

Lateral erosion is not uniform along the fine-grained beaches. The short-term measurements indicates rates of erosion ranging from a high of 4.9 m/yr to .7 m/yr of

Table 2 - 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	Maximum Lateral Change (meters) 2)	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 Change (meters/yr) 3)	Average Lateral 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.

of deposition (Table 2A). Similarly, the aerial photographic analysis shows rates of erosion of up to 3 m/yr with 10 m/yr at scattered locations. A few sites have expanded through deposition.

The average rate of lateral erosion from the photo analysis is .3 meters per year (Table 3). However, the great variability of erosion rates makes average figures of little use in planning. Therefore each contiguous sand deposit (a beach) was classified according to the maximum change recorded by the aerial photo analysis. The beaches so defined occurr with an average density of about 8 per mile. About 16 percent of these beaches underwent severe erosion between 1965 and 1973 (defined as an average rate exceeding 2 meters per year) while only 6 percent underwent an equivalent rate of deposition (Table 3). The unavoidable mis-estimates of discharge during the various sets of aerial photography used in the analysis have affected these figures by increasing the number of cases of extreme erosion and deposition, but they would have had less effect upon the average rates. Therefore the actual number of cases of severe erosion is less than 16 percent of the total, perhaps considerably less. The management implication remains the same, however. Severe lateral erosion sufficient to affect camping activities over the next few years will be rare and of localized occurrence. Over the long run, measured in decades, the slow progress of erosion will gradually reduce the number of sandy beaches. The rate of this process cannot be reliably estimated from the aerial photo analysis. Rather, long-term monitoring of the baseline surveys and establishment of detailed study sites will be necessary.

Erosion rates will decrease when the coarse-grained substrate beneath the terrace (bedrock, talus, alluvial fan debris, or Colorado River gravels) becomes exposed. Exposure of the cohesive silts also reduces erosion rates, and sandy beaches that are deeply inset between headlands or resistant rock are protected from current and swash (Fig. 5). Finally, the input of sediment from the Paria River, the Little Colorado River, and ungaged tributaries below Lee's Ferry may eventually be sufficient to sustain an equilibrium between supply and removal of sediment before the sand beaches are completely eroded away.

The pre-dam terrace deposits above present-day high water have been modified by three natural processes,

Table 3 - POST-DAM SHORELINE CHANGES OF THE COLORADO RIVER, 1965-1973, USING AERIAL PHOTOGRAPHY

Miles	Average Channel Width (meters)	Total Shoreline Length (meters)		Net Areal Change (meters)[2]		Average Shoreline Change (meters)	
		Fan Deltas	Fine Alluvium	Fan Deltas	Fine Alluvium	Fan Deltas	Fine Alluvium
0.5	138.5	0	1560	0	8855	0	+5.68
2.1	101.5	955	1225	81	-5645	+0.08	-4.61
3.6	74.5	145	1570	0	-6871	0	-4.38
4.6	98.5	395	815	0	516	0	+0.63
6.0	88.0	385	550	2581	1452	+6.70	+2.64
7.2	97.0	640	590	677	677	+1.06	+1.15
8.7	78.5	405	1160	613	1065	+1.51	+0.92
10.0	62.5	105	1135	0	-290	0	-0.26
11.3	57.0	680	730	1790	-323	+2.63	-0.44
12.8	41.5	755	400	484	-516	+0.64	-1.29
14.2	46.0	410	115	306	0	+0.75	0
15.4	57.5	575	685	0	-355	0	-0.52
16.7	66.5	640	655	1806	371	+2.82	+0.57
18.0	59.0	585	790	1242	742	+2.12	+0.94
19.4	59.5	730	1035	1355	3532	+1.86	+3.41
20.5	54.0	185	580	2613	1274	+14.12	+2.20
29.9	64.0	670	930	323	306	+0.48	+0.33
31.2	65.0	665	900	0	-3210	0	-3.57
33.0	65.0	275	1340	81	-2065	+0.29	-1.54
34.4	80.5	310	1110	371	-6758	+1.20	-6.09
35.5	70.5	425	1150	161	-5758	+0.38	-5.01
36.9	78.5	375	1125	1903	-3242	+5.07	-2.88
38.1	83.5	330	1365	919	-2935	+2.78	-2.15
39.7	85.0	260	1695	387	-9339	+1.49	-5.51
40.9	88.5	260	1565	387	-1968	+1.49	-1.26
42.2	94.5	65	490	0	-1226	0	-2.50
43.8	81.0	570	2305	3145	-9210	+5.52	-4.00
45.3	95.5	285	1155	806	-7113	+2.83	-6.16
46.7	104.5	700	1320	645	-11952	+0.92	-9.05
48.1	102.0	565	1495	694	-7468	+1.23	-5.00
49.5	110.0	530	1200	0	-8500	0	-7.08
50.7	93.5	210	1295	0	-10903	0	-8.42
52.5	113.5	800	1985	2258	-2790	+2.82	-1.41
129.5	50.0	290	210	1984	500	+6.84	+2.38
130.8	58.0	285	845	0	-1774	0	-2.10
132.2	49.0	515	1080	81	-9903	+0.16	-9.17
133.5	60.5	825	1375	355	-6806	+0.43	-4.95
135.0	48.0	415	1205	597	-5548	+1.44	-4.60
136.4	48.0	430	1285	0	-5613	0	-4.37
137.7	63.0	690	1315	48	-1952	+0.07	-1.48
139.4	56.5	700	1135	887	-4984	+1.27	-4.39
140.5	51.0	880	900	0	-3613	0	-4.01
142.0	55.5	0	270	0	0	0	0
143.4	56.0	385	170	5726	-613	+14.87	-3.61
155.8	42.8	265	210	565	0	+2.13	0
157.3	45.0	345	220	613	-677	+1.78	-3.08
158.8	44.0	210	390	371	0	+1.77	0
160.4	48.5	155	415	0	1016	0	+2.45
161.5	50.5	150	420	323	+81	+2.15	+0.19
163.2	54.5	395	475	565	-403	+1.43	-0.84
164.8	63.5	220	1160	565	242	+2.57	+0.21
166.5	65.5	285	1180	0	500	0	+0.42
167.7	76.5	335	1615	806	-4661	+2.41	-2.89
169.4	68.0	105	585	0	0	0	0
170.8	65.0	480	950	1016	2581	+2.12	+2.72
172.3	72.5	155	1560	65	-7081	+0.42	-4.54
173.5	68.0	680	1265	2097	2823	+3.08	+2.23
175.1	69.5	425	1195	565	-3548	+1.33	-2.97
176.4	81.5	160	595	0	-2097	0	-3.52
	68.9	24,665	57,030	42,857	-141,177	+1.738	-2.476
	(226 ft)				Change/yr	+.217	-.310

Percent of Total

Explanation

1) Maximum lateral erosion of fine-grained shoreline segment greater than 15 meters in 8 years (50 ft. or 6 feet per year).
2) Maximum lateral change between 0 and 15 meters of erosion.
3) Maximum lateral change between 0 and 15 meters of deposition.
4) Greater than 15 meters deposition.

Number of Fine-Grained Shoreline Segments with Indicated Maximum Changes						Number of Fan Deltas with Indicated Maximum Changes			
Severe 1) Erosion	Moderate 2) Erosion	No Change	Moderate 3) Deposition	Pronounced 4) Deposition	Total Cases	No Change	Moderate Deposition	Severe Deposition	Total Cases
1	1	1	1	2	6	0	0	0	0
3	1	5	4	0	13	7	1	0	8
2	3	3	4	0	12	3	0	0	3
1	1	4	2	1	9	4	0	0	4
2	0	2	0	0	4	3	1	2	6
0	3	1	3	0	7	2	2	0	4
1	1	4	3	2	11	4	1	0	5
1	1	8	2	0	12	1		0	1
0	3	6	1	0	10	2	1	1	4
1	1	4	2	0	8	3	2	0	5
0	0	3	0	0	3	2	1	0	3
1	2	4	1	1	9	5	0	0	5
1	1	4	1	2	9	1	1	3	5
0	1	7	0	1	9	2	4	0	6
0	3	7	5	3	18	4	3	1	8
0	0	5	2	0	7	0	0	1	1
0	1	3	1	1	6	6	1	0	7
1	6	4	3	0	14	9	0	0	9
1	3	9	1	0	14	4	1	0	5
3	6	0	1	0	10	2	1	1	4
4	3	6	0	0	13	4	2	0	6
3	2	6	0	0	11	2	0	1	3
2	4	5	2	1	14	1	2	1	4
4	1	6	0	1	12	2	1	0	3
3	2	3	0	2	10	1	1	0	2
0	3	1	1	0	5	1	0	0	1
8	2	2	2	2	16	3	1	1	5
4	0	7	1	0	12	1	0	1	2
5	0	6	1	1	13	5	0	1	6
5	1	9	0	0	15	5	0	1	6
3	1	6	0	0	10	5	0	0	5
4	0	5	1	0	10	3	0	0	3
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3	1	14	0	1	19	2	0	1	3
0	0	7	0	0	7	1	0	0	1
2	0	3	0	3	8	1	0	1	2
4	2	10	1	0	17	1	1	0	2
1	4	6	1	2	14	6	0	2	8
1	0	8	4	4	17	2	1	0	3
2	3	6	0	1	12	1	0	0	1
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16	18	50	10	6	100	73	17	10	100

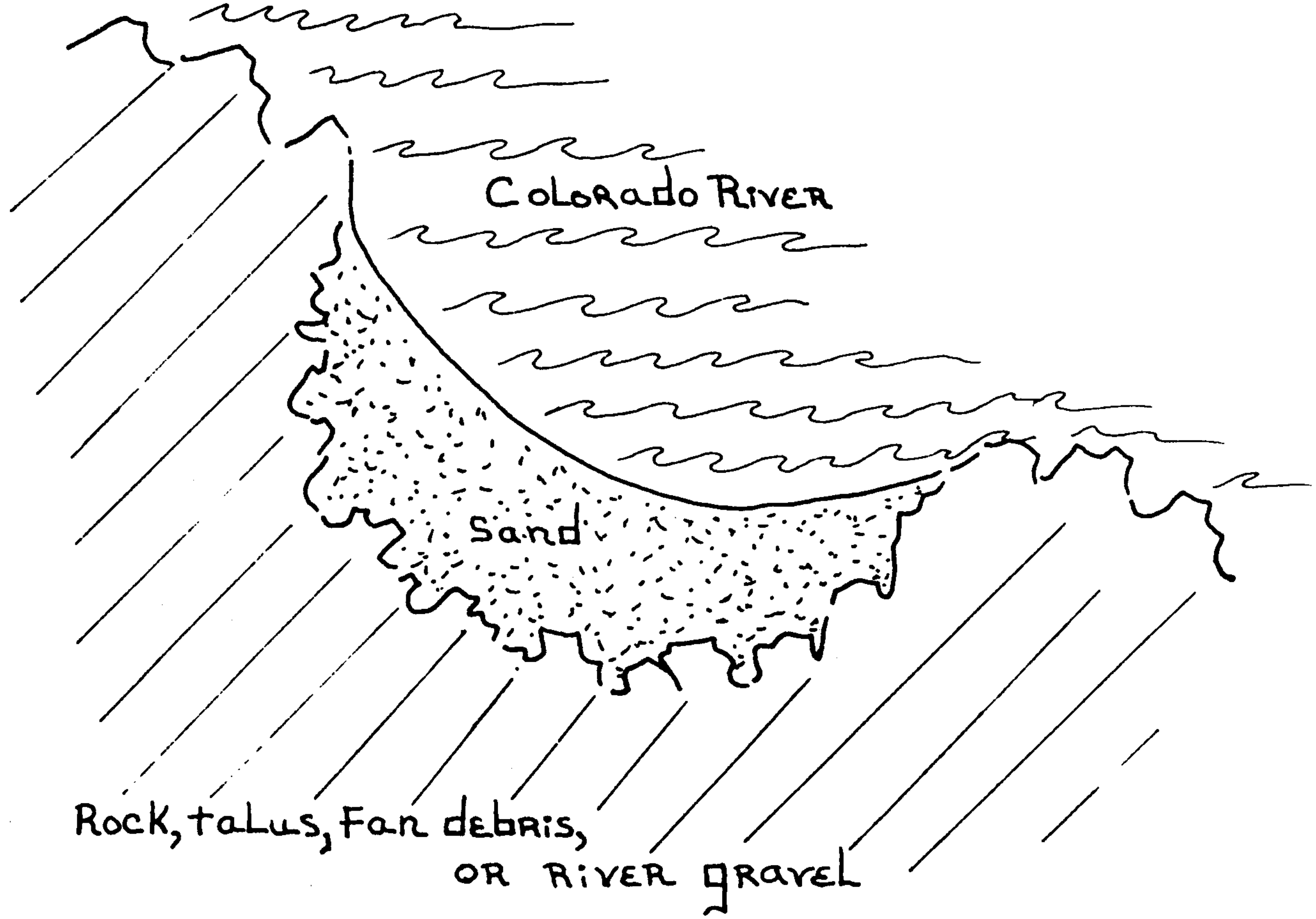

Figure 5: Inset beach protected by resistant buttresses.

eolian transport, rainfall runoff, and vegetation. Eolian sand movement occurs mostly where vegetation is sparse and the local winds are strong. Under such circumstances, rates of vertical erosion or deposition may exceed a meter/yr. Eolian transport is greatly diminished by even a sparse vegetation cover.

Rainfall and associated runoff also erode the pre-dam terraces on a localized basis. Two types of runoff erosion occur; slope wash and tributary canyon flooding. Heavy rainfall causes runoff and local gullying. Because of the high infiltration capacity of the terrace deposits and the rarity of intense, long-duration rainfall, this type of erosion is only important locally and is difficult to forecast. A recent thunderstorm at the Nankoweap campsite (M53.0) caused severe local gullying on steep slopes, but only minor erosion on gentle slopes. This pattern of erosion is influenced by human use of the beaches, and will be discussed further in this report. Of the fine-grained deposits, the silt-sands are the most easily eroded. The cohesive silts are less easily detached by running water and are commonly protected by a vegetative cover. Coarse sand, on the other hand, is highly permeable, so that a very heavy rain is necessary before erosion takes place.

The other erosional process is the flooding of tributary streams that flow across the alluvial fans mantled with fine-grained deposits. When in flood the tributary streams cause wide-scale erosion of the fine-grained mantle.

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 percent of tributary fans in the study sites have built outward, but narrowing of the river by more than 15 meters has occurred on only 10 percent of the fans (Table 3). 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 can have two effects upon human use of the river. Firstly, rapids may become impassable to river traffic. Secondly, deposition of coarse material in the river, steepening its gradient, can increase the total fall through the rapids and back up the river upstream, raising the water level of the river by several feet a mile or more upstream. The backwater effect, of course, could drown out beaches formerly used for camping. Such major floods are rare and unpredictable in specific occurrence, and even their frequency of occurrence along the river is uncertain. Human adjustment to any such major flood will have to be done on an after-the-fact basis. However, the likelihood of occurrence of a flood of sufficient magnitude to create an impassable river over the next few decades seems remote.

Impact of Human Use

The second type of impact upon the river deposits is caused by people on float trips. During overnight camping, lunch stops, and sightseeing hikes, the effects are several, depending upon the type of activity and location on the beach and terrace deposits.

Mooring and round trips to the boat during unloading and repacking greatly impact the beach zone between normal high and low water. For reasons of convenience and safety, the boats are usually moored adjacent to the fine-grained beaches rather than along rocky shorelines. The gentle coarse sand beaches are preferred to the steeper, densely vegetated cohesive silts, whenever possible. The boat itself affects the shorefront by diverting or concentrating currents and swash at the shoreline. On beaches with strong currents the boats may cause temporary local scour of the mooring site. On cohesive silt banks the concentration of current or swash may speed backcutting.

Foot traffic to and from the boats during loading and unloading of as many as 20 persons can be so dense as to completely saturate a wide zone of the beach with overlapping footprints. The foot traffic affects the beach in two ways. First, each footprint dislodges and moves a quantity of material downslope. The amount of dislodgement is greatest on coarse, sandy beaches, and may be very small on vegetated cohesive silt banks. The downslope movement per footfall increases with the steepness of the beach. Second, foot-traffic roughens the beach surface, which increases the turbulence at the bed surface and promotes erosion during subsequent high water.

The degree of permanent erosion below the high water line caused by foot traffic and boat mooring depends upon the composition and steepness of the beach substrate.

Human impact on the terrace deposits above high water is long-lasting and visible. This impact is caused by several interrelated effects of camping activities . Human use generally decreases rapidly away from the main camping site, approximately exponentially with distance. Use, however, is channeled by the topography and vegetation, concentrating along pathways that cross or bypass these obstacles. Most of the foot traffic on camping beaches is concentrated within 100 meters of the mooring sites, even on large beaches, (Fig. 6). The higher terraces covered by mesquite and cat-claw acacia are seldom used for camping, because of distance from the river, steep slopes, and density of vegetation. A second type of foot traffic occurs on the larger beaches with archeological sites, side canyons, and scenic overviews. Paths radiate towards these locations from the camping areas. Such paths cross and branch copiously (Fig. 6).

Foot traffic on camping beaches produces several effects. Firstly, it dislodges the substrate, especially on sandy deposits, and moves it downslope, with the amount of downslope movement being proportional to the slope angle and density of foot traffic. The average rate of movement becomes especially rapid as the slope angle approaches the angle-of-repose for the material.

Foot traffic has an indirect influence on erosion through destruction or inhibition of the vegetative cover and associated soil. Most heavily-used beaches have large areas close to the mooring sites which are completely devoid of vegetation. In many cases the bare areas contrast with adjacent densely vegetated sites which have the same general morphology, exposure, substrate, soil moisture, and flora, but lack human traffic. The lack of vegetation on campsites is partially due to trampling or uprooting of seedlings, a destruction of the thin surface crust of organic matter and cohesive soil minerals, and to vegetation removal by campers. Destruction of the soil and vegetative cover by camping opens the area to accelerated erosion by wind and runoff. The rate of indirect erosion caused by baring of the terrace deposits to wind and rain erosion is difficult

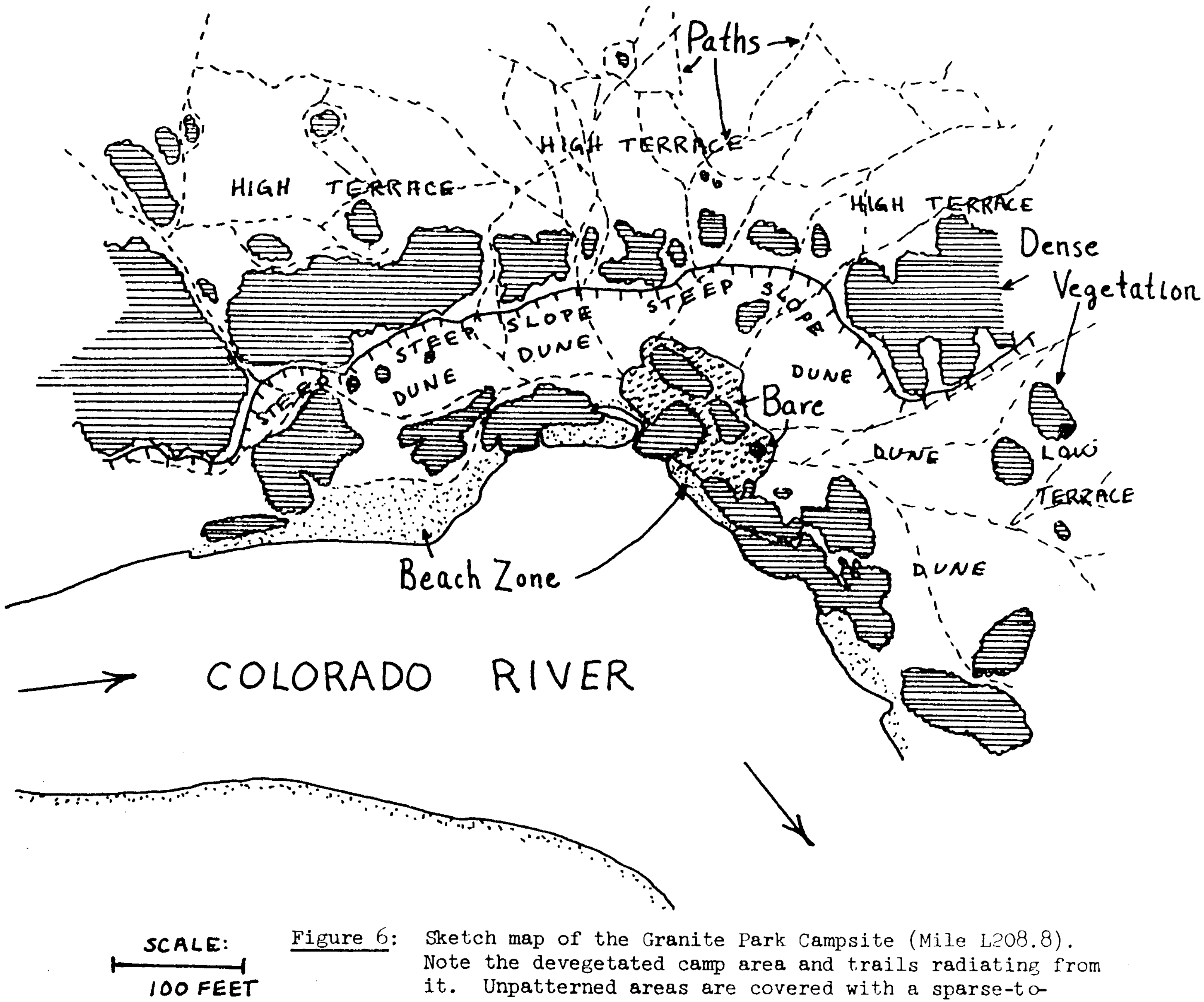

Figure 6: Sketch map of the Granite Park Campsite (Mile L208.8). Note the devegetated camp area and trails radiating from it. Unpatterned areas are covered with a sparse-to-moderate flora.

to quantify. However, the overall effect of camping is erosional, and it will proceed until exposure of the coarse-grained substrate. On many beaches several meters of fine-grained deposits are present, so that even severe erosion would not result in loss of campsites over a period of a few decades.

Severe erosion may result locally when thunderstorm-induced gullying is channeled through the many paths carved by campers.

The one-to two-year resurveys of 13 profiles 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 Nankoweap, Mile 53.0 (Table 2A), due to surface runoff during an intense thunderstorm. Since many of these profiles pass through heavily used campsites, the measurements suggest that the combined effect of natural and man-induced erosional processes above high water is very 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 .1 meter per year on steep slopes with high rates of human traffic.

Human impact on the erosion of camping beaches is not a simple function of the number of visitors per year to the camping beach. The greatest effect occurs at that small rate of visitation which results in destruction or inhibition of the vegetative cover over an appreciable area. The lack of vegetative cover allows the processes of wind transport and runoff to modify the campsite. Beyond this critical rate, the amount of erosion by wind and water will remain constant, but the direct downslope transport by foot traffic will increase in proportion to the number of camping user-days. These relationships are illustrated in Figure 7, which shows, conceptually, the rate of erosion at a campsite as a function of camper user-days per year. The critical visitor density, v_c, depends upon the grain size and cohesion of the substrate, the slope of the campsite, and the type and density of the vegetation that would be present in the absence of campers. The ratio of the vegetated to bare area rates of erosion depends upon the vegetation type and density, the nature of the substrate, the slope of the beach, the rainfall frequency, and exposure to wind action. For an originally bare beach this ratio would be unity. The slope of the line beyond the

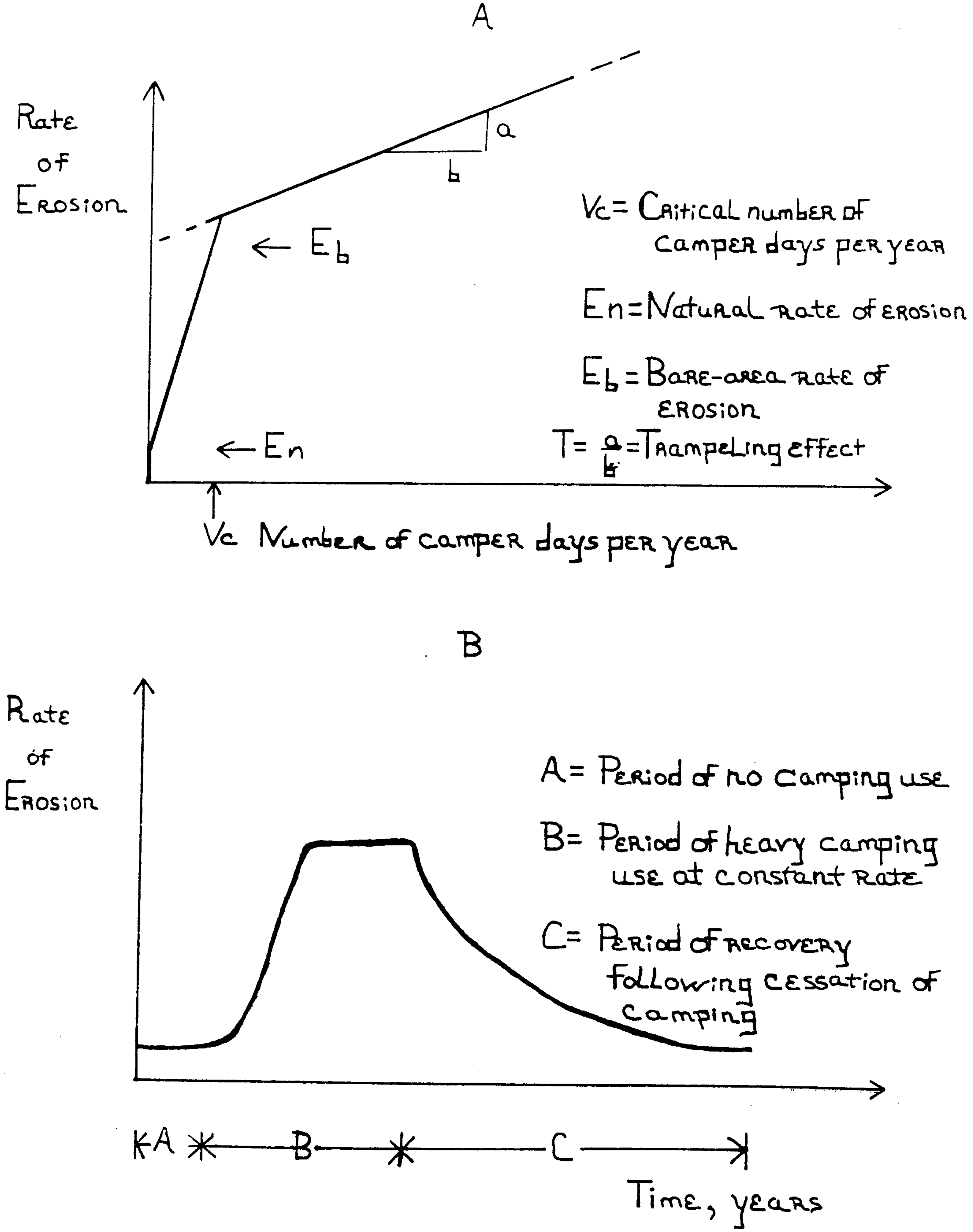

Figure 7: Effect of frequency of camping on erosion of terraces.

critical visitor density, the "trampling effect," depends upon the grain size and cohesion of the beach deposit and the slope of the surface. This illustration is figurative only, for the values of the parameters will vary from beach to beach and from location to location on the beach.

Another form of human impact, and potentially as important to management as erosion, is the systematic incorporation of human debris and human waste into the sedimentary deposits used for campsites. Almost everyone agrees that commendable efforts are made to keep the campsites clean. Most of the noticeable litter is collected and transported out of the canyon by the river boatmen; however, there is a "what you don't see can't hurt" attitude about campsite wastes. For this reason, the most heavily used campsites are rapidly approaching what we term a "sandbox condition" in that human waste is being incorporated into the sand/silt deposits at rates that exceed purging capacities by natural processes. Therefore, the sedimentary deposits begin to look and smell like sandboxes found in heavily used public parks.

This human material ranges from small food particles, to cigarette butts, paper, and charcoal. Under magnification, the amount of these materials is surprisingly high. We sampled seven large campsites for human impact during a 1976 float trip and reached the conclusion that the best indicator for the rate and the amount of debris incorporated into the beaches is charcoal, even though NPS policy now prohibits open fires. Charcoal leaks out of the now required firepans into the campsite deposits and, equally important, the approved practice of tossing used charcoal into the river does little to correct the problem, because it simply floats down the river to the next sedimentary deposit where it is incorporated in the active beach deposit, or it is transported via the winds up and onto the campsites. Therefore, we determined that a measure of charcoal content is a good measure of stress levels the various campsites are being subjected to.

The following method was developed for estimating relative charcoal content of our sample beaches. Randomly selected one-square meter surface samples were taken at each site. The number of charcoal particles, larger than the sand matrix, were counted over the sample area. In addition, small core samples were taken from within each

Table 4 - RESULTS OF CHARCOAL COUNTS

Beach Location Below Lee's Ferry	Beach Sand Grain Size	Surface Charcoal per m^2	Charcoal Sand Matrix
19 mile beach-			
sample No. 1	.13 mm	288	29
sample No. 2	.21 mm	276	98
sample No. 3	.17 mm	184	68
Mean	.17 mm	249	65
52 mile beach-			
sample No. 1	.19	2536	213
sample No. 2	.17	769	110
sample No. 3	.20	639	187
sample No. 4	.14	236	80
Mean	.18	1045	148
UNKAR 71 mile			
sample No. 1	.18	181	54
sample No. 2	.18	251	62
Mean	.18	216	58
72 mile beach			
sample No.1	.11	1286	485
sample No. 2	.10	630	81
sample No. 3	.10	2581	626
Mean	.10	1499	397

Table 4 (continued)

Beach Location Below Lee's Ferry	Beach Sand Grain Size	Surface Charcoal per m^2	Charcoal Sand Matrix
121 mile beach			
sample No. 1	.17	242	113
Mean	.17	242	113
National			
sample No. 1	.10	242	178
sample No. 2	.19	197	117
Mean	.15	220	148
Granite Park			
sample No. 1	.15	378	96
sample No. 2	.14	494	67
sample No. 3	.10	507	258
Mean	.13	460	140
Grand Mean	.15	627	162
Standard Deviation	.0013	(Not Normal Distribution)	

grid for laboratory analysis of smaller sized charcoal. The number of samples collected per campsite depended upon the size of the campsites; for the largest sites four sample grids were counted, and for the smallest, one sample grid was counted.

Our data show, as indicated on Table 4, that the more popular campsites have five to six times more charcoal per unit of sediment than those less often used. For example, Nankoweap Beach with 360 pieces of charcoal per m^2 versus 19 mile beach with 60 pieces per m^2. Clearly, there are major differences in the rate at which debris is being incorporated into the deposits. The fine grain material, shown on Table 4, indicates similar ratios between the various beaches as do the larger particles.

Although the relative charcoal content of the sediment matrix of the campsites appears to be a good thermometer of the relative "health" of the beaches, we have found a wide range of other types of human debris within the samples. This included food particles, paper and fabric, fibers, tobacco, marijuana, small pieces of metal, and a variety of plastic substances. Nankoweap Beach and Granite Park Beach contained by far the largest amounts of foreign substance - roughly 1.5 percent of the sand matrix.

CONCLUSIONS

Are the beaches along the Colorado River of the Grand Canyon being significantly altered? Are they undergoing irreversible change? Our evidence suggests that the answers to these questions is yes. However, what this means to management cannot be answered in equally definite terms. The Colorado River alluvial system below Glen Canyon Dam is clearly undergoing rapid changes so what is happening to the beach deposits because of visitor use may be insignificant relative to the larger-scale modifications. And, there is always the question of what is a quality wilderness environment? Perhaps the people floating down the river in the future will not be concerned about the quality of the campsites? This question will become academic if visitation is increased 25 to 50 percent in the near future without a plan for obtaining a better distribution of visitor use along the river because it is inevitable that the campsites are going to degrade further, and hardly represent a wilderness landscape.

The alterations to beaches that we have quantified are of two types, 1) wholesale addition or removal of fine sediment by natural processes and human impact, and 2) alteration of vegetation and reworking of, and accumulation of debris in, the sandy soils due to camping activities. Our data indicate that over the next few years the removal of fine sediment from the beaches will have little impact upon the number or use of campsites, although a few beaches may become unusable due to exposure of the underlying coarse rocks or bedrock at the mooring or camping sites. Over a longer period (several decades) this erosion may force appreciable readjustment to a diminishing supply of campable beaches.

However, more immediate deleterious effects upon the soils and vegetation of the beaches has resulted from camping activities. These include inhibition of vegetation growth, destruction of the thin natural soil, accumulation and intermixing by foot traffic of foreign detritus in the sandy deposits (including food residues, feces, charcoal, tobacco, pop-tops, bandaids, cloth fragments, etc.), odors resulting from the accumulated debris, increase in scavenging wildlife (ravens, red ants, small mammals, etc.), and possible displacement of fauna sensitive to human interference. The inhibition of floral growth and destruction of soil profiles could be considered to counteract the effects of the dam, which has been responsible for much of the growth of river front vegetation, were it not for the localized nature of the camping activities (which advertises the presence of human use) and their extension, by formation of paths, to elevations above normal pre-dam high water. However, the other effects, particularly the accumulation of human debris in the sandy deposits and the encouragement of scavengers clearly cause major alterations to the natural environment. Many of these impacts can be reduced by changes in the format of camping activities.

RECOMMENDATIONS FOR FUTURE RESEARCH AND MONITORING

The changes brought about by the Glen Canyon Dam and by float trips occur slowly, but their effects on removal of terrace deposits are cumulative. Because this change occurs over a wide range of magnitudes, our estimates of the rates of change are subject to a degree of uncertainty. These uncertainties are due, mostly in the case of the benchmark studies, to the short period of observation. Trends established from one or two years of measurement may not be representative, and the amounts of change on the subaerial portions of the profiles are in some cases less than the surveying errors. The aerial photographic comparison, while it affords an eight-year record, is also subject to errors, particularly in the estimate of discharge at the time of the photography. A fuller discussion of these limitations is contained in our Technical Reports No. 1 and 5. Continued updating is essential. Additionally, in order that changes can be quantified, it is necessary that the present state of the beach and terrace system be well documented. This is especially true in view of the possibility of an impending change in the visitor traffic through the canyon. We therefore recommend that:

1) Additional baseline data from high resolution vertical color aerial photography of selected beaches be obtained at a negative scale between 1:500 and 1:1000. This should be taken to metric, or near-metric standards with stereo pair coverage. Such photography can readily resolve, when compared to similar photography taken a few years later, changes in species composition, distribution and size of individual plants or clumps of plants, as well as allowing quantification of changes in camp size and movement of surficial materials. The photography should cover a good sample of beaches selected to provide a cross-section of geomorphic setting, vegetational characteristics, and human-use density. Field calibration following shortly after the photography will be necessary to correlate patterns on the aerial photographs with features on the ground, especially in distinguishing species type in vegetational studies and providing a control network for planimetric base maps.

2) The general coverage of the river and its environs by black-and-white aerial photography flown in 1973 (1:7000) should be reflown between 1980 and 1985 to provide a documentation of all major changes along the river during the seven to twelve year period. If possible, this photography should be flown under similar discharge conditions as the 1973 flight.

3) A resurvey of all profiles on the 20 benchmark beaches should be undertaken sometime in the period from 1978 to 1981, that is, three to six years after their initial establishment. This resurvey will allow a much more accurate assessment of rates of erosion and deposition caused by natural processes and human impact.

4) An effort should be made to quantify the relationship of camper use and vegetation destruction and opening of the campsites to the effects of wind and rain. Use data has already been collected on current rates of usage of the canyon campsites, supplied voluntarily by commercial trips. This density information should be correlated with field measurements of human impact, such as accumulated charcoal, number of port-a-potty sites, etc. At the same time, field or aerial photo interpretation of the campsite should be included.

5) Several beaches should be made off-limits to camping and day use in order to provide a control for comparison of human impact on other beaches. These beaches can also be used as study sites for the natural processes. The beaches selected should provide a good cross-section of physical and floral characteristics. Research use of the reserved beaches should be tightly controlled, if possible, with access only by hiking from an adjacent unrestricted camping location or by restricting camping to a small area. At the same time, very heavy camping should be encouraged at a few sites to determine the cumulative effects of maximum levels of human use. The degree to which this is possible will depend upon the future level of control over itineraries of commercial and private river runners. All of these manipulated sites should be part of the sample of beaches covered by color vertical aerial photography prior to the change in use rate. Benchmark study sites should be established where they do not presently exist.

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