281 from Brent Taylor

PRELIMINARY DRAFT

GLEN CANYON DAM

ENVIRONMENTAL IMPACT STUDY

PROPOSAL

FOR

TEST/EVALUATION

OF

SAND-PUMP BEACH NOURISHMENT

(i.e., sediment augmentation)

IN THE

GRAND CANYON

December, 1990

Dave:
This is a more current version than the one I gave to Larry & Julie
Mark

Remember: Chunks / Maps

TABLE OF CONTENTS

(SEDIMENT — AUGMENTATION)

PROPOSAL FOR SAND-PUMP BEACH NOURISHMENT TEST/EVALUATION

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I. PURPOSE:

1) To test the feasibility of selectively pumping (harvesting) nominal quantities of replaceable sand from the river channel bed along depositional sub-reaches, and transporting pumped-sand to specific target beaches for nourishment.

2) Test specific portable-pumping equipment capabilities, and identify field procedures and logistics necessary for a full-scale Grand Canyon beach nourishment program.

3) Determine the potential volumetric rates of sand placement possible with portable-pumping equipment that can be transported in a rubber raft and can be set-up and operated by a 3-5 personnel.

II. BACKGROUND:

1) Pre-Dam River Mechanics -

Under natural conditions the Colorado River in the Grand Canyon experienced large seasonal and annual variations in peak stream discharge and volume; sediment transport, channel depths, flow velocities, and 'beach' deposits along the river. In the Grand Canyon, the Colorado River is neither fully free i.e. flood plain alluvial river, nor fully constrained i.e. hard-rock geologic controls. It is a mixture of both types of river conditions. Prior to the advent of Glen Canyon Dam, with its large sand inputs from upstream and lateral tributary sand inflows, the bed was composed partially of sand and gravel material, and partially of very coarse material and hard-rock bed controls. Laterally, the narrow hard-rock canyon walls severely constrain the river's movement and 'overbank' flooding. Also, with coarse debris up to several feet in diameter, which is periodically inputed to the river by lateral streams in flood, and hard-rock spalling from canyon walls. These coarse debris 'flows' typically create large scale obstructions which are not easily transported downstream by the river. These debris-obstructions, and hard-rock bed and bank controls created a channel geometry where there is nominal variations in channel width along individual sub-reaches of the canyon, variations in mean width from one sub-reach to another, variations in channel depth i.e. a 'rapids and pools' profile, and an average channel slope of 5 to 10-feet per mile.

Thus, the sedimentary mechanics of the river in the canyon, have always been interactive with and complicated by the alluvial/hard-rock/coarse-debris bed and bank conditions. Beach conditions then, have never been static, but rather constantly changing with periodic accretion, degradation, and reshaping, with changes in discharge, sediment inputs, and natural stream instabilities. Typically, there was a natural renourishment of beach areas during pre-dam spring floods when large quantities of sand-sized material was scoured from the bed, and deposited along the slack water bank areas where beaches usually form. There was generally a net accretion of beach areas with this spring flooding, but with the significant change in hydraulic flow conditions with the large discharges at some locations existing beaches were scoured during high flow conditions.

The sand and gravel sections of the stream bed allowed for severe vertical channel scouring during the rising limb of the spring-flood. Scour depths of a much as 50-feet have been reported (Leopold, 1969, page 141) along the Colorado River. On the falling limb of the spring flood, there was typically significant redeposition particluarly in the pool and slack water area, with approximate pre-flood bed levels re-established by the following fall. This spring-flood bed scour/aggradation phenomena is illustrated for two different years - 1948 and 1956, in Figures A and B, respectively.

During pre-dam years the discharge in the Grand Canyon ranged from more than 200,000 cfs to less than 1000 cfs; and the annual sediment transport through the Grand Canyon ranged from 50 to 300 million tons, with an average annual value of roughly 140 million tons. Data provided by Smith et al. (1960, Figure 53) indicate that 50%-60% of this material was finer than 0.064 mm, and 40%-50% was sand sized material (>0.064mm). This would suggest that under pre-dam conditions the sand average annual sand transport was roughly 60-70 million tons.

2) Post-Dam River Mechanics -

The flow of the Colorado River has been regulated at Glen Canyon Dam since 1963. The discharge ranged from about 5,000 to 33,000 cfs most of the time in the post-dam period 1965-82. With the advent of dam closure along a river, 'un-natural' changes begin to take place in downstream sedimentation processes, bed composition and channel geometry, primarily as a result of:

- changes in the river discharge hydrograph (reduced annual peak discharge and streamflow volume,
- clear water (sediment-free) discharge from the dam, and
- changes in water temperature regime in the river.

These changes typically include:

- Channel Geometry:
  - reductions in mean bed elevations along the river channel
  - possible changes in planform stability, i.e. 'beach' patterns along the river

- Channel Bed Material:
  - increase in mean size of bed sediment through removal of finer size fractions i.e. armouring

- Sediment Transport:
  - reduced competence of stream to transport coarse (>0.062mm) sediment fractions, due to reduced discharge levels
  - reduced transport of fine sediment (silts and clays), due to reduced upstream imputs
  - reduced bed material transport at a given discharge, as a result of coarsening of bed material in the channel,
  - possible increase in mean size of coarse material transported by the stream,
  - following channel adjustment period (10-years?) sediment transport becomes equal to lateral tributary inflow loading;

In the Colorado River the following downstream dam-effects have been observed:

A) Bed Profile Development

Data presented by Williams and Wolman (1984, Figure 8) indicate that during the first decade or so following dam closure at Glen Canyon, in the downstream channel bed scouring of more than 12 feet were measured (see attached Figure C).

Figures C, D, E, and F summarize data from Williams and Wolman, and Pemberton (1976, Figure 7), which indicate that post-dam quasi-stable bed profile conditions obtained at least along the upper part of the 220-mile study reach, by 1965. As illustrated in Figure G, during the initial post-dam adjustment period downstream effects generally decrease with distance downstream from the dam. With time dam closure effects progress downstream and a new quasi-equilibirum bed profile is developed all the way to Lake Mead. Williams and Wolman data (Table 13 in USGS Prof. Paper 1286) suggest that within 10 years after Glen Canyon Dam, effects downstream 50 miles had reached approximate equilibrium. According to data compiled by Pemberton (1986), the following summarizes channel bed composition along the study reach for post-1983 conditions:

Reach	Length (mi)	Boulders	Smooth (gravel/sand and flat)	Sediment Wave
1	61	53%	33%	14%
2	26	44%	52%	4%
3	78	63%	31%	7%
4	60	33%	56%	11%

Pembertom describes the 'Smooth' pattern as mixture of gravel and sand in a generally flat configuration, which is suggestive of the Missouri River armoring conditions, and the sediment wave as composed of sand. The above data do not indicate an increase in 'sand bed' conditions with increasing distance below the dam, thus suggesting essentially uniform armoring throughout the 220-mile study reach, an thus that quasi-equilibrium conditions have developed.

see Burkam's discussion on bed change

During the 1983-86 flood years, with the sustained higher than normal discharges, it would be expected that there would be some changes in the bed profile, even at some locations where armoring had occured, due to the much greater bed scour potentials with the higher discharges. And Lanky (1986) notes "The 1983 surveyed river sections do indicate some degradation to have taken place since the 1975 survey.."

B) Bed Armoring Processes

General Information

Vanoni (1975, pgs 181-183) notes, "The fact that the bed sediment load of streams is finer than the bed sediment from which it derives, leads to the conclusion that as a stream degrades its bed will coarsen (Vanoni, 1962). Conversely, the fact that beds of degrading streams do coarsen may be taken as evidence that the load is finer than the bed sediment. Stream beds downstream from large reservoirs are known to coarsen as they degrade. This was observed to occur on the Colorado River downstream from Hoover Dam. Lake Meade, the reservoir formed by the dam, has a capacity of twice the mean annual runoff so that the river is completely controlled. Also, no significant flow is contributed to the river by the arid area downstream of the dam. Lane, et al (1949) found that after closure of the dam the discharge of sediment decreases consistently [see attached Figure H]. This decrease was explained by the observed coarsening of the bed sediment.

"Prolonged degradation and coarsening of the bed sediment of streams can lead to armouring of the bed and to drastic reduction in the rate of degradation and sediment discharge. A spectacular case of this kind on the Missouri River downstream from Fort Randall Dam was reported by Livesey (1965). The tail water level downstream from the dam was expected to lower at the rate of about 1 ft/yr but after 10 years the level has lowered less than 3 feet. Inspection of the bed at low water revealed that the bed surface was armoured with one layer of gravel [see attached Figure I]. The median size of the sediment in the bed surface before closure of the dam was about 0.17 mm and tended to coarsen after closure.

"Harrison (1950) studied bed armouring in a flume by first recirculating the sediment load and then trapping it at the discharge end of the flume and introducing clear water flow into the flume. When sediment was recirculated the coarse sediment particles that moved very slowly or not at all tended to collect at the base of the dunes thus forming a lens of large particles. When clear water was introduced into the flume the dunes moved through the system in unison leaving behind a flat armored bed. The armor particles were always only one particle in thickness and covered less than one half of the bed surface. Despite this incomplete coverage the sediment discharge with the armored beds was 1% or less of that of the same water flow with with recirculated sediment. Figure [2a] shows that the armor in the Missouri River also does not cover the entire bed area although it appears to cover more than half the bed. This figure also shows that the armored bed is flat as Harrison found in his experiments.

"Harrison observed that the particles armoring the bed were arranged in a shingle pattern, i.e., they were tilted with the downstream end resting on an adjacent particle and raised higher than the upstream end.

"Einstein and Chien (1953a) outlined the transport process for wash load. They advance the idea that the rate of transport of a given size-fraction of bed material of a stream depends on: (1) The ability of the stream to entrain the grains of a given size; and (2) the availability of grains of this size on the bed. If the material is available in large quantities, as in the case of bed sediment, the availability remains essentially constant and the sediment discharge depends only on the ability of the flow to entrain the grains. For this case a unique relation exists between velocity and bed sediment discharge. On the other hand, if, as in the case of wash load, the material is easily entrained and very little of it is present in the bed, so that entrainment of some of it will materially reduce the supply, the discharge of this material will depend mainly on its supply. The xsperiments of Einstein and Chien showed that although the amount of fine sediment found in the bed increased as wash load discharge increased, the relative amounts present were small. Thus with a relatively large wash load discharge a relatively small amount of fine sediment is found in the bed. Conversely much greater quantities of the coarser fractions are found in the bed when the bed material discharge is relatively small".

Bed Armoring in the Grand Canyon

As suggested by data plotted in Figure J, channel scouring like that which occurred downstream from Glen Canyon Dam, has typically increased the mean size of in the active transport layer of bed material. As noted above, with coarser bed sediments at a given discharge the river is not able to pick-up and transport as much sediment, and thus as shown in Figure H is steadily reduced, until a general equlibrium bed profile condition is reached. When this quasi-equilibrium obtains, the river's fine and sand-sized sediment transport becomes equal to the ammount input by lateral tributaries downstream from the dam.

As noted earlier, in the absence of lateral inflows, with bed armoring we would expect a coarsening of the material transported by the stream. With lateral inflows of sediment having the same (sand) sizes as the pre-dam river load, this coarsening would be reduced but still present. With quasi-bed profile equilibirum, when there is no bed scour and essentially 100% of (sand) load comes from lateral inflows, the size of the river's sand transport material should be approximatley the same as the composite size of the upstream lateral inflow sand size.

A rough statistical sampling of basic data from 1983, provided by Pemberton (1986) indicated that for the Pariah, the Little Colorado River, and the Colorado River at Diamond Creek, the mean sizes of the respective suspended loads are 0.19 mm, 0.22 mm, and 0.20 mm. Thus these data do not indicate any significant difference between the load sizes for primary lateral inflows and the Colorado River. These results support the conclusion that essentially all of the river transport is from lateral inflows.

C) Sediment Transport Rates

As noted above, following the closure of Glen Canyon Dam, sediment transport was reduced, and probably by 1966, annual sediment transport along the river was probably equal to tributary inflows of fine, and sand-sized materials.

In an alluvial river, the sand transport rate typically varies exponentially with water discharge. Thus sand transport rate data is often plotted against the water discharge for the development of sediment transport rating relations.

Sand transport relations for the river under present conditions i.e. last few years, developed by Pemberton (1988), indicate that the total sand discharge rating curves vary significantly along the Grand Canyon. Figure K, which relates river discharge and sand transport at five gaging stations, gives a two to 10-fold variation in the total load sand-discharge rating curves between Lees Ferry and Diamond Creek USGS Gaging Stations.

In Figures L-1 and L-2, a sand-discharge rating curve (suspended load) based on data collected at Grand Canyon for a fairly typical 4-year pre-dam period is developed. A comparison of Figures K, and L-2 suggests that under present conditions the sand-discharge levels at the Diamond Creek Gaging Station are roughly 1/5th of the pre-dam levels in the Colorado River; and at the Lees Ferry Gaging Station the sand-discharge levels are perhaps 1/10th to 1/50th of the pre-dam levels. Since total sand transport is nominally larger than suspended sand transport, these pre- versus post-dam ratios may be conservative. Such results indicate that under present conditions the river is significantly underloaded compared with pre-dam conditions. In other words, the river could probably transport more than 5 times it present load, without becoming a 'overloaded' stream.

Sub-Reach Variations in Sediment Transport

All flows from streams tributary to the Colorado River between Glen Canyon and Lake Mead, are unregulated. In Figure K, there are essentially three different sand transport relations plotted, one for the Lee's Ferry Station (LF), another for the Little Colorado River (LCR), and a third for the three stations below the LCR. The LCR sand transport relation is roughly 8 times the LF relation; the Grand Canyon Station (GC) sand transport relation is about twice the LCR relation; and the essentially identical National Canyon (NC) and Diamond Creek (DC) relations are only marginally greater than GC relation.

The minimal increase in estimated sand transport at NC and DC over LCR, which represent a river reach that two-thirds of the 220-mile study reach, suggest that the downstream increases in the sand transport relations must be due essentially to lateral inflows. Since if there is still significant bed degradation taking place, over a (lower) sub-reach length of 2/3rds of the total study reach there should be a considerable increase in sand trasport at a given discharge*, and this does not appear to be the case. Thus the available sand transport relations along the river also suggest quasi-equilibirum bed profile conditions.

* Rough calculations suggest that bed scour along the study reach cannot be significant in terms of depth, without having a marked effect on sand transport.

These data then suggest that the Paria River sand input is roughly half of the sand input of the Little Colorado River; and that these two lateral tributaries are responsible for almost all of the sand input to the Colorado River along the study reach.

It should be noted that lateral inflows also provide significant quantities of fines (silt and clay sized sediments) into the river. However, analysis of available data (Pemberton, 1986) suggest that under present conditions less than 10% as much fine material (by weight) is transported as was carried by the river during a typical year, under pre-dam conditions.

D) Debris-Obstructions & Lateral Channel Irregularities

In the Grand Canyon, most of the two thousand feet of vertical drop in the river occurs in rapids that extend over only 10% of the overall length. These rapids are created by hard-rock bed controls, or boulder-sized debris dams made up of very coarse material transported into the canyon from upstream areas prior to closure of Glen Canyon, and material delivered to the main channel via lateral inflow tributaries before or after Glen Canyon Dam. Following the dam closure, at least some of these coarse debris obstructions have become more severe, due to the additional supply from lateral inputs without the large spring flood discharges which partially eroded these obstructions each year.

These debris obstructions create significant non-uniformities in the velocities and depths of flow along the river. Typically (see Figure M), through the debris-obstruction rapids (Section A) velocities are high and depths are minimal, just below the rapid there is a deeper hole (Section B) where the kinetic energy developed in the rapid scours the bed and maintains a sizeable plunge zone. Just above the debris obstruction there is a quasi-reservoir 'pool' condition (Section C) where flow velocities are much reduced below those in the rapids and plunge zones, and depths are greater than in the rapids. Below the plunge zone, there can be a short or longer sub-reach of failure uniform (constant flow velocity and depth) depending on the distance downstream to the beginning of the next pool.

E) Fluctuations in Bed Elevations with Sand Load and River Discharge

In addition to variations in velocity and depth resulting from hard-rock channel controls and very coarse debris-obstructions dams, there are additional lateral variations in channel width resulting from hard-rock controls and debris deposits that give rise to additional variations in velocity and depth of flow.

Without any lateral inflows it would be expected that after the initial post-dam adjustment period is over, at each location along the quasi-equilibirum reach, the bed would have coarsened (armored) to the point where there was no longer any significant transport of bed sediment material. It might be noted however, that the size of material in the armored layer will in general depend on: a) general local flow conditions i.e. rapid, pool, etc., and b) the antecedent flow condition. For example, if dam closure occurred at the peak of the spring flood, the antecedent condition of the bed profile would be one of severe scour, and the lesser, regulated post-dam discharges would quickly come to equlibrium with reduced scour in pool areas, and essentially none at rapids. Whereas, if dam closure came in October during the low flow period, with a fully re-aggraded bed following the spring flood, the antecedent condition of the bed profile would finer material at a relatively high elevation, and with 5,000 to 30,000 cfs post-dam flows, there would be severe degradation, with significant coarsening of the bed material in pool areas, but again essentially none at the rapids. With Glen Canyon, in 1965, there was a sustained period of high flows (40,000-60,000 cfs) released from the dam, and this 'flood flow' after dam closure put the bed profile in a condition similar to the bed profile that would obtain with dam closure at the time of peak spring-flood discharge. And so this helps to explain why essentiall bed profile quasi-stability was achieved relatively rapidly after regulated flows began (1963), i.e. by 1965 (see Figure E).

The sand transport rate at a given location along a river typically varies exponentially with local mean velocity, with a given discharge. Thus along the Colorado River in the Grand Canyon, there are significant variations in the amount of sand the stream can carry. Assuming equilibrium conditions and constant discharge, depending on the initial conditions of the channel, there would be deposition in the pool areas until the depth of flow provided a stream velocity at each location such that generally, at every location the stream would be able to transport the sand delivered from upstream. But with a change in stream (Glen Canyon Dam) discharge, or the amount of sand supplied to the river, there would be a change and a new equilibrium would be established over some time period.

As a example, in a channel like the Grand Canyon, if the discharge is set at X-cfs, and sediment is artificially fed just below Glen Canyon Dam at a rate Y-tons/second and there are no downstream lateral inputs of sediment or water, the stream would at every location adjust its depth (and width) such that the given rate of sediment transport would maintained. If the discharge were increased to X+DX-cfs after equilibrium was established, the sediment transport rate would increase exponentially all along the river; and the river would readjust by scouring the bed where it could i.e. pool sections were there was a sand bed, until the depth was increased and the velocity decreased to the point where with the new higher discharge at every location the stream would just be able to transport the given sand load. Conversely, with a decrease in discharge X-DX cfs, there would be aggradation in the pools where with the reduced discharge, the velocity and depth were such that the given sediment transport could not be maintained; and so there would be deposition until the depth was reduced to produce a velocity (and depth) such that equilibrium sediment transport could be maintained.

If, rather than stream discharge, sediment loading is increased to Y+DY tons/sec there would again be pool aggradation until the depths were decreased to the point that the local velocities would be able to provide equilibrium transport of the increased sand load. And with a decrease in sediment load, and constant discharge, the opposite effect would be expected - scour of the sand bed.

Summarizing these effects:

Change	Result
Increased Discharge	Scour of sand in Pools, with increased depths. No change at Rapids

Decreased Discharge	Aggradation of sand in Pools, with decreased depths. No change at Rapids
Increased Sand Loading	Aggradation of sand in Pools, with decreased depths. No change at Rapids
Decreased Sand Loading	Scour of sand in Pools, with increased depths. No change at Rapids

With the Grand Canyon under existing conditions, there are continual fluctuations in stream discharge with the hourly, daily, seasonal, and annual variations in dam discharge and lateral inflows; and also continual fluctuations in sediment loading with hourly, daily, seasonal, and annual variations in sediment inputs. And as already discussed, there are significant changes in cummulative sand lateral input along through the Canyon.

Prior to dam closure with the spring flood there was basically channel scour on the rising limb and channel aggradation on the falling limb, as illustrated in Figures A, and B for the years of 1956 and 1949.

Based on the above model, and the basic armoring processes discussed earlier, the following offers a reasonable explaination of the basic changes in pool depths and bed conditions since the advent of Glen Canyon Dam.

From 1956-1965 the streambed was scoured as the competence of the clear water discharge was significantly greater than the sediment input to the stream, with the reduction in sediment supply to the reach due to the dam.

In 1965-66 after 10-years of moderate discharges from the dam, there was a 40-day scheduled discharge of 45,000 cfs from Glen Canyon Dam. This increase in the peak discharge over the previous 9 years, caused additional scour of the bed, where armoring had not taken place, and a new equal or deeper channel configuration was established (Sections C and D, Figure M). However, after this high-discharge period, with the reduced discharges that followed some sand and gravel aggradation took place in pool areas, as the river adjusted to the lower discharges, the same as occurred qualitatively under pre-dam conditions.

Then from 1966-1983, a lower-discharge regime was maintained in the river, and the lesser discharges and fluctuations in lateral sediment inflows (including very coarse debris) were essentially responsible for the minor fluctuations that occured in the river bed profile, since basic bed adjustment to the advent of the dam had already occurred.

In 1983-86 with the very large dam discharges (+95,000 cfs), there was again a major readjustment of the bed of the pools (and some rapids), with considerable souring and removal of sand. As discussed earlier*, the generally continuous relation defined by the suspended sand trasport rating-curve data over the past 15-years suggests that there were significant exposed deposits of sand along the river, and that with the increased discharges there was a readjustment in the bed along the pool areas, with significant scour. However, following the high discharges, on the declining limb, and with lower discharge regime since, there has been the same qualitative readjustment as there was with pre-flood conditions.

* The general continuity in the Qsa vs Q relations for 30,000 to 90,000 cfs flood flows; and also the similar patterns for 1985, 1986 (less severe in 1984) suggests exposed sand sources along the channel, otherwise the sand tranport relation should have shifted either up or down for Q vs Qsa with sub-armor layer sand as primary source of Qs vs Qsa material. However, the scatter in the data could be due to some armor layer destruction with scouring

of the finer sub-surface bed materials, in addition to additional removal of exposed bed sand, and lateral inflow variations, as measurement errors.

With regard to the variations in lateral inflows of sediment, at times the Paria or Little Colorado River produce quantities of sand input to the Colorado River that the Colorado can not instantly adjust to, and thus as noted by the Committee to Review the Glen Canyon Environmental Studies (1987), at times: "The Paria, and the LCR will introduce slugs of sediment which will be deposited in the Colorado and move as waves through the system".

Burkham (1988), in analyzing changes in hydraulic variables at the USGS Gaging Stations 'at Lees Ferry', and 'near Grand Canyon', makes the following specific observations which provide further illustration of the above river mechanics model:

"The channel of the Colorado River has a pool-and-rapid form through most of the Grand Canyon (Leopold, 1969). The rapid section, generally part of an alluvial fan located at the mouth of a tributary stream, is usually composed of gravel, cobbles, and large boulders. A typical rapid is relatively stable, except during floods and debris flows in the tributary stream when fill may occur. The typical pool represents a sediment sink. The bed of the pool has an elastic characteristic--the boundary of alluvial sediments typically scouring as the discharge increases and filling as the discharge decreases.

"Colorado River at Lees Ferry -
. . . In 1922-62, before construction of the dam, the riverbed at the gage site (composed mainly of sand and gravel) typically scoured as streamflow velocity progressively increased above a critical value (5.0 ft/s) and filled as the velocity returned to the critical value. The discharge needed to produce a 5.0 ft/s velocity when the bed was at a high level was about 18,000 cfs. During some winter floods, the alluvial deposit was scoured more than 20 feet. However, the riverbed at the low point in the measurement section was at a pool-full (high) level (about 1.0 to -2.0 ft elevation [local datum] most of the time . . . because the streamflow velocity was usually less than that required to start and sustain erosion.

"Each year, . . .the riverbed at the low point returned to a pool-full level soon after the cessation of high discharges.

"In post-dam 1965, when the regulated discharge ranged from 40,000 to 60,000 cfs for more than 40 days, the alluvial sediments at the low point in the measurement section scoured about 27 feet. The amount of fill in 1965 and 1966, after the cessation of high discharges, was only about 12 feet. [Note: It is thought that this partial return to the pre-flood level is probably the result of the presence of an armor layer at the surface prior to the flood flow, which prevented the river from scouring down to its (sand bed) equilibirum level following closure of Geln Canyon Dam.]

". . .As a result of high flows released in 1983, the bed scoured an additional 6.0 to 7.0 ft but filled back to about its former level, -15 to -16 ft, after recession of the high discharge.

". . .A progressively larger-size sediment apparently was encountered as the depth of scour increased during high discharges in 1922-62. The size of sediment on the bed at the -14 to -16-foot level in 1967-84 was larger than that on the bed at the 1- to -2-foot level in 1922-62.

"Colorao River near Grand Canyon -
. . .The riverbed in 1922-62 was at a low-bed level, -11.5 to -13.0 ft (local datum), during high winter discharges and during several summer periods, when

the discharge was relatively low. During the remaining time in 1922-62, the riverbed was primarily at a high-bed level, -9.0 to -5.0 ft elevation. The range in bed level was about 8.0 ft, compared to more than 20 ft for the Lees Ferry site.

"The level of the riverbed at the Grand Canyon site did no return immediately to its pre-flood level after the cessation of high discharges during several years in 1922-62. This fact indicates that only a very limited supply of sand- and gravel-size sediments was available for deposition in the pool during the recession of some floods. Apparently the riverbed in 1922-62 reached a high-bed level mainly in response to large sediment inflows from local tributaries, primarily the Paria and Little Colorado Rivers. The riverbed scoured to about the -13-foot level during 1965 when the release rate of sediment-free water was in the range from 40,000 to 60,000 cfs.

"Starting in 1967 and ending in 1983, the riverbed stayed at the high-bed level. Two factors were involved in keeping the bed at this level: a flood on Bright Angel Creek in 1966 and the regulation of flow at Glen Canyon Dam. The 1966 flood brought large amounts of debris--large boulders, cobbles, gravel--to the mouth of Bright Angel Creek. Much of this debris became lodged on the control (rapid) downstream from the Grand Canyon gage. The elevation of the riverbed at the rapid increased, causing the riverbed at the Grand Canyon gage to rise by about 4.0 ft. Because the regulated flow did not create enough energy to remove it, the debris largely stayed in place on the rapid in 1967-82. However, the riverbed at the rapid scoured some in 1971-73, and the debris on the rapid apparently was slowly being eroded in 1977-82 because the bed level at the gage was gradually being lowered. The 1983 flood in the Colorado River removed the debris from the rapid at the mouth of Bright Angel Creek, and the riverbed at the gage returned to a low-bed level.

". . .In 1922-62, when the bed was at a high-bed level, a velocity of about 5.5 ft/s (at a discharge of about 20,000 cfs) was required before scour began. However, a discharge of more than 100,000 cfs and velocities of about 10 ft/s would not cause the bed to scour to more than about -14 ft. The bed did not scour below the -14-ft level because the size of sediment in the bed increased and the mean velocity for a given discharge decreased with scour depth.

". . .Most of the results and conclusions for the two gage sites are applicable to similar sites at pool-and-rapid reaches along the Colorado River upstream from the Grand Canyon gage. They also may be applicable to similar sites downstream from the Grand Canyon gage.

". . .The Colorado River in the Grand Canyon, because of the stability of the rapids, does not represent a typical degrading stream which often develops when a dam is constructed. Rapids along the Colorado River in the Grand Canyon are eroding only gradually, if any, during the present regulated-flow regime. The levels (elevations) of the rapids, however, are subject to abrupt increases during periods of debris flow in tributaries."

F) Beach Stability

With the dynamic variations in the river discharges, sediment imputs, bed profiles in the pool sections, and sediment transport rates along the river, it is to be expected that the loose sand bank deposits i.e. beaches, might also fluctuate. And especially so with the high flood discharges such as occurred in 1965-66, and again in 1983-1986, when there was complete submergence of lower-discharge regime beach areas. Generally the high-discharge flood periods produce a net building of beach areas, but some beaches experience a net scour during these floods.

At present there have only been partial quantitative studies of the long term patterns regarding beach building versus degradation, and shorter term responses to variations in stream discharge and sand input. So there is as yet an unsettled controversy regarding the effects of specific changes in river regime versus beach stability, and the long-term pattern of change (degradation rate) with existing dam discharge patterns. However, what quantitative studies have been made (Lojko, 1990) do not indicate significant long term degradation or aggradation of beaches, but rather a rough state of equilibrium with perhaps marginal long term degradation of net beach area, along the Grand Canyon.

Beach areas generally occur in backwater areas where there are reduced stream velocites but significant vertical and lateral turbulence for maximum sand suspension and lateral diffusion to bank area of sand. These areas most often occur just below rapids (Sections B and D, in Figure M), but also along the inside bend of the channel. In these areas the competence of the stream to erode and transport sediment is close to equilibrium at all times, and thus with continual variations in river discharge and sand inputs to the local beach area, there will be almost continual adjustments in the beach. Upstream changes in the configuration of the rapid, or channel geometry can change flow patterns and velocities in the vicinity of the beach, and thus effect changes in beach configuration.

G) Lateral Tributary Sand Inputs

In an attempt to roughly estimate the annual sand inputs of the two primary lateral tributaries - the Paria and Little Colorado Rivers, data compiled by Iorns et al. (1965), provide the following annual suspended sediment transport data for the Paria River from 1948 to 1957:

Paria River at Lees Ferry (Iorns et al., 1965, pg 357)

Water Year	Water Discharge (acre-feet)	Suspended Sediment Load (tons)
1948	19,110	2,643,000
1949	19,590	2,592,000
1950	13,490	1,437,000
1951	13,910	1,522,000
1952	18,860	1,975,000
1953	17,880	4,553,000
1954	15,690	2,300,000
1955	17,670	4,315,000
1956	9,940	1,041,000
1957	9,940	3,198,000
	Average:	2,558,000

For this 10-year period, the estimated annual suspended sediment transport ranges from 1,437,000 tons to 4,553,000 tons for a ratio of 4.4, and the 10-year average is 2,558,000 tons. If it is assumed that the suspended load is 20% sand, and that the total sand load is 20% greater than the suspended load, the estimated average annual sand load would be 640,000 tons, or roughly 260,000 to 1,140,000 tons per year.

With regard to the Little Colorado River, Leopold et al. (1965, pg. 76) reports that at Woodruff Arizona, over a 6-year period, the average suspended sediment load in the Little Colorado River was: 1.6 million tons. Since the drainage area at Woodruff is 8100 square miles and at the mouth it is about 30,000 square miles, linearly extrapolating for average suspended load at the mouth, we get 6.0 million tons. Again, if it is assumed that the suspended load is 20% sand,

and that the total sand load is 20% greater than the suspended load, the estimated avarage annual sand load would be 1.5 million tons.

As noted earlier, with the 'slugs' of sand inputed to the river and basic river mechanics i.e. the tendency of a sand-transporting stream to form slowly moving dune-like waves on the bed even when the stream is not fully loaded with sand (Vanoni, 1975), it would be expected that along the study reach there would, at different times, be intermittent sand waves moveing downstream, the composition of which must come from lateral inflows.

3) Basic Channel Sand-Source/Beach Nourishment Hypothesis -

With the exposed sub-surface river sand in the pools and backwater areas, which is constantly readjusting to changes in stream discharge and sand input from lateral tributaries, there appears to be an opportunity for 'harvesting' sand from these areas particularly during or following periods of several months when river discharge has been lower than average, and lateral sand input higher than average. Under such conditions, if exposed sub-surface pockets of sand could be located and collected, this sand material could be placed on the above-surface existing sand beach areas which have demonstrated basic stability under existing general river regime, and would provide an increase in the quantity of sand on the beach i.e. increase the size of the beach for environmental, aesthetic, and/or recreational purposes.

This sand transfer would be similar to that which apparently takes place during high-water flood flows like 1983-86, when sub-surface channel sand sources were suspended and part of the suspended sand (and coarser material) was deposited on beach areas. However, unlike the natural processes, specific beaches could be targeted, and designated amounts of nourishment provided, rather than the hit-and-miss approach of the natural processese. Thus, this type of artificial beach nourishment would seem to be not only technically feasible and very efficient, but also aesthetically and environmentally optimal. Preliminary estimates indicate that it would also be relatively inexpensive.

It should also be noted that while there may also be loose fine gravel materials, etc., also in sub-surface sand deposits, with proper screening in the removal and/or beach placement processes, the size range of sand placed on the beach areas can be controlled, and only material matching the desired size range i.e. fine sand (e.g. 0.064mm - 1 mm) would be placed on the beach.

It is anticipated that in the sub-surface areas where there was artificial removal of sand, this perturbation would have only minimal effects on the general river-beach regime and thus not produce any significant 'additional' scour of existing beach material (assuming the material was not removed from the stabilizing 'toe' of the existing beach; and also that there would be a natural replacement of the material removed within a few weeks. As an example of the rapid adjustment rate of the river in this regard, recently a new rapid was formed by a debris flow into the channel, and within just a few weeks a new beach had been easily formed by the river utilizing a fraction of the sand being transported by the river through the main channel.

Finally, it might be noted that the healing processes, and infact the amount of exposed sand available along a reach should vary with the cummulative lateral sand input to a given location. Thus, it would be expected that along the reach upstream from the Litte Colorado River, there would be less exposed sand along the channel, and the 'healing' process following artificial sub-surface sand removal would be slower than along the downstream reach below the Little Colorado River.

III. APPROACH:

1) Assumptions -

A) At present the sand inputs to the Colorado River along the Grand Canyon are primarily determined (about 90%) by the annual inflows of the two primary lateral tributaries - the Paria River at Lees Ferry, and the Little Colorado River located about 1/3rd of the way down stream along the 220-mile reach.

B) Except for short periods of bed elevation readjustments, essentially all of the lateral sand inputs are transported through the Grand Canyon and deposited in Lake Mead.

C) Due to the large flood flows in 1965-66, and 1983-86 the bed 'armoring' layer in the pools and backwater areas is below the surface of the bed which has generally been backfilled with sand in these areas, since shortly after the flood peaks.

D) Annual variations in the sand inputs which are probably closely correlated, and can vary 5-times or more, from one year to another.

E) Target beach requirements for size and long-term stability will not require that more than at most a few tens of thousands of tons per year of artificial nourishment.

F) Annual sand supplies from lateral tributaries are more than sufficient to provide sand requirements for NPS target-beach nourishments.

G) With estimated mean annual values of sand input in the range 750,000 tons (Paria sub-reach), to between 2,000,000 and 2,500,000 tons below the Little Colorado River, it is assumed that as much as several tens of thousands of tons of sand could be removed from the channel and placed on the beaches without significantly altering channel bedload transport processes, since at present there are ongoing 'natural' cycles of scour and aggradation in these areas with fluctuations in sand inputs and dam discharges, and evidence indicates that artificial removal quantities would be replaced through riverine sedimentation processes typically within a few days or weeks.

H) So long as dam discharge is maintained signifcantly below the 1983-86 peak discharge levels, there will be 'harvestable' sand in pool and backwater areas; however, these exposed sand sources will be largest in years when dam discahrges are lowest, and lateral-tributary sand inputs are largest i.e. dry years on the upper Colorado sub-basin and wet years on the lower Colorado sub-basin.

I) It is guestimated that along the Grand Canyon, there are channel sand sources in pool and backwater areas which can provide sufficient (recurring) quantities of fine sand suitable for beach nourishment, to meet NPS objectives for target beach size and long-term stability.

J) It is feasible, using existing equipment (sonar, and bed sampling) to identify potential sand source areas in the vicinity of target beaches.

K) It is feasible, using existing equipment (i.e. pumps that can be transported and operated on rubber rafts, boats, tubes, inlets and outlets) to pump sand from pool and backwater areas onto nearby beach areas, at moderate economic costs.

2) Application -

A) Field test/evaluation of sand source mapping techniques/equipment, and sand pumping operations [This Proposal]

B) Official identification of NPS target beach locations and annual artificial sand nourishment requirments [Not included in this Proposal]

C) Purchase/Procurement of Equipment/Personnel for full implementation of sand-pump beach nourishment program in the Grand Canyon [Not included in this Proposal]

IV. JUSTIFICATION:

Justification for this proposed approach to artificial beach nourishment is based on consideration of environmental and economic factors. Benefits of this approach over alternative approaches include:

1) Environmental -

A) Utilizes native sand, no possibility of introducing additional undesireable contaminants, or changing riverine sand regime significantly,
B) Does not require +40,000-cfs periodic flood pulse to nourish beaches,
C) Provides for 'rifle' approach to beach nourishment, with controlled (surgical) placment or sand for predictable beach characteristics; rather than 'shotgun' approach which gives hit-and-miss results
D) Low-profile program which requires no large or permanent construction type activities anywhere in the canyon

2) Economic -

A) Inexpensive (<25,000) field test/evaluation prior to final decision for program inplementation
B) Initial full-program implementaion costs of 1/10th-1/100th compared with alterative approaches i.e. $100,000-$200,000.
C) Annual full-program operation costs of 1/10th-1/100th compared with alternative approaches i.e. $100,000-$200,000.
D) With minimum economic investment and no permanent construction requirments, this approach offers (NPS) maximum flexibility with regard possible future changes in basic overall approach e.g. discontinuance if long-term beach stability is obtained in 5-10 years, or augmentation with additional river sand input program if available sand sources are insufficient for future beach nourishment requirements.

V. ALTERNATIVE METHODS OF TEST/EVALUATION:

There are different approaches to specific test and evaluation of the sand-pump idea. In the following, three alterantive approaches are sketched. The basic differences of these alternatives are: a) scale of the sand-pump operation considered, b) the scale of the test program, and c) the size of the individual steps in the evaluation program. With Method A, primary objectives are to test feasibility and effectiveness of a small-scale sand pump operation, gradually building up to a specific target beach prototype test in the Grand Canyon, with small indivudual steps which would allow for review and evaluation and decision making regarding the next step at each step in the processes. With Method B, the objective would be to use moderate sized sand-pump equipment with the same step by step evaluation up to a prototype test on one specific beach to be designated by the NPS; and with Method C, the objectives would be to utilize the same equipment as Method B, but with a basic 1-step test and evaluation processes, at multiple (10-12) target beaches. Specific procedures in each of these three alternative approaches might include:

1) Method A: (Small-Scale, Small-Step Test/Evaluation) -

There are four specific steps in assessing the capability of this proposal.

A) Reconnaisance of exposed sand layer above Paria Riffle near Lees Ferry utilizing (BOR, Denver) Underwater Television Camera, small (BOR, Provo) bed material grab or penetration samplers, or commercial Sonar, in January or February, 1991

B) Rig up 'sand-pump' equipment (5-hp gasoline engine/pump, 2-3 inch reinforced rubber hoses, with inlet (no-clog, smooth sand feed) head and outlet head (e.g. burlap bag), and test in (BOR, Provo) tank during January and February, 1991

C) If Reconnaisance identifies exposed sand layer, conduct prototype test at Lees Ferry, by mounting sand-pump on (BOR, Provo, 22-ft hard-bottom motor boat, and pumping sand (less than 100 cyds) from the bottom above the Paria Riffle near the USGS Gaging Station, and placing this sand on nearby beach; during March or April, 1991

D) If prototype testing at Lees Ferry confirms the basic feasibility of sand-pump beach renourishment, a prototype demonstration will be conducted at one of the beaches that may be later targeted for program remediation. In this demonstration the sand-pump apparatus will be mounted in a motorized rubber raft, which will be floated down the river to the demonstration beach area; during May or June, 1991

E) ESTIMATED COST: $10,000

2) Method B: (Medium-Scale, Small-Step Test/Evaluation) -

Again, there are four specific steps in assessing the capability of this proposal.

A) Reconnaisance of exposed sand layer above Paria Riffle near Lees Ferry utilizing (BOR, Denver) Underwater Television Camera, small (BOR, Provo) bed material grab or penetration samplers, or commercial Sonar, in January or February, 1991

B) Rig up 'sand-pump' equipment (50-100 hp gasoline engine/pump, 4-6 inch PVC tubing), for field test/evaluation, during January and February, 1991

C) If Reconnaisance identifies exposed sand layer, conduct prototype test at Lees Ferry, by mounting sand-pump on commercial (e.g. CROSS Marine Consultants, Provo) rubber raft and pumping sand (less than 100 cyds) from the bottom above the Paria Riffle near the USGS Gaging Station, and placing this sand on nearby beach area; during March or April, 1991

D) If prototype testing at Lees Ferry confirms the basic feasibility of sand-pump beach renourishment, a prototype demonstration will be conducted at one of the beaches that may be later targeted for program remediation. In this demonstration the sand-pump apparatus will be mounted in a motorized rubber raft, which will be floated down the river to the demonstration beach area; during May or June 1991

E) ESTIMATED COST: $20,000

3) Method C: (Medium-Scale, Single-Step Test/Evaluation) -

There is just one step in assessing the capability of this proposal.

A) Contract with commercial company (CROSS Marine Consultants, Provo) for bed-reconnaisance/sand-pump test and evaluation at 2 or 3 possible target beaches; for verification of suitable sand source areas, and field test of sand-pump procedures and efficiencies; during May or June, 1991

B) ESTIMATED COST: $25,000

The prototype-demonstration test site(s) may be chosen from one of the following sites which have been unofficially selected as candidates for the target beach program:

Designation	Location
Anasazi Bridge	43.0 Left
Upper Kwagunt	55.6 Right
Cardenas Creek	70.0 (?) Left
Lower Canyon	194.0 Left
Supai Gorge	19.1 Left
Clear Creek	84.0 Right
Last Chance	155.6 Right
Second Last Chance	158.3 Right
Lower Marble Canyon	51.5 Left
Forester Camp	122.6 Left
Lower Canyon	207.0 Left
Buck Farm Canyon	41.0 Right
Soap Creek	11.0 Left
Upper Hermit Strip	94.9 Left or Right
Upper Granite Gorge	103. Right
Lower Granite Gorge	224.8 Right

VI. LOGISTICS:

1) Personnel -

All reconnaisance or test/evaluation activities associated with this proposal or any of the three alterative Methods identified, will allow for office and on-site over-viewing by National Park Service personnel, and Bureau of Reclamation personnel, in addition to whatever technical personnel from NPS and BOR, are utilized along with possible commercial company personnel, for actual work-tasks associated with field operations.

2) Equipment (general listing, not complete) -

A) Undervater TV Camera [UC Geology Division]
B) Underwater Drop Tube Bed Material Sampling Tubes
C) Portable shallow-water Sonar Unit
D) Suction Hose including head
E) Portable Sand/Water Pump
F) Delivery Hose including low-velocity discharge head
G) Utah Projects Office: Ekman Dredge sampler
H) Utah Projects Office: Drop-tube core sampler
I) GENFLOW Jet Pump

3) Time Period:
A) January through June 1991

4) Cost: $10,000 - $25,000*

* Specific costs depend on which Method is chosen.

VII. FINAL REPORT:

The final report, to be included with the reports for other structural and "mitigation" measures will be used as a basis for analyzing the merits of this element in the alternatives. The final report will identify the feasibility of this type of beach restoration measure and make recommendations pertaining to full-implementation of this programm, for target beach nourishment throughout the Grand Canyon.

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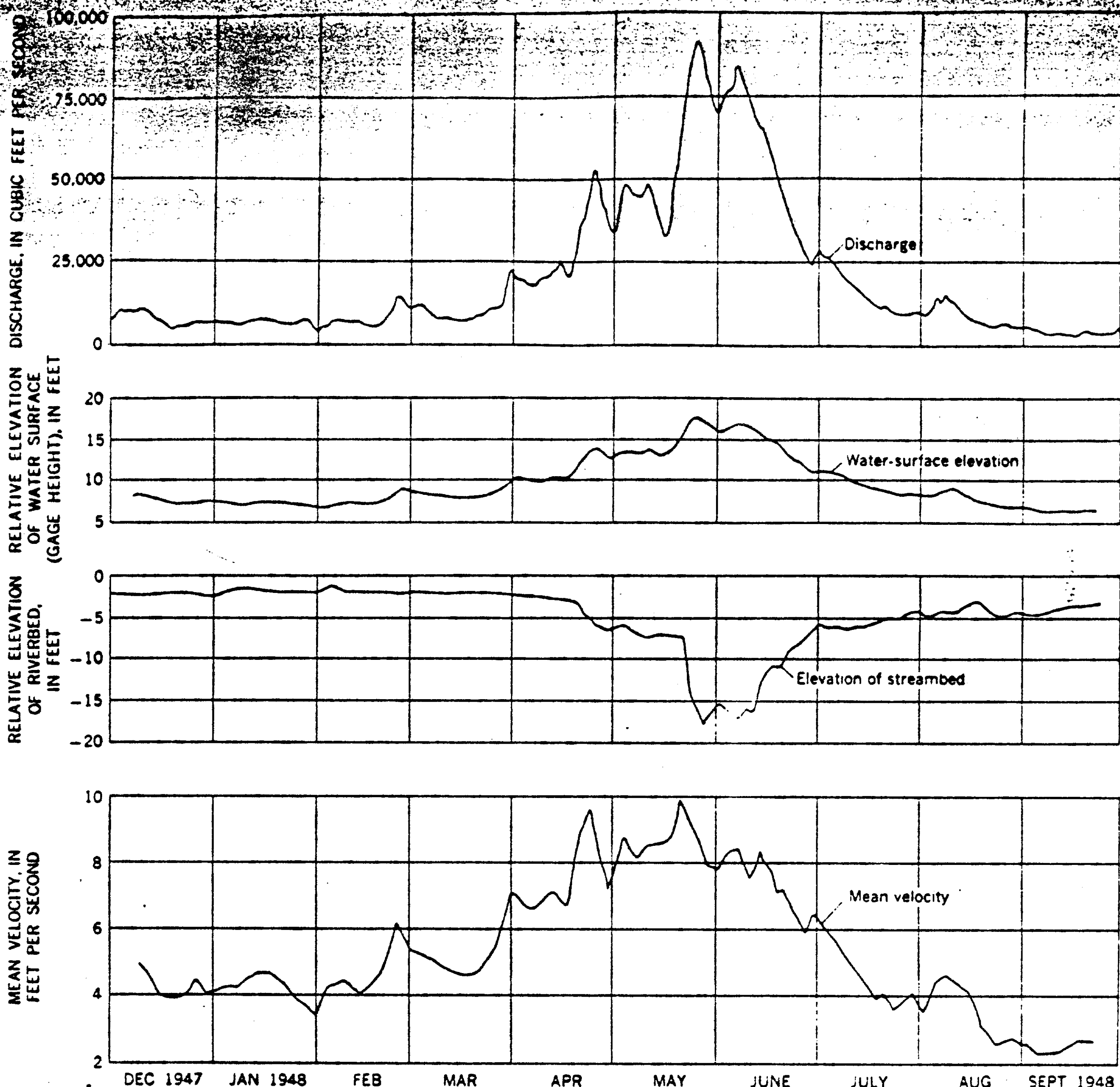


FIGURE ~~26~~ A.—Changes in discharge, water-surface elevation, bed elevation, and mean velocity during a 10-month period at the Lees Ferry measuring station, Colorado River. Note that the streambed had been scoured 16 feet between mid-April and late May as the discharge increased. (after Leopold, 1969)

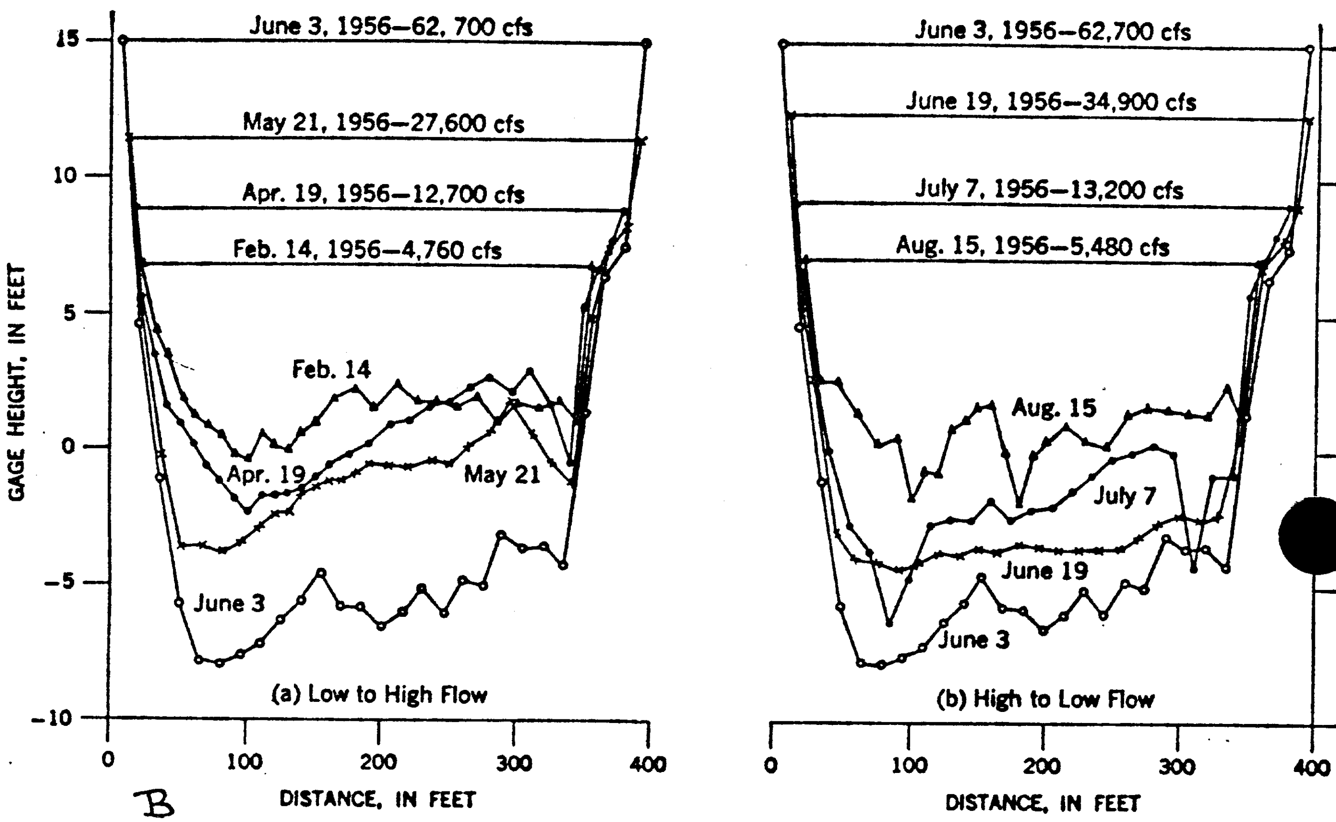


Figure ~~7-15~~ B. *Scour and subsequent fill during flood passage, Colorado River at Lees Ferry, Arizona, water year 1956.* **A.** *Low to high flow.* **B.** *High to low flow.* (after Leopold, 1965)

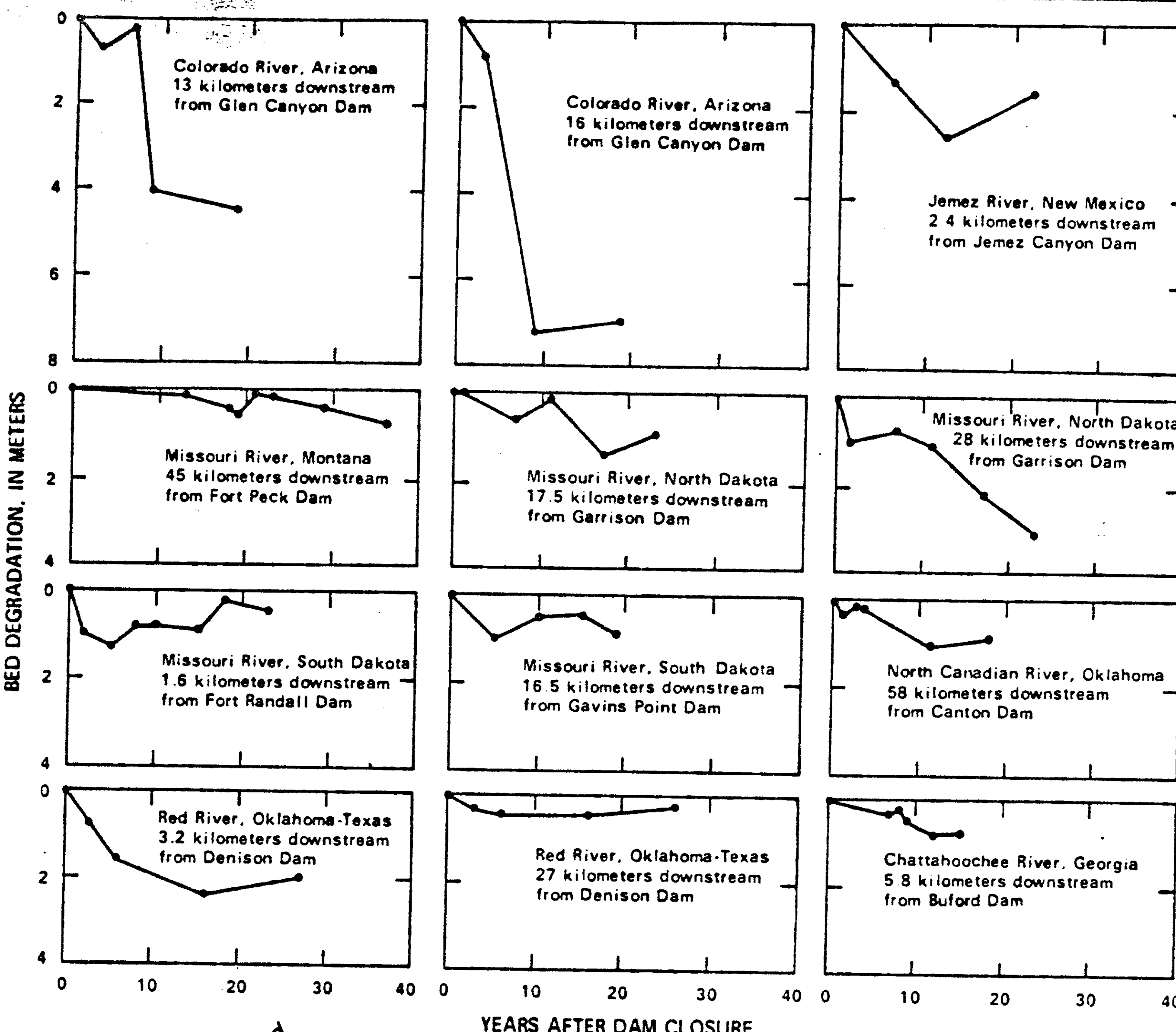


FIGURE c.—Examples of irregular rates of bed degradation with time. Data from table 13.

(after Williams and Wolman, 1984)

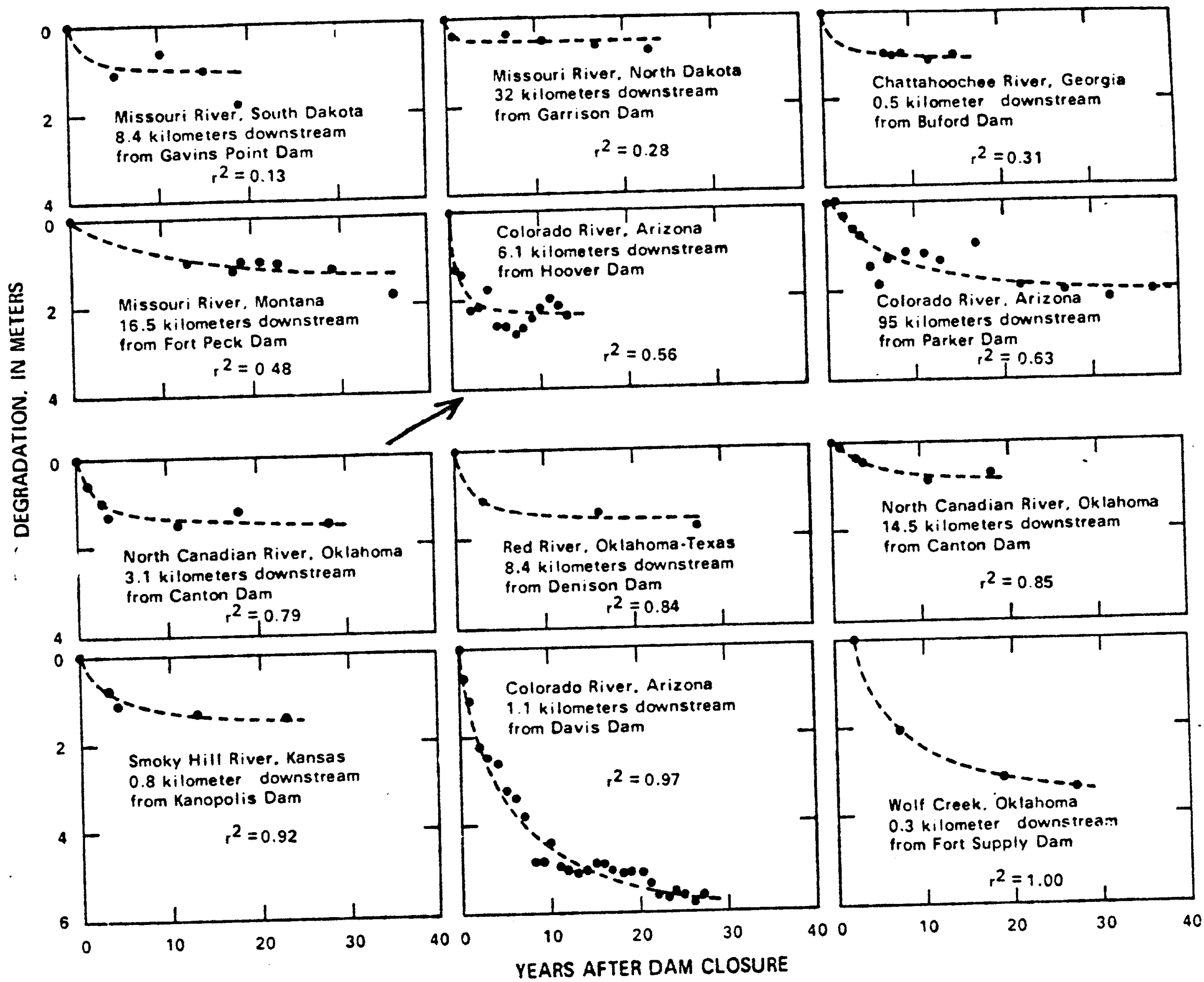


FIGURE ~~9~~ D.—Representative regression curves (dashed lines) of bed degradation with time at selected sites. Data from table 13.
(after Williams and Wolman, 1984)

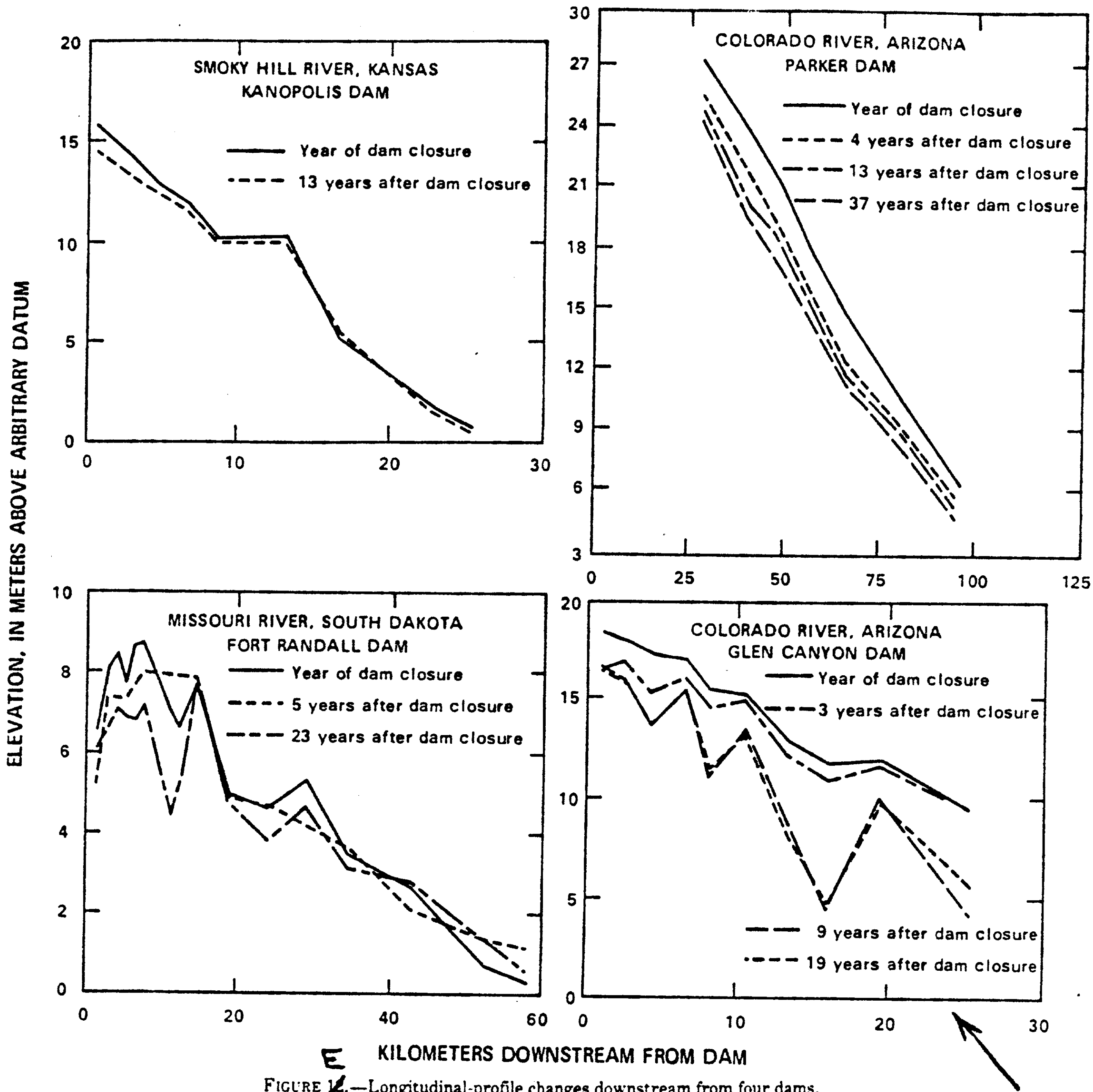


FIGURE E.—Longitudinal-profile changes downstream from four dams.
(after Williams and Wolman, 1984)

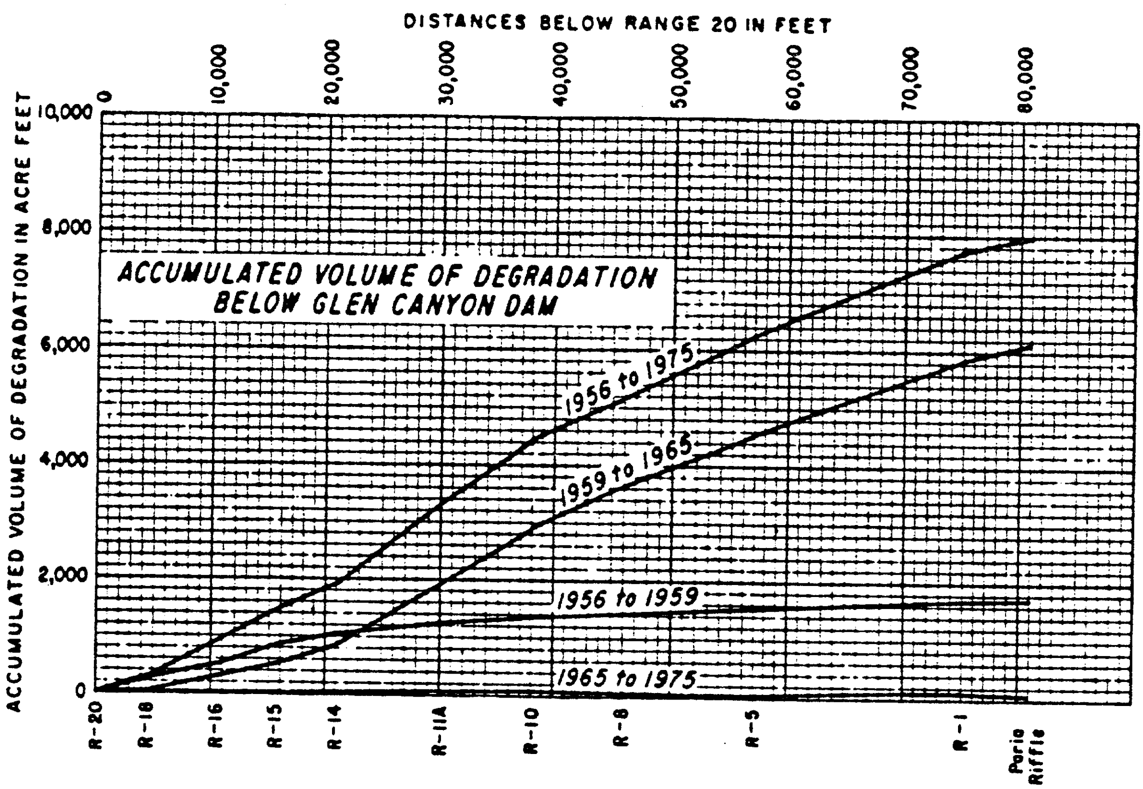


FIGURE F

(after Pemberton, 1976)

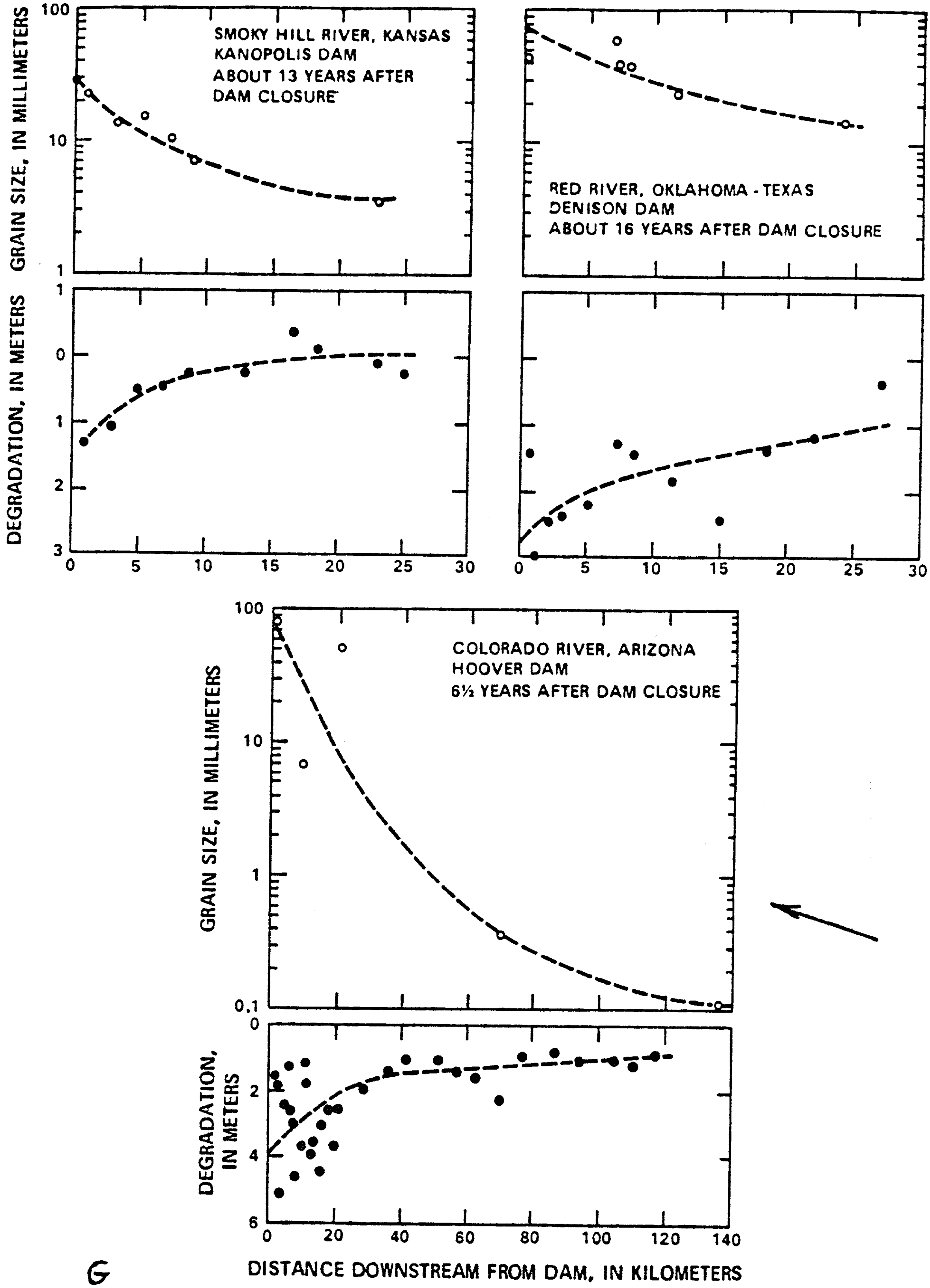


FIGURE 14.—Variation in bed-material diameter and bed degradation with distance downstream, at a given time after dam closure. Smoky Hill and Red River data are median diameter from pebble counts on gravel bars; Colorado River size data are d_{50} for entire sample of sieved bed material. Degradation data are from table 13.

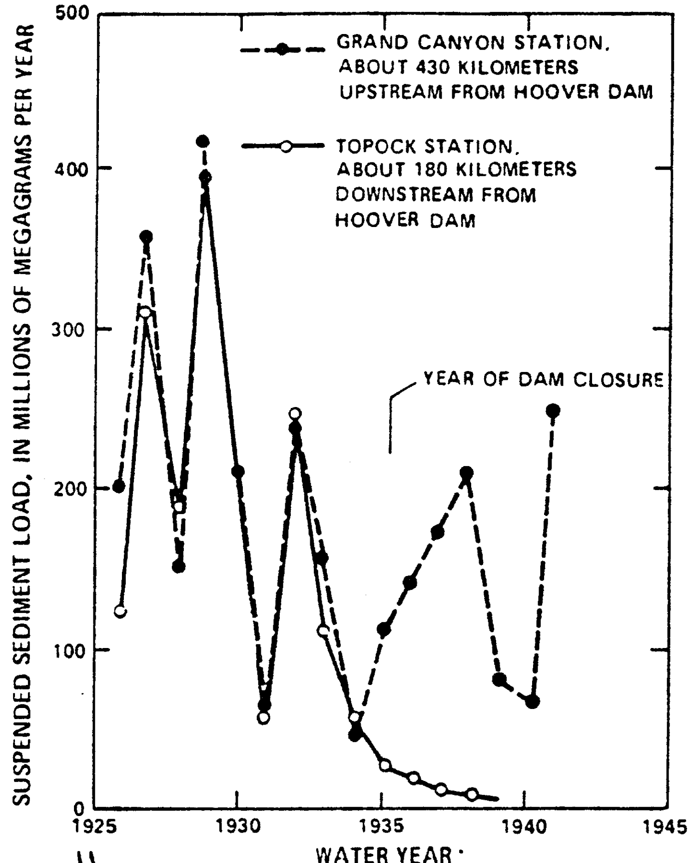


FIGURE ~~7~~ H.—Variation in annual suspended-sediment loads before and after closure of Hoover Dam, Colorado River, Arizona, at a station upstream from the dam (Grand Canyon) and downstream from the dam (Topock). (after Williams and Wolman, 1984)

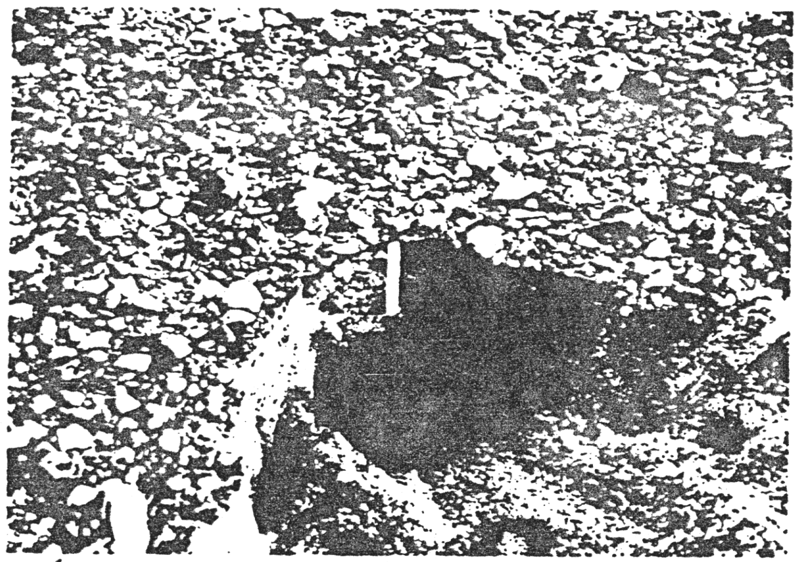


FIG. 2.87.—Armored Bed of Missouri River below Fort Randall Dam in 1962 (Livsey, 1965) (Scale in Picture is 6 in. Long; Flow is toward Lower Left Corner of Picture)

I

(after Vanoni, 1975)

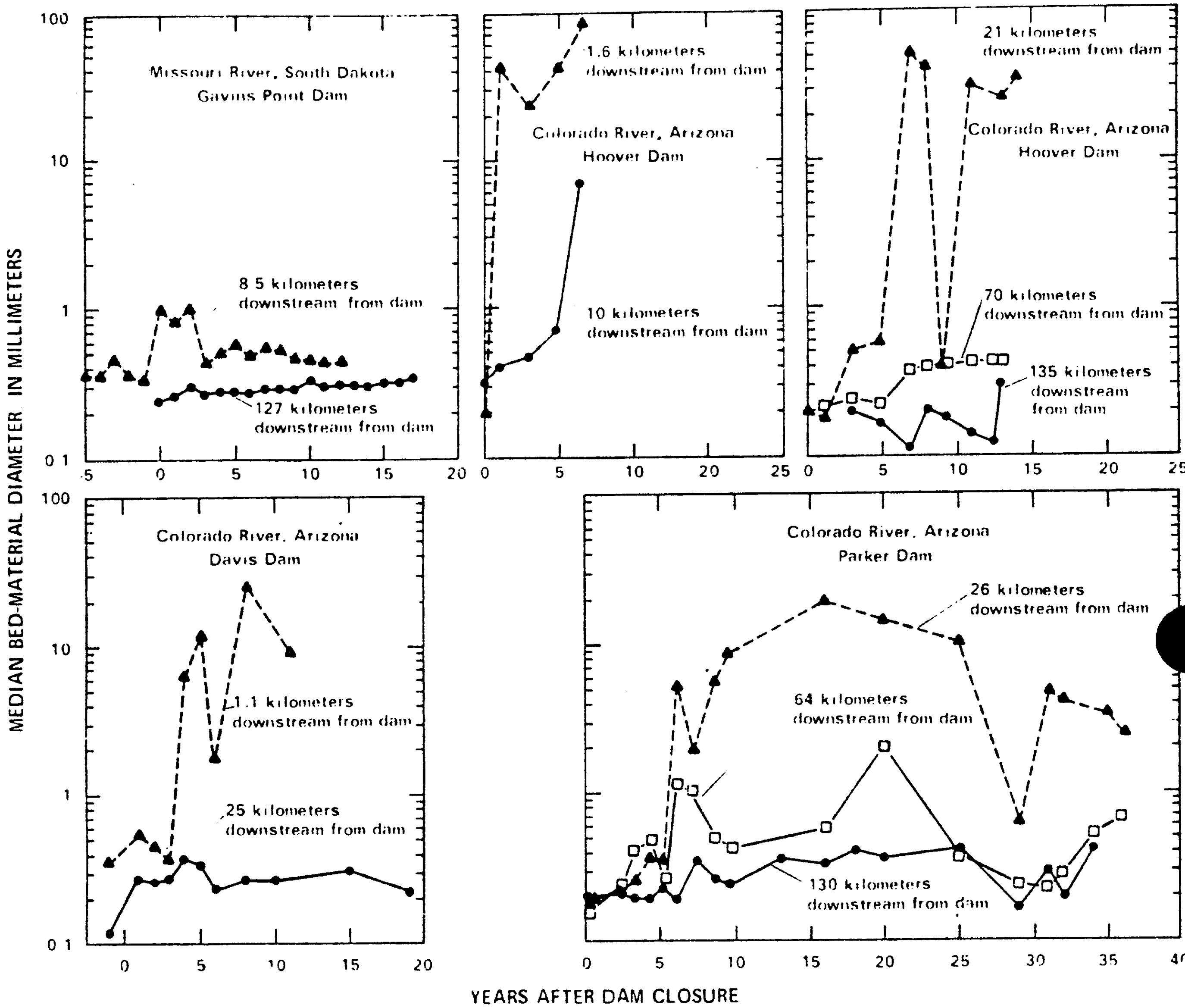


FIGURE J.—Variation in bed-material size with time at a site, after dam closure.
(after Williams and Wolman, 1984)

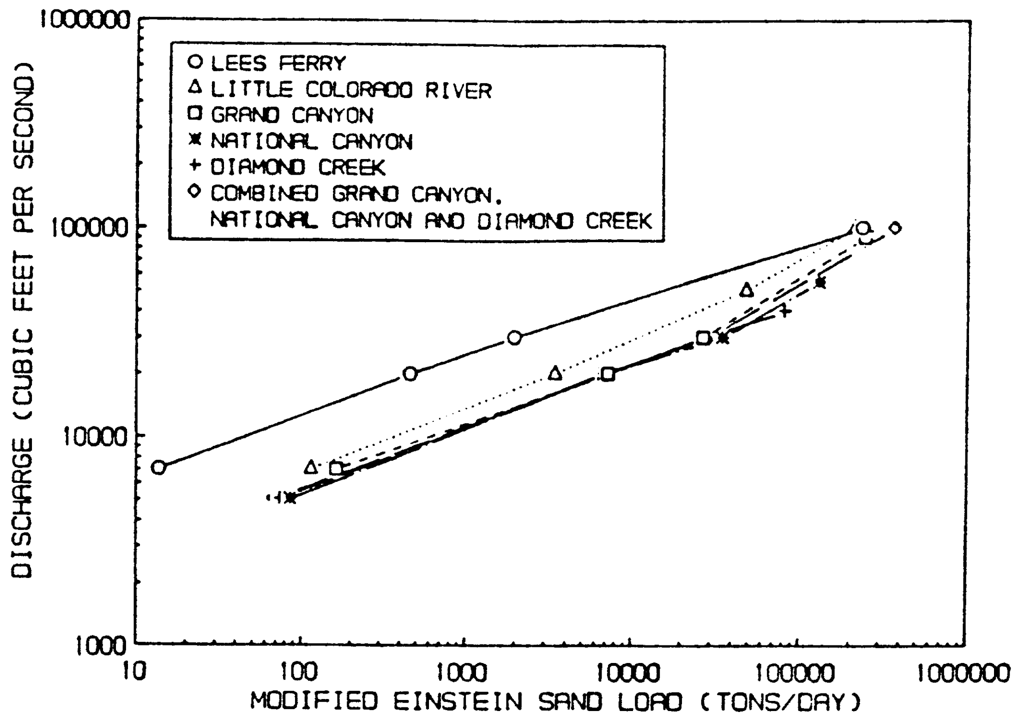
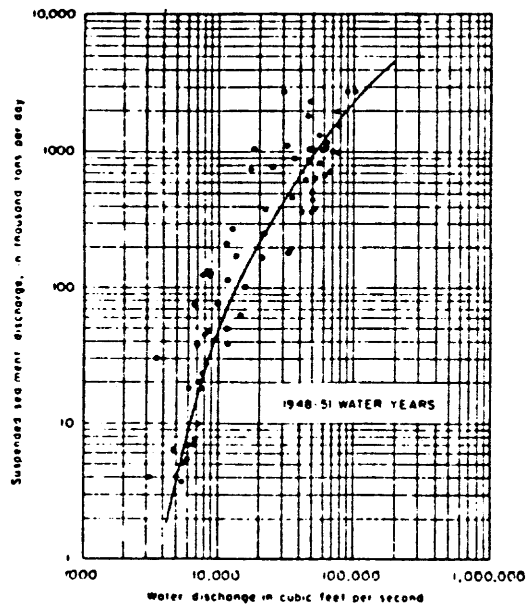
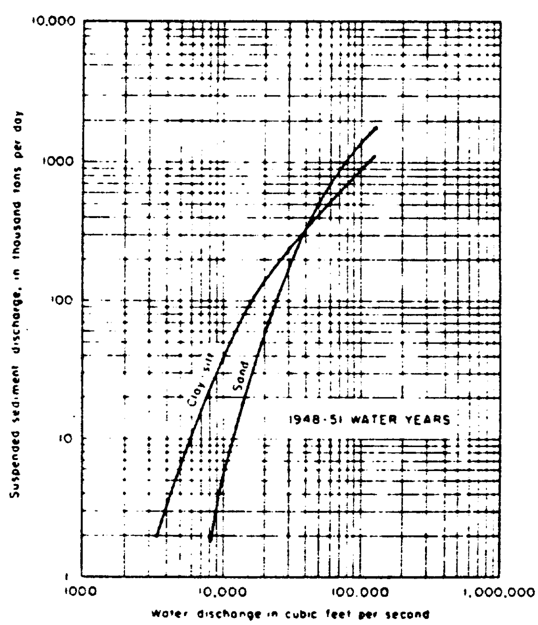


Figure ~~3~~ K. Modified Einstein sand load rating curves, Colorado River in Grand Canyon. (after Pemberton, 1988)



L-1

FIG. ~~3.28~~.—Suspended-Sediment Transport Curve, Colorado River near Grand Canyon, Arizona (after Vanoni, 1975)



L-2

FIG. ~~3.29~~.—Suspended Clay-Silt and Sand Transport Curves, Colorado River ne: Grand Canyon, Arizona (after Vanoni, 1975)