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ON SEDIMENT TRANSPORT THROUGH THE GRAND CANYON

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ABSTRACT

With the closure of the Colorado River by Glen Canyon Dam, both the amount and the nature of the sediment movement through the Grand Canyon has changed. At present, the mean annual capacity of the river to carry beach-building material is about 12 million metric tons per year. The tributaries supply about 2.7 metric tons of beach-building sediment per year. The difference of about 9 million metric tons per year must be obtained through scour of bed and/or banks. It is estimated that without remedial measures it may take somewhat more than 200 years before the beaches and sand bars between Glen Canyon Dam and Lake Mead disappear.

THE PROBLEM

With the closure of the Colorado River by Glen Canyon Dam, both the amount and the nature of the sediment movement through the reach from Glen Canyon to the headwaters of Lake Mead changed. In the past the flow of the Colorado was characterized by long periods of low flow and by floods of varying magnitude and duration. Most of the sediment load over a year was moved during the flood period; and the amount was a function of the flood magnitude, the flood duration, and the composition of the sediment supplied to the stream from the watershed. Table I shows the yearly water discharge and sediment load at Lees Ferry and Grand Canyon. The Lees Ferry gaging station is 26 kilometers (16 miles); the Grand Canyon station 167 kilometers (104 miles), and the headwaters of Lake Mead, about 480 kilometers (300 miles) downstream from Glen Canyon Dam. The major tributaries below Glen Canyon are the Little Colorado River and Paria River; their flows and loads are shown in Table II. It is probable that the minor tributaries below Lees Ferry add to the Colorado considerably less sediment than the two major tributaries. Although high water years in general move more sediment than low water years, annual discharge alone is not sufficient to allow the prediction of the load.

Figure 3 shows the relationship between the instantaneous discharge and load; the scatter is correlated, more or less, with the percent of the suspended load finer than 0.016 mm. The scatter is great: For a discharge of 300 m^3/sec (10,000 cfs) the sediment load can be anything from 27,000 to 1,350,000 metric tons per day (30,000 to 1,500,000 tons) and the size distribution of the sediment is the primary factor in the scatter. Other factors are the variations in the flow characteristics and the temperature of the water.

Lake Powell behind Glen Canyon Dam is a regulating reservoir for the flow and a trap for the sediment load from the upper basin. Essentially all the flow at Lees Ferry, 98 percent of the flow at Grand Canyon, and 97 percent of the flow entering Lake Mead from the Colorado are released from Lake Powell in a

TABLE I

Measured Yearly Discharge and Sediment Load
of the Colorado River at Lees Ferry and Near Grand Canyon

	LEES FERRY		GRAND CANYON	
Water Year	Average Discharge Cubic Meters per Second	Suspended Sediment Million Metric Tons	Average Discharge Cubic Meters per Second	Suspended Sediment Million Metric Tons
1948	534	99.5	542	131.0
1949	560	87.8	561	108.0
1950	432	48.5	433	54.1
1951	384	43.4	385	44.1
1952	703	104.0	710	135.6
1953	344	37.6	347	44.2
1954	239	31.3	244	37.0
1955	285	52.5	296	75.5
1956	342	46.0	347	69.0*
1957	677	109.0	685	141.0
1958	565	102.0	570	120.0*
1959	264	14.4	272	22.2*
1960	359	25.4	374	36.0
1961	260	35.8	275	42.5
1962	577	56.7	595	77.5
1963	98	14.0	107	18.3
1964	95	4.0	106	18.5
1965	424	5.4	430	36.0
1966			326	8.2
1967			323	21.2
1968			350	14.8
1969			464	13.1

* Estimated

regulated, non-natural pattern. Since Lake Powell traps all the sediment delivered to it, very little sediment is now supplied to the river between Glen Canyon Dam and Lees Ferry. The small sediment load moving past Lees Ferry now is coming largely from the bed and banks in the reach between Glen Canyon Dam and Lees Ferry. Eventually the flow past Lees Ferry will be almost always clear, as the bed, banks and beaches are swept away or gradually armored through self sorting, leaving a natural riprap protecting the surface.

Because the sediment supplied to the flow past Lees Ferry most of the time will be zero, there will be general degradation in the reach above; and it is

TABLE II

Measured Yearly Discharge and Sediment Load of the Paria River at Lees Ferry and the Little Colorado River Near Cameron

	PARIA RIVER AT LEES FERRY		LITTLE COLORADO NEAR CAMERON	
Water Year	Average Discharge Cubic Meters per Second	Suspended Sediment Million Metric Tons	Average Discharge Cubic Meters per Second	Suspended Sediment Million Metric Tons
1948	0.75		7.86	4.03
1949	0.77	1.96	11.22	12.95
1950	0.53	1.31	1.84	2.92
1951	0.54	1.38	1.96	4.51
1952	0.74	1.80	13.77	17.30
1953	0.70	4.14	2.40	3.77
1954	0.61	2.09	4.25	8.24
1955	0.69	3.92	7.65	20.20
1956	0.39	0.95	0.76	1.83
1957	0.65	2.91	6.85	9.93
1958	1.54	10.20	6.55	10.40
1959	0.54	2.52	2.01	6.21
1960	0.41	0.37	7.59	8.01
1961	1.21	11.80	1.51	3.18
1962	0.59	1.89	6.17	5.31
1963	0.78	5.40	3.30	9.82
1964	0.52	1.15	6.69	15.58
1965	0.60	1.23	8.82	8.76
1966	0.63	1.22	7.92	9.59
1967	1.02	5.15	7.45	17.31
1968	0.93	6.21	8.35	8.64
1969	1.04	3.50	5.46	7.81

the competence rather than the capacity of the stream, in respect to sediment movement, which is of interest. In the next reach down to Grand Canyon it is the comparison between capacity to transport sediment and sediment supplied by the tributaries which is of interest. If the capacity exceeds the supply, there will be general degradation and a tendency to enlarge the stream until the reduced capacity equals the supply. If the supply should exceed the capacity, there will be a tendency to aggrade until a smaller, swifter stream is formed with a capacity equal to the supply. In the reach below Grand Canyon and above Lake Mead there should be a smaller tendency to degrade, mainly because the attenuation of the surges in the releases from Glen Canyon reduces the capacity to transport.

THE ANALYSIS

In order to explain the variability of the sediment load, a sediment-transport relationship was needed which would predict the sediment concentration and composition as a function of the flow, the cross section of the stream, and the composition of the bed material. For obvious reasons - nepotism and solidarity - the Laursen relationship was chosen (Laursen, 1958). Zernial has demonstrated that this relationship is capable of explaining the commonly encountered scatter of the sediment load versus discharge plot (Zernial, 1963).

In applying the relationship to the gaging stations at Lees Ferry and Grand Canyon, the cross section was divided up as it was when gaged by the U.S. Geological Survey; and the measured depth and velocity for each subsection were used in the computations. The temperature was always assumed to be 11°C (51.8°F), and the fall velocity of the sediment was taken as that of a quartz sphere. The slope at Lees Ferry was taken as 0.00028 and the slope at Grand Canyon as 0.00063. The sediment load of the subsections was combined for a value for the entire section. Using the measured bed material samples, the concentration computed was less than the measured suspended load concentration, and the composition of the computed suspended sediment was coarser than that measured.

It is very difficult to obtain a true bed material sample; the presence of the sampler near the bottom can cause high velocities at the bed which remove the fine particles before the sampler can take the sample. Therefore, small amounts of fines were arbitrarily added to the measured bed material and the computations were repeated. Reasonably close agreement was then achieved for both the concentration and composition of the suspended load. Since the suspension tended to be largely fine material not found in the bed material samples, it was concluded that the imagined bed material was closer to correct and that the Laursen relationships would probably describe the sediment-transporting characteristics of the stream reasonably well.

As is shown in Figure 1, the size composition of the beach material collected during a reconnaissance trip down the Colorado River by the principal investigators was remarkably constant all the way from Lees Ferry to Diamond Creek. Several bottom samples obtained during the same trip were also quite uniform as shown in Figure 2. Although the bed material samples were obtained with a crude grab bucket, they gave a computed suspended sediment composition which could explain that of the beach material, and computed sediment loads along the low side of the scatter band of measured sediment load and discharge (Figure 3). The scatter of the computed points in Figure 3 is the result of channel instability in that actual velocities and depths were used from stream gaging records.

The computed beach-building suspended sediment load has a somewhat greater range of size variation than the beach sand, which is to be expected. The coarser fractions of the suspended load are in greater concentration near the bed than up toward the water surface; thus the coarser material tends not to be supplied to the deposition area of the beach. The finer fraction of the suspended load, on the other hand, does not tend as much to deposit in the eddy and is swept on away. Thus, it is the middle fraction of the suspended load which builds the beaches.

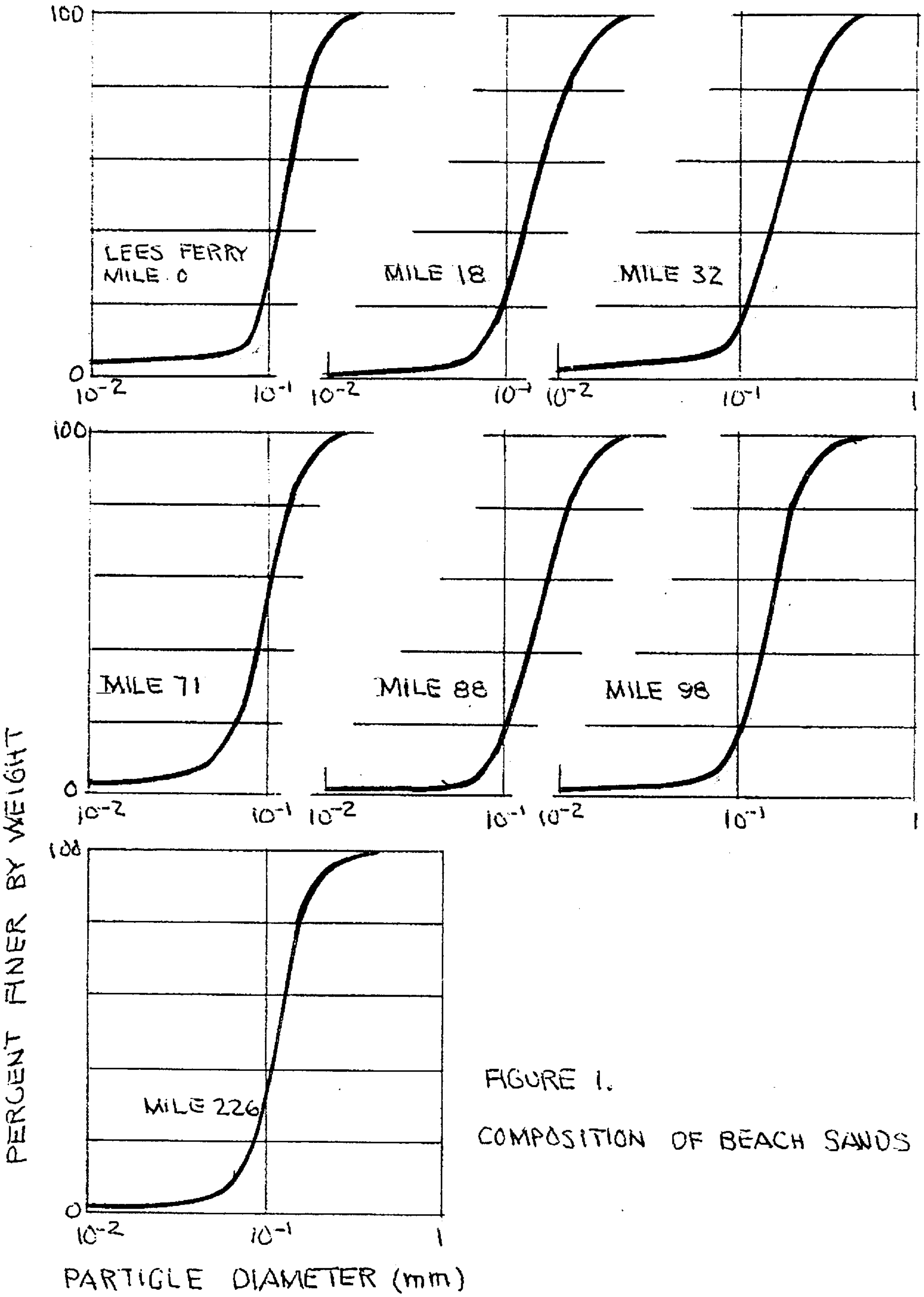

FIGURE 1.

COMPOSITION OF BEACH SANDS

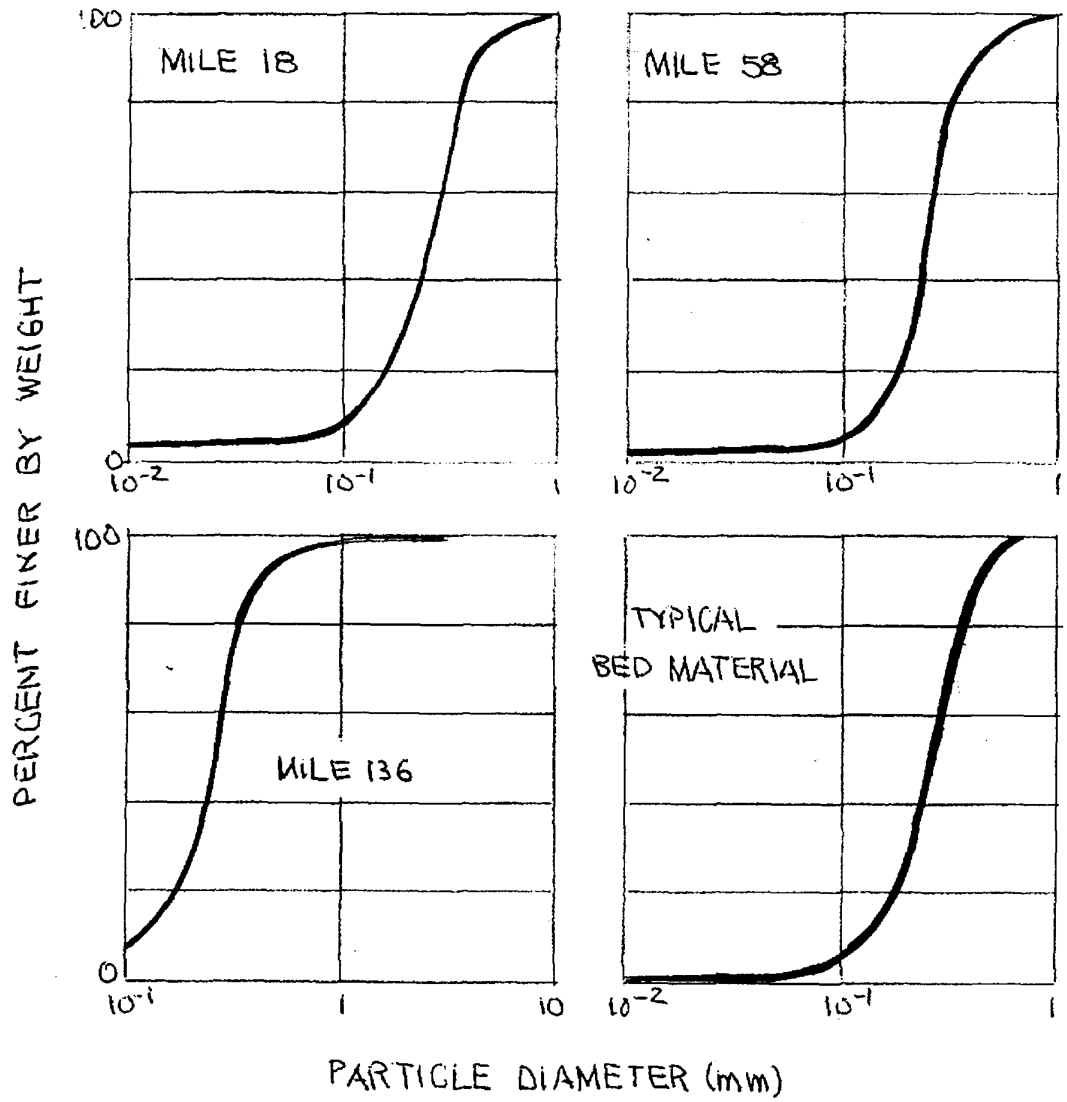

FIGURE 2. COMPOSITION OF BED MATERIAL

Straight lines were put through the computed beach-building sediment load points by eye in Figure 3, with some attention to the edge of the scatter band of the measured values. These relationships were then used to compute the annual beach-building sediment load past Lees Ferry and Grand Canyon as shown in Table III in which the annual load is the summation of the daily loads through the water year. In years without a large magnitude flood the load of beach-building material past Lees Ferry was greater than the load past Grand Canyon indicating that there was deposition between the two stations. However, over the 15 years used in the calculations, the amount of beach-building

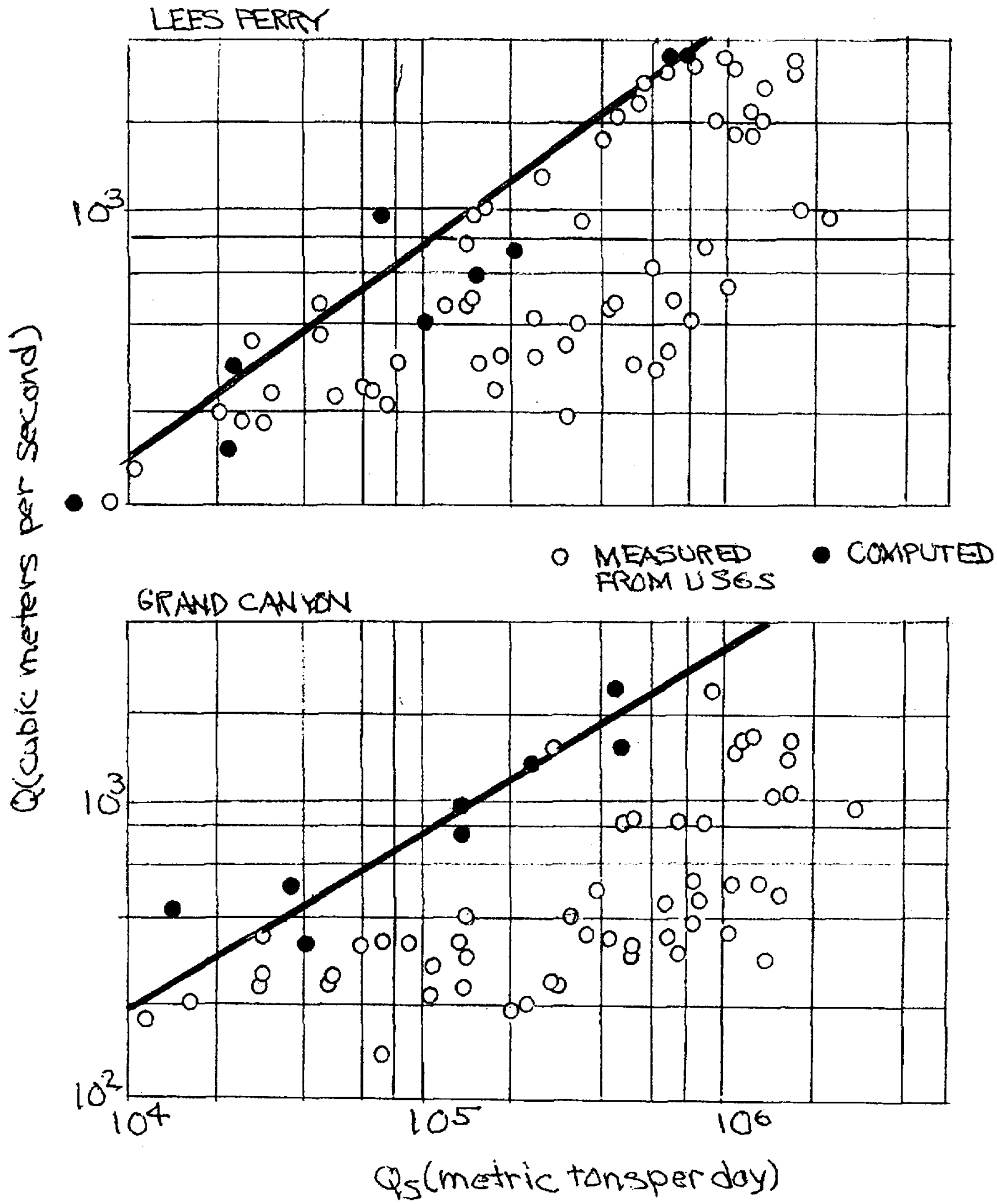

FIGURE 3. LOAD RELATIONSHIP FOR THE COLORADO RIVER

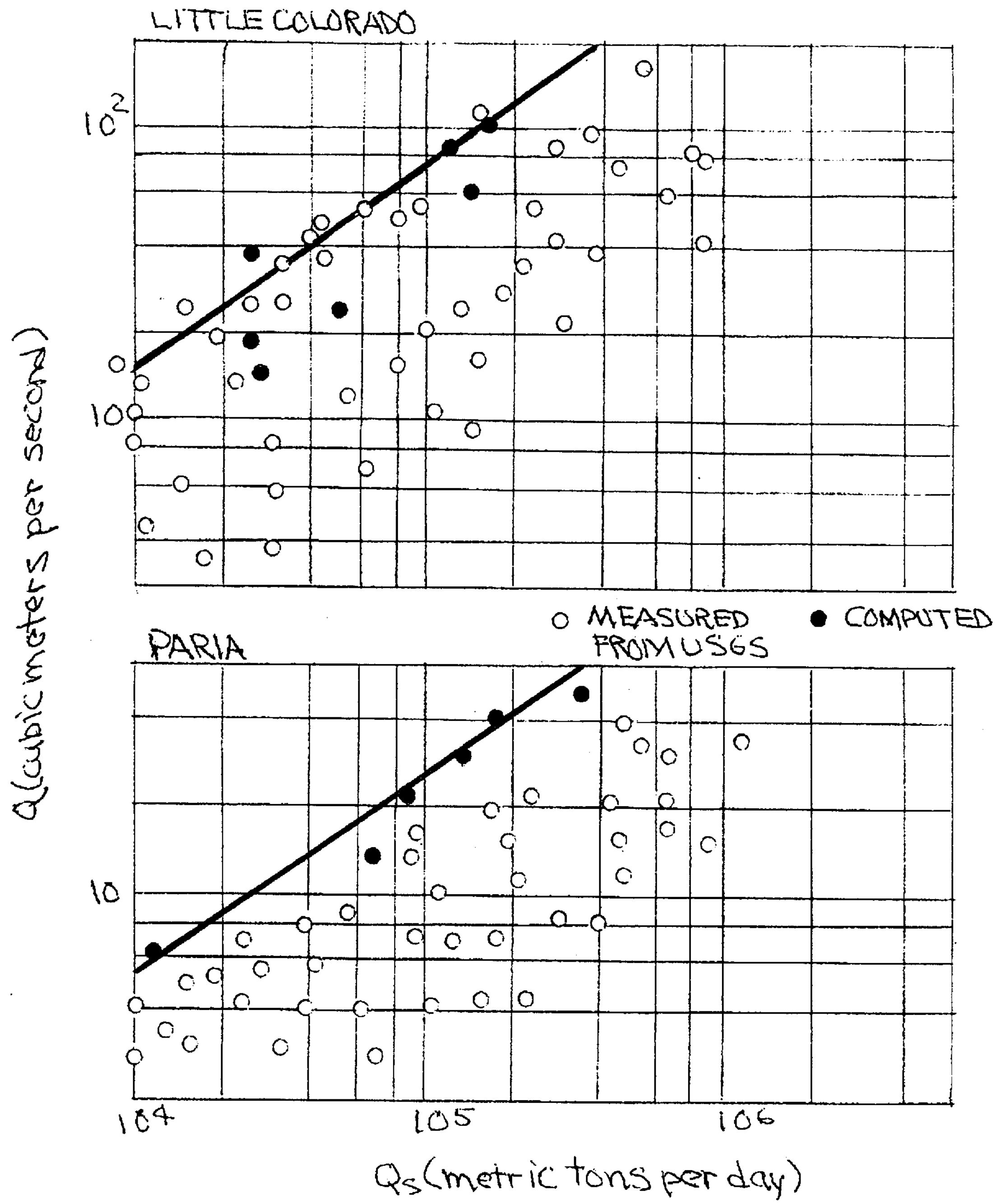

FIGURE 4. LOAD RELATIONSHIP FOR THE TRIBUTARIES

TABLE III

Computed Annual Beach-Building Sediment Load
for the Colorado River at Lees Ferry and Grand Canyon

Water Year	Lees Ferry Million Metric Tons	Grand Canyon Million Metric Tons
1948	29.3	32.1
1949	32.5	35.5
1950	21.2	19.9
1951	18.9	17.4
1952	45.3	55.5
1953	15.8	15.0
1954	8.8	6.8
1955	11.6	10.2
1956	16.5	16.2
1957	44.5	52.5
1958	32.3	38.0
1959	10.6	9.4
1960	16.5	16.0
1961	10.2	9.2
1962	32.1	35.6

material moving past Grand Canyon was greater than the amount moving past Lees Ferry. Presuming that over the 15 years the scour and fill compensate, the difference between the two stations would be the amount supplied by the tributaries in the reach between - especially the Little Colorado and the Paria. Similar computations were made for the Cameron station on the Little Colorado and the Paria station near the junction with the Colorado. Using the same bed material as before with slopes of 0.0049 at Cameron and 0.0042 at Paria, and the measured velocities and depths, the transport of beach-building material was computed. Computed and measured points are shown in Figure 4; straight lines were drawn in by eye through the computed points. These relationships for beach-building sediment load were used with the daily discharges for the Little Colorado and the Paria as shown in Table IV. The computed difference between Lees Ferry and Grand Canyon indicates that the tributaries supply about 1.8 million metric tons per year (2 million tons per year) of beach-building material; the computed loads for the Little Colorado and the Paria indicate that these two major tributaries add about 2.7 million metric tons per year (3 million tons per year). Further work is needed to refine these estimates, but for the moment it is sufficient to estimate that on the average the tributaries between Lees Ferry and Grand Canyon supply about 2.25 million metric tons per year (2.5 million tons per year) and that between Glen Canyon and Lake Mead the tributaries supply about 2.7 million metric tons per year (3.0 million tons per year) of beach-building material. Before Glen Canyon Dam much more fine material passed through the river, and even now somewhat more fine material is supplied; however, the

TABLE IV

Computed Annual Beach-Building Sediment Load
for the Little Colorado and Paria Rivers

Water Year	Paria Million Metric Tons	Little Colorado Million Metric Tons
1948	0.43	4.60
1949	0.35	3.24
1950	0.17	0.42
1951	0.28	0.93
1952	0.33	7.10
1953	0.43	0.61
1954	0.34	1.73
1955	0.37	3.80
1956	0.10	0.13
1957	0.33	2.58
1958	1.50	2.20
1959	0.26	0.58
1960	0.10	2.97
1961	1.42	0.32
1962	0.31	2.42

stability of the river is a matter not of the fine material but of the beach-building material.

Computations were made of the beach-building sediment load which could be carried by the regulated river for the three years 1967-68, 1968-69, 1969-70. Bi-hourly values were used to obtain a factor to account for the daily surge in the flow, and then daily values were used to obtain the yearly values. As shown in Table V the capacity for transport at Lees Ferry is slightly larger than for Grand Canyon (there are no more large floods), but they are both in the order of about 12 million metric tons per year (13 million tons per year). At Lees Ferry virtually all of this load must be made up from scour of the bed and banks between Glen Canyon Dam and Lees Ferry, if indeed there is sufficient supply left. Indications are, however, that very little beach-building material is moving past Lees Ferry. At Grand Canyon, some of the load is supplied by the tributaries - Paria and Little Colorado and a number of smaller ones - but about 9 million metric tons per year (10 million tons per year) must be obtained through scour of bed and/or banks.

As many of the banks of the Colorado River are characterized by shear rock walls 9 million metric tons per year represents a lot of material. There may be some self sorting so that the beaches gradually become paved with coarser material which cannot be moved as readily by the flow. However, there may also be a tendency for the pools to fill and for the flow to keep working on the beaches. The beaches are mostly in eddy zones before and after rock falls or large boulder deposits, and the erosive action of the flow on the beaches does not decrease a great deal as the beaches retreat.

TABLE V

Annual Beach-Building Sediment Load
of the Regulated Colorado River

Water Year	Lees Ferry Million Metric Tons	Grand Canyon Million Metric Tons
1968	12.6	11.2
1969	12.2	11.7
1970	13.2	11.4

THE PRELIMINARY CONCLUSIONS

Preliminary investigations show that the beaches of the Colorado River between Glen Canyon Dam and Lake Mead could be in danger of being washed away since the transport capacity of the regulated river is in excess of the amount of beach-building material being supplied from the tributaries in this 480 kilometer (300 mile) reach. How long they will last cannot as yet be estimated; certainly more than 10 years, probably less than 1000 years; but how much more or less than 100 years is a matter for continued study. However, it is possible to say that on the average the capacity of the Colorado River to transport beach-building material is about 12 million metric tons per year (13 million tons per year) at present, and the tributaries supply only about 2.7 million metric tons per year (3 million tons per year). Since the closure of the river by Glen Canyon Dam, no sediment is being supplied from the upper basin.

This general tendency for degradation may be alleviated to some degree if the river deposits (bed and beach) become self armored through coarsening by self sorting as the river degrades. However, there is very little coarse material in the beaches, so that they would probably continue eroding and become small vestiges of the present beaches which are now none too large.

On the other hand, with no floods in the regulated river there may be a tendency to fill the pools all along the reach. In that case the beaches would be in even a greater danger as all the capacity for transport would tend to be satisfied by erosion of the beaches. And as the pools fill, the velocities, and hence the shear on the banks, would tend to become greater.

POSTSCRIPT

During an inspection of the Colorado between Lees Ferry and Glen Canyon Dam in June of 1973 much evidence of bank erosion was apparent. Almost all of the talus slopes and beaches either had vertical slump faces or exposed rock protecting the underlying material. Some of the growth on the beaches undercut in the slumping of the banks was far older than Glen Canyon Dam. Most beaches left were in the lee of obstructions or other bank configurations giving rise to a lee eddy. Beaches upstream from the obstructions were either very small, and in an eddy zone or covered with self-sorted riprap. There were a few large sand bars off lee beaches which had reportedly been growing. The source of sand for these bars, however, was the lee beach itself which was eroding. Probably with the cutting back of the beach, the lee eddy became large enough so that a sand bar could build up in the central low velocity area. As the beach disappears, so will the sand bar. On the few sizable beaches left the "campsite" sign has had to be moved back several times as the beachline retreated.

The river bottom which was observable was mostly cobble and much of it was covered with moss. There were a few sand bars with ripples moving upstream on the bank half; these are probably temporary transitional features. In only one small area was there an active bed with dunes of coarse sand.

What has happened in this first 26 kilometer (15 mile) reach of the river below the dam is in conformity with the preliminary conclusions - that degradation can be expected through the Grand Canyon, that the beaches will gradually disappear, but that there may be some natural revetment by self-sorting in the erosional process and some vestiges of beaches may remain in the low velocity eddy in the lee of obstructions.

Since the closure of Glen Canyon Dam about 10 years ago, the degradation has progressed to the vicinity of Lees Ferry. Below Lees Ferry, the Paria and Little Colorado and other tributaries contribute their sediment load; therefore, the rate of degradation in the 480 kilometer (300 mile) reach to Lake Mead would be somewhat less than 26 kilometers (16 miles) per 10 years. Hence it may be somewhat more than 200 years before most of the beaches vanish.

ACKNOWLEDGEMENT

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