A STUDY OF CHANNEL EROSION AND SEDIMENT TRANSPORT

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A STUDY OF CHANNEL EROSION AND SEDIMENT TRANSPORT[a]

By Carl F. Nordin, Jr.[1], A. M. ASCE

Synopsis

Field observations of some aspects of channel erosion and of flow and sediment transport for a reach of the Rio Puerco near Bernardo, New Mexico, are given.

The Rio Puerco is an ephemeral stream which transports high concentrations of suspended sediment. At the initiation of the study, the bed of the channel was armored with a mixture of sand, silt, and clay, which limited the availability of sand for transport and provided a cohesive boundary for the flow. Subsequent channel erosion in the form of a head cut through the armored layer caused changes in the characteristics of the channel cross section and in the size distribution of the bed material and of the suspended sediment. Some of the factors influencing the rate of advance of the head cut are documented, the influence of high sediment concentrations on the vertical distributions of velocity and sediment concentration is discussed, and some examples of extreme concentrations are given.

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[a] Presented at the ASCE Hydraulics Division Meeting, University Park, Pa., August 7-9, 1963.

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Introduction

Ephemeral streams in semiarid regions carry extremely high concentrations of suspended material and deliver large quantities of sediment to the major water courses. The sediment loads from these streams often require consideration in the design of reservoirs, conveyance channels, water-treatment facilities, and related structures. The sediment loads of streams have been observed for many years, and something is known of the magnitudes of the loads carried by streams in semiarid environments; yet, the details of the mechanics of flow and sediment transport and of the erosional and depositional processes occurring within the ephemeral channels remain somewhat obscured.

In 1961, a study was initiated by the U. S. Geological Survey to investigate the flow and sediment transport in ephemeral streams with high concentrations of suspended fine material. It is the purpose of this report to summarize some of the information collected in 1961 and 1962 on channel erosion and sediment transport in a study reach of the Rio Puerco near Bernardo, New Mexico.

The Rio Puerco Drainage Basin and the Study Reach

The Rio Puerco, tributary to the Rio Grande in New Mexico, drains approximately 6,200 square miles (Fig. 1). Elevations in the basin range from 4,700 feet above mean sea level near the confluence with the Rio Grande to about 10,000 feet near the headwaters. Rainfall varies roughly with altitude. The average annual rainfall ranges from 20 inches or more in the headwaters to less than 10 inches over a major portion of the basin.

In the past, some irrigated agriculture was practiced in the Rio Puerco Valley. In more recent times, the major land use has been for raising cattle and sheep. Vegetation is sparce, consisting mostly of pinon, juniper and rough range grasses.

Large quantities of readily erodible sediments are available over much of the watershed. Clays derived from weathered shales, primarily the Chinle Formation of Triassic age and the Mancos Shale of Cretaceous age, represent the bulk of the sediment load carried by the Rio Puerco. At times the Rio Puerco also transports large quantities of sand. An abundant supply of sand is generally available for transport from the deposits of fine windblown sands which are present over much of the watershed and from the Santa Fe Group which is exposed along the lower 50 or 60 miles of the Rio Puerco. The bed material of the active channel of the Rio Puerco from the Chico Arroyo to the confluence with the Rio Grande is composed primarily of fine sand with thin layers of clay. Core drilling in the channel at the Rio Puerco near Bernardo, New Mexico, showed alternating layers of fine sand and clay to a depth of about 70 feet with layers of sand and coarse gravel at greater depths.

The major tributaries to the Rio Puerco, the site of the U. S. Geological Survey gaging station near Bernardo, and the location of the study reach are shown in Fig. 1. The study reach, which was the site of detailed observations on flow and transport characteristics, was located approximately 1/4 mile downstream from the gaging station and about 3 miles upstream from the confluence with the Rio Grande. A view of the reach as it appeared in June 1961 is given in Fig. 2.

At the beginning of this investigation in the spring of 1961, the bed of the Rio Puerco was armored with a layer of clay, silt and sand to a depth of from 6-12 inches (Fig. 3). The armored layer, a mixture of about 50 percent sand, 23 percent silt and 27 percent clay, had been deposited by previous flows. Upon drying, the deposited sediment formed an extremely hard, erosion-resistant, continuous surface. There was no evidence of stratification within the layer, and surface cracks from drying did not form, except in a thin veneer of clay at the uppermost surface. Underlying the armored layer was a fine sand with a median diameter of about 0. 20 mm.

By October 1961 a head cut in the armored layer of the bed had moved upstream through the study reach (Fig. 4). The cut channel was quite uniform in cross section, averaging about 25 feet wide and 3 feet deep. Figure 5 shows a comparison of the cross sections before and after the head cut.

Observations of Channel Erosion

The channel of the Rio Puerco had been aggrading for a number of years prior to the development of the head cut. The precise amount of aggradation has not been determined, but the general pattern may be seen from the shifting stage-discharge relation shown in Fig. 6. For any given discharge, the stage, or water-surface elevation, was about 2-1/2 feet higher in 1960 than in 1950. After the head cut, the relation of the water-surface elevation to the discharge (shown by the broken line on Fig. 6) for low flows was quite similar to the 1950 rating. For higher flows, the stage-discharge relation was not affected greatly, and was similar to the 1960 curve.

The precise causes of the aggradation, the armoring of the bed, and the head cut in the armored layer are not known. Probably, aggradation in the Rio Grande caused the base level of the Rio Puerco to rise, promoting general aggradation through the study reach. The head cut was probably initiated by local scour in the Rio Grande which created a plunge pool at the mouth of the Rio Puerco. Movement of the head cut upstream was caused by the flow undercutting the fine sand beneath the armored layer.

Below the lip of the head cut, sand was eroded from the plunge pool to a depth of 6 to 8 feet. The coarser fractions of the sand were redeposited in the cut channel a few yards downstream from the plunge pool, and the finer fractions were moved through the reach. Analysis of core samples taken to a depth of 3 feet in the cut channel showed the bed material to be sand with a median diameter of 0.35 mm. Core samples taken at the same location and to the same elevation prior to the head cut showed the material to have a median diameter of 0.20 mm. Thus, there was an appreciable sorting of the bed material downstream from the head cut.

The head cut and the plunge pool were observed in the dry channel and under various conditions of flow. Records were kept of the location of the plunge pool; photographs were taken; and when possible, dimensions of the cut channel and the plunge pool were obtained, along with water discharge measurements and samples of suspended sediment and bed material above and below the head cut. The general features of the head cut, for several discharges, are shown schematically in Fig. 7. Below discharges of about 10 cfs (cubic feet per second) the flow was sufficient to keep the plunge pool scoured out, but the energy of the water dropping into the plunge pool was not sufficient to cause appreciable undercutting of the sand underlying the armored layer (Fig. 7A). The upstream rate of movement of the head cut was negligible for extremely low flows. The optimum discharge for rapid undercutting of the lip of the plunge pool was around 100 cfs, Fig. 7B, and the rate of movement of the head cut was at a maximum. At higher discharges, sand filled the plunge pool and the channel below the head cut (Fig. 7C) and the flow above 1,000 cfs was characterized by standing waves and violent antidunes. At these higher discharge rates, the head cut did not move.

Figure 7C shows why the rating curve for flows after the head cut (Fig. 6) was unchanged at the higher discharges. When the cut channel became filled with sand, the cross section of the channel was about the same as the cross section before the head cut.

A summary of the observations on the rate of advance of the head cut is given in Table 1. From these data, it was concluded that distance advanced by the head cut was not related to the magnitude of the peak flow, but rather was roughly a function of the accumulated discharge or total volume of flow, as shown in Fig. 8A. In fact, if all flows greater than 1,000 cfs are excluded from the accumulated discharge under the assumption that the head cut does not move during these higher flows, a reasonable correlation results for the first five observations, as shown in Fig. 8B. From this and from the data in Table 1, it is concluded that the distance advanced by the head cut was related more closely to the duration of the intermediate and lower flows than to the total volume of flow or to the peak discharge.

The break in the relation for the last several observations indicates that the advance of the head cut had been partially checked. Several factors contributed to partially checking the advance of the head cut. Bed erosion upstream from the head cut reduced the thickness of the armored layer, with a consequent reduction in the depth of the plunge pool and in the width and depth of the cut channel. Roots from riparian vegetation extending under the channel (Fig. 9) contributed to the reduction in width and depth of the cut channel, and quite effectively reduced the rate of advance of the head cut. In Fig. 9, which was taken a mile upstream from the study reach, the roots were about a foot below the armored surface, the cut channel was approximately 12 feet wide and 1-1/2 feet deep, and the armored layer on the bed was from 1 to 2 inches thick. It should be noted, however, that roots very near the surface of the bed may provide an erosion-resistant layer which will actually contribute to the under-cutting and to the development of a plunge pool. Thus, depending upon local conditions, the presence of vegetation may either aggravate or inhibit the activity of a head cut.

The cut channel through the study reach provided an opportunity to observe the depositional pattern and the sedimentary structure of 3 or 4 feet of the bed of the channel. These observations have been reported elsewhere[2], and will not be repeated, but one item of interest deserves comment.

The cut channel exposed numerous deposits of clay balls formed and transported during previous flows. Figure 10 shows one of these deposits. It was found that the clay balls which formed on and moved over the sand bed of the channel were armored with a layer of coarse sand and pebbles in a clay matrix, formed by selectively accreting the coarser and more angular particles of the bed material. On the other hand, the balls which formed and moved over the cohesive bed of the channel before the head cut were composed completely of clay and silt, with no material coarser than 0.062 mm.

The armored clay balls were deposited with remarkable regularity in groups or bars, roughly parallel to the channel, with distances between deposits ranging from 4 to 8 times the channel width. The pattern of deposition corresponds closely to the pattern of meanders or riffles given by Leopold and Wolman[3], who show that the meander wave length or twice the distance between successive riffles is approximately 10 times the channel width.

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[2] "Formation and Deposition of Clay Balls, Rio Puerco Near Bernardo, New Mexico," by C. F. Nordin, Jr., and W. F. Curtis, U. S. Geological Survey Prof. Paper 450-B, art. 28, 1962.

[3] "River Meanders," by L. B. Leopold and M. G. Wolman, Geol. Soc. America Bull., Vol. 71, p. 769-793, 1960.

These observations are of academic interest only. However, where clay balls are found in sedimentary deposits, this information might be useful in interpreting the depositional environment, in tracing old stream channels, and in estimating the channel widths.

Observations of Sediment Transport

During the summer of 1961, detailed information was collected on the characteristics of flow and sediment transport[4]. Observations were made at a cable section in the study reach both prior to the head cut, when the flow was over a cohesive clay boundary, and after the head cut when the channel had a sand bed.

Figure 11 shows the mean daily discharge and concentration for the several runoff events observed. Typically, the flow rose rapidly over the dry stream bed from runoff of short-duration high-intensity storms. The peak sediment concentration preceded the peak water discharge; both the flow and the concentration changed rapidly with time; and the sediment concentration was high so long as there was flow, at no time falling below 50,000 ppm. On the rising flows, the rapidly changing stage and the heavy load of debris within and on the water precluded reliable observations of either the flow characteristics or the sediment transport.

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[4] "A Preliminary Study of Sediment Transport Parameters, Rio Puerco near Bernardo, New Mexico," by C. F. Nordin, Jr., U. S. Geological Survey Prof. Paper 462-C (in press).

A summary of observed and computed data for several observations is given in Table 2. Prior to the head cut, the flow over the cohesive bed had a relatively low Froude number and a low water-surface slope. Flow over the sand bed after the head cut was in upper regime[5]; the Froude number was high; and the bed was plane. At times, stationary waves were present and violently breaking antidunes were not uncommon. Surface waves did not form in flow over the cohesive bed. There was no apparent difference in the channel roughness for flow over the clay-armored bed and over the sand bed after the head cut. In both cases, Manning's n averaged about 0.015, and it is concluded that the channel roughness was independent of the condition (i.e., cohesive or noncohesive material) of the bed.

Excluding flows where stationary waves were present, the vertical velocity distribution followed a logarithmic law[4]. Values of the coefficient of turbulent exchange, k, computed by the velocity profile method[6] were found to average 0.39 for flow over the clay bed and 0.26 for flow over the

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[5]"Forms of Bed Roughness in Alluvial Channels," by D. B. Simons and E. V. Richardson, Journal of the Hydraulics Division, ASCE, Vol. 87, No. HY3, May 1961.

[6]"Roughness Spacing in Rigid Open Channels," by W. W. Sayre and M. L. Albertson, Journal of the Hydraulics Division, ASCE, Vol. 87, No. HY3, May 1961.

sand bed. Two observations of particular interest, summarized in Table 2, show that on August 18 for sediment concentrations of around 175,000 ppm when practically all of the sediment was in the clay and silt sizes, there was no reduction in k ; while on September 11 when the concentration was about the same but 40 percent of the material was sand size, k values of 0.23 were computed.

Several explanations have been advanced for the reduction in k due to suspended sediment. Einstein and Chien[7] and Vanoni and Nomicos[8] attributed the reduction in k to a dampening of the turbulence due to sediment, and correlated the reduction in k with the ratio of the energy expended supporting the sediment to the total energy expenditure of the stream. Elata and Ippen[9], from investigations of suspensions of neutrally buoyant particles, concluded that there was no dampening of turbulence, rather the reduction in k was due to a change in the turbulence structure, and they correlated the reduction in k with the volume concentration of the particles.

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7 "Second Approximation to the Solution of the Suspended Load Theory," by H. A. Einstein and Ning Chien, U. S. Corps of Engrs. Missouri River Div. Sediment Ser. 3, 1954.

8 "Resistance Properties of Sediment-Laden Streams," by V. A. Vanoni and G. N. Nomicos, Transactions, ASCE, Vol. 125, 1960.

9 "The Dynamics of Open Channel Flow with Suspensions of Neutrally Buoyant Particles," by C. Elata and A. T. Ippen, Technical Report No. 45, Hydrodynamics Lab., Massachusetts Inst. of Tech., Cambridge, Mass., 1961.

In both cases, there was general agreement that changes in flow characteristics somehow were related to modifications of the energy balance within the turbulent flow, and that the direct effect of particles was greatest in a narrow zone near the bed where the turbulence is generated.[8,9]

The Rio Puerco observations shed no new light on this vital problem, the data equally support either point of view. However, there are some interesting minor implications. Assuming a constant specific weight of sediment, the volume concentrations would be almost equal on August 18 and September 11, so the concentration by itself is not a factor of importance in the reduction of k . However, the particle-size distribution of the sediment is important. Large particles near the boundary may effect an increase in turbulence production through additional unsteadiness in the flow created by their presence, as postulated by Elata and Ippen[9], whereas the presence of fine particles does not appear to influence the turbulence production.

For flow in the Rio Puerco on September 11, the volume concentration was about 7.5 percent, the median diameter of material was approximately 0.10 mm[4], and the value of k was 0.23. For an equal volume concentration and similar diameter of neutrally buoyant particles, Elata and Ippen show a k value of about 0.33. This difference suggests that modifications of the energy balance within turbulent flows are different for suspensions of coarse particles which require an expenditure of energy for their support than for suspensions of fine particles or neutrally buoyant particles which require almost negligible energy.

Of course, suspensions in the Rio Puerco are complicated by the physio-chemical properties of the fine sediments, the chemical composition of the native water, and other factors[4] which cannot be evaluated. Certainly, any comparison between the field data and laboratory data must be viewed with mental reservations, and the need for additional studies in both the field and the laboratory is apparent.

The sediment concentration, like the velocity, followed a conventional vertical distribution[4]. Values of $D-y/y$, where D is the depth of flow and y is the distance from the bed, plotted logarithmically against the concentration at the distance y from the bed, C_y, for various size classes, defined a straight line. The slope of this line may be called Z_1, the observed exponent of the concentration distribution[10]. The observed exponent Z_1 was, of course, much less than the theoretical exponent Z, indicating that the sediment was distributed more uniformly than the theory would predict, the usual finding in the case of field data[11]. The theoretical exponent Z was computed from the equation

$$Z = \frac{\omega}{\beta k U_*}$$

[10] "Computations of Total Sediment Discharge, Niobrara River near Cody, Nebraska," by B. R. Colby and C. H. Hembree, U. S. Geological Survey Water-Supply Paper 1357, 1955.

[11] "Vertical Distribution of Velocity and Suspended-Sediment Concentration, Middle Rio Grande, New Mexico," by C. F. Nordin, Jr., and G. R. Dempster, Jr., U. S. Geological Survey Prof. Paper 462-B (in press).

where ω is the fall velocity in distilled water of a particular size class of sediment, U_* is the shear velocity, and β is the ratio of the sediment-diffusion coefficient to the momentum-diffusion coefficient for the fluid, assumed equal to unity. The difference between Z and Z_1 was largely due to the influence of the fine sediments upon the apparent viscosity and hence, upon the fall velocity ω. A correction for the influence of the fine sediment on fall velocity was defined empirically for various size classes of sand and for a temperature of 24°C and concentrations up to about 150,000 ppm of fine material (Fig. 12).[4] Using the fall velocity from Fig. 12 in the equation for the theoretical distribution exponent, a reasonable agreement between the theoretical and measured values of Z was found, as shown in Fig. 13.

The armoring of the bed and the subsequent head cut did not noticeably affect the sediment transport rate for any given discharge, but there were marked differences in the size distributions of the sediment loads. For example, referring to Table 2, the sediment transported over the clay-armored bed contained 712 ppm of material coarser than 0.062 mm in a total concentration of 178,000 ppm. After the head cut and for a higher discharge, the suspended sediment contained 69,100 ppm of sand in a total observed concentration of 175,000 ppm.

Streams with high concentrations of suspended fine sediment have a much greater capacity for transporting sand than do streams with clear-water flow. The increased transport capacity is due mostly to the increased viscosity and mass density of the transporting media. Figure 14 shows the relation of the transport rate of suspended sand per foot of width, q_s, to unit discharge, q, for the Rio Puerco near Bernardo, and as a base of reference, for the Rio Grande near Bernalillo. The concentrations of fine sediment in the Rio Grande are relatively low, on the order of 500 to 1,000 ppm, and there is an unlimited amount of sand available for transport. The range in depth, velocity, and water-surface slope for the Rio Grande is about the same as for the Rio Puerco[12]. The figure shows that for any given unit discharge, the Rio Puerco may transport many times as much sand as the Rio Grande, provided the sand is available for transport, that is, the bed is not armored with clay. The higher transport rates of sand are associated with the higher concentrations of fine material. When the bed of the Rio Puerco was armored with clay as it was in 1961 and 1953, the transport rates were comparable to the transport rates for the Rio Grande and the plotted points fall along the reference line. In both 1953 and 1961, the flows originated above the

[12] "A Study of Fluvial Characteristics and Hydraulic Variables, Middle Rio Grande, New Mexico," by J. K. Culbertson and D. R. Dawdy, U. S. Geological Survey Water-Supply Paper 1498-F (in press).

confluence of the Chico Arroyo and the Rio Puerco, some 100 miles upstream from the study site, so it is assumed that the bed was armored throughout the entire length of this reach. Thus, although the Rio Puerco is capable of transporting large quantities of sand, under certain conditions the availability of the sand may be limited.

Perhaps the most distinguishing characteristic of the Rio Puerco and of many streams in arid and semiarid regions is the extremely high sediment concentrations which accompany the flows. In fact, there appears to be no upper limit to the capacity of these streams to transport material delivered to their channels by surface runoff, other than the upper limiting "fluid" concentration when the mixtures commence to behave as a granular paste and the flows must be classified as "mud flows." For uniform spheres, Bagnold[13] gives the upper limiting "fluid" concentration by volume of 0.6 or for particles with specific gravity of 2.65, a concentration by weight of about 800,000 ppm. Probably the upper limiting fluid concentration for natural sediments should be of the same order of magnitude. Documentation of such high concentrations in natural channels has not been accomplished, but some of the recorded concentrations of samples taken with standard Geological Survey sampling

[13] "The Flow of Cohesionless Grains in Fluids," by R. A. Bagnold, Royal Soc. (London) Philos. Trans., Vol. 249, No. 964, 1956.

equipment (Table 3) range upward to about 650,000 ppm with up to 500,000 ppm of material in the sand size range (0.062-2.0 mm). Probably the highest recorded concentration was 680,000 ppm for the Rio Puerco reported by D. C. Bondurant[14]. Recalling that the samples in Table 3 were probably taken after the peak flow and concentration occurred, it is easy to speculate that concentrations of these streams grade upward to mud flows. Of course, these are not equilibrium transport conditions, both stage and concentration change rapidly with time.

Regardless of the upper limiting concentrations, it is obvious that in dealing with flows with concentrations of sand of 50 percent or more by weight, it becomes necessary to abandon some of the conventional techniques which are commonly used in sediment transport problems. For example, the conventional idea of a fall velocity becomes meaningless and it is difficult to visualize how turbulence could be effective in suspending the sediment. In these cases, the concept of a dispersive stress as given by Bagnold[10] may be a more realistic approach. At lower concentrations, say below about 150,000 ppm, it is sufficient merely to correct for the influence of the sediment on the apparent viscosity of the mixture and to consider the increase in the mass density[4, 15].

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[14] "Sedimentation Studies at Conchos Reservoir in New Mexico," by D. C. Bondurant, Transactions, ASCE, Vol. 116, No. 2466, 1951.

[15] "Some Effects of Fine Sediment on Flow Phenomena," by D. B. Simons, E. V. Richardson and W. L. Haushild, U.S. Geological Survey Water-Supply Paper 1498-G, 1963.

Conclusions

This report presents some preliminary findings of a continuing study of flow and transport in ephemeral streams with high concentrations of fine suspended sediment. The principle conclusions are summarized as follows:

1. At the beginning of the study, the bed of the channel was armored with a layer of clay, silt and sand mixture which provided a cohesive boundary for the flow and effectively limited the availability of sand for transport.
2. Channel erosion, in the form of a head cut moving through the study reach, resulted in changes in the channel geometry, in the characteristics of flow, and in the composition of the bed material and suspended load.
3. The rate of advance of the head cut was found to be related more closely to the duration of intermediate flows than to the peak discharge or total volume of flow.
4. The velocity in a vertical varied logarithmically with distance from the bed, and the turbulence coefficient, k , was reduced by high concentrations of sand but was unaffected by high concentrations of fine material.
5. The concentration distribution of sand sizes can be described by a conventional distribution equation if the fall velocity of the sand

is corrected for the influence of fine sediment upon the viscosity of the mixture. A corrected fall velocity, empirically defined for a temperature of 24°C and for concentrations up to about 150,000 ppm is given.

6. Examples of extreme concentrations observed in ephemeral streams suggest that the upper limiting concentrations of sediment which may be transported is the limiting "fluid" concentration at which the material may be classified as a "mudflow."

7. The observations show that in dealing with flow in streams such as the Rio Puerco, two important features must be considered. First, the concentrations of suspended sediment are so great that the influence of the particles upon the properties of the fluid cannot be neglected, second, both the flow and concentration change rapidly with time so the usual assumptions of uniform flow and equilibrium transport do not hold. Further,. the channel may be rapidly aggrading or degrading, or shifting laterally due to channel erosion, so neither the channel shape and cross section nor the size distribution of the bed material may be assumed constant.

8. Finally, the observations reported here point out the extreme complexity of the natural erosion and transport processes operating in the Rio Puerco, and indicate the need for a better

understanding of the factors controlling the flow and the sediment transport in streams with high concentrations of suspended material.

Appendix - Notation

The following symbols have been adopted for use in this paper:

C_y	=	concentration of a particular size of suspended sediment at the distance y from the bed
D	=	depth of flow
k	=	the turbulence coefficient
n	=	Manning's n
q	=	water discharge per unit width
q_s	=	discharge of suspended sediment coarser than 0.062 mm per unit width
U_*	=	shear velocity
y	=	distance from the bed
Z	=	theoretical exponent of the relative concentration distribution
Z_1	=	observed exponent for the relative concentration distribution
β	=	ratio of the sediment-diffusion coefficient to the momentum-diffusion coefficient for the fluid
ω	=	fall velocity of a sediment particle in distilled water
ω'	=	empirically determined fall velocity

TABLE 1. -- OBSERVATIONS ON THE MOVEMENT OF THE HEAD CUT

Date	Distance from initial point in feet	*Discharge in cfs-days	Peak discharge in the period in cfs	Cumulative discharge in acre-feet	Cumulative discharge excluding flows greater than 1000 cfs in acre-feet	Remarks
Aug. 19, 1961	0	-	-	-	-	Initial point is at highway bridge, interstate 25.
Aug. 19-Aug. 30	867	3,150	2,400	6,230	2,180	Depth of plunge pool on Aug. 30 was 3.5 ft, discharge 5.6 cfs.
Aug. 31-Sept. 15	2,030	1,840	1,700	9,880	4,790	Plunge pool filled with sand on Sept. 11, standing waves were present over the head cut. Discharge was 1,110 cfs.
Sept. 16-Oct. 5	3,660	1,460	1,800	12,800	6,650	Depth of plunge pool on Oct. 5 was 2.0 ft. Channel was dry.
Oct. 6-Feb. 6, 1962	3,780	510	300	13,800	7,760	Plunge pool approximately 4 ft deep on Feb. 5. Discharge was 124 cfs.
Feb. 7-Mar. 24	5,380	1,430	520	16,600	10,500	Roots from bank vegetation exposed along the cut channel.
Mar. 25-May 25	5,670	1,180	240	18,900	12,800	Depth of plunge pool on May 25 was 5.0 ft. Channel was dry.
May 25-Aug. 15	5,690	996	560	20,900	14,800	Depth of plunge pool on Aug. 15 was 1.5 ft. Roots extended across cut channel. Most of the armoring upstream from the head cut had been eroded from the bed.

All discharges are based upon provisional records subject to revision.

TABLE 2. --OBSERVED AND COMPUTED DATA

Date	Water Discharge, cfs	Mean Depth, ft	Mean Velocity, fps	Water Surface Slope	Water Temp. °F	Froude No.	Manning's n $ft^{1/6}$	Turbulence Coefficient k	Suspended sediment concentration		Remarks
									All sizes, ppm	Coarser than 0.062 mm, ppm	
1961											
July 10	403	1.71	2.88	0.00038	72	0.39	0.014	0.32	75,800	454	Cohesive bed
Aug. 18	31.4	.74	1.76	.00073	82	.36	.018	-	110,000	-	Cohesive bed
Aug. 18	636	2.08	3.40	.00049	75	.42	.016	.40	178,000	712	Cohesive bed
Aug. 19	2,380	4.47	4.46	.00024	74	.37	.014	.46	132,000	3,560	Cohesive bed
Aug. 30	5.46	.29	1.14	.00105	79	.37	.018	-	60,000	-	Cohesive bed
Sept. 11	1,110	2.08	5.87	.00122	66	.72	.014	.23	175,000	69,100	Sand bed
Sept. 20	1,430	2.48	6.48	.00148	63	.73	.016	.29	240,000	83,300	Sand bed

TABLE 3. --EXTREME SEDIMENT CONCENTRATIONS OBSERVED IN EPHEMERAL STREAMS

Station	Date	Discharge (cfs)	Concentration (ppm)	Concentration of sand (ppm)
Rio Puerco below Cabezon, New Mexico	Aug. 6, 1951	-	414,000	-
	July 22, 1954	1,080	327,000	131,000
Rio Puerco near Bernardo, New Mexico	July 24, 1949	-	418,000	117,000
Paria River at Lees Ferry, Arizona	Aug. 27, 1952	-	646,000	-
	Aug. 26, 1954	408	468,000	300,000
	Oct. 8, 1954	435	427,000	205,000
	Aug. 4, 1961	-	596,000	447,000
	Aug. 4, 1961	-	451,000	262,000
Little Colorado River at Cameron, Arizona	Aug. 20, 1957	-	620,000	-
	Aug. 25, 1957	3,080	299,000	111,000

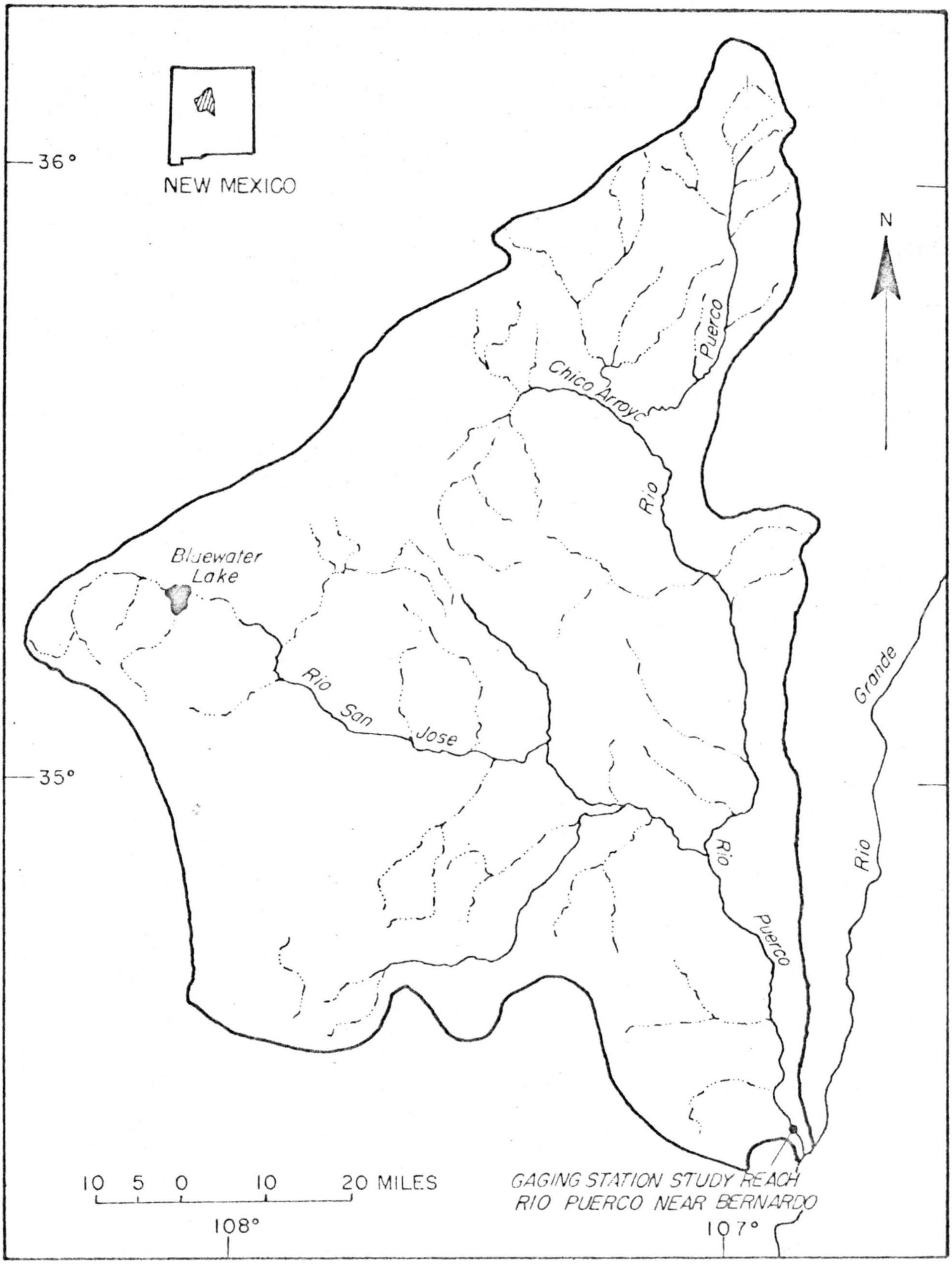


FIG. 1. --THE RIO PUERCO DRAINAGE BASIN

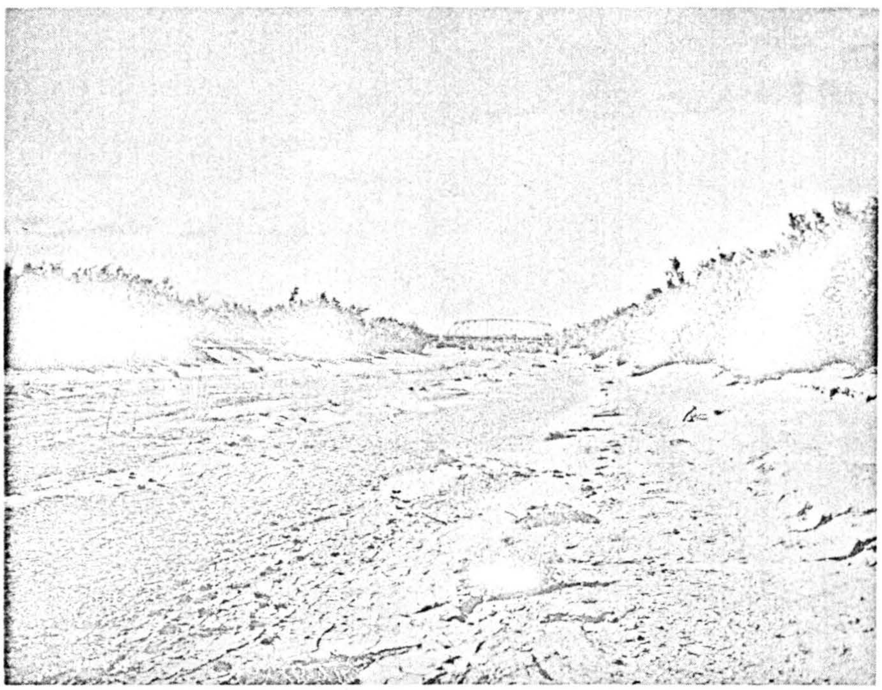


FIG. 2.--THE STUDY REACH, LOOKING UPSTREAM, JUNE 1961

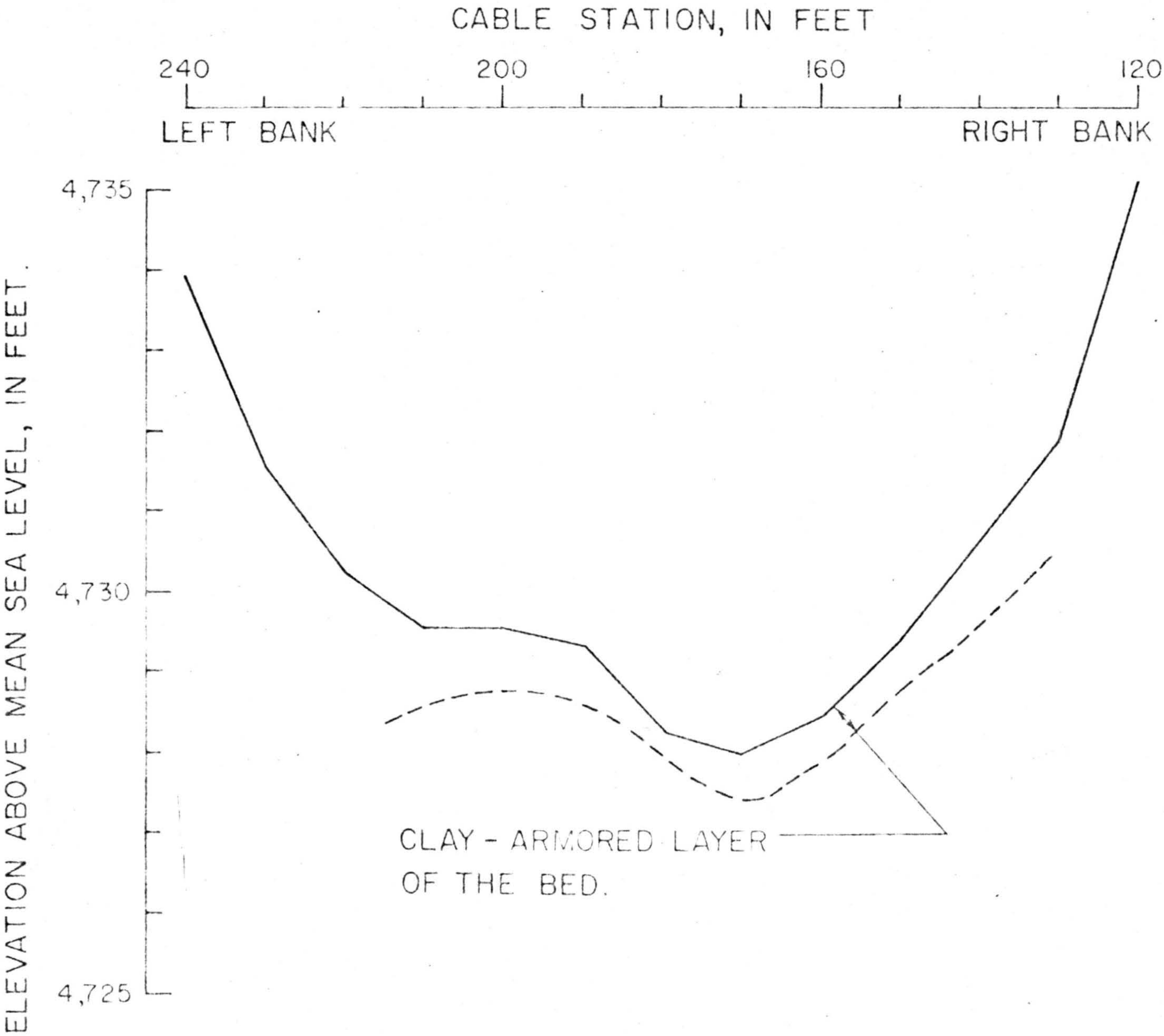


FIG. 3.--CROSS SECTION SHOWING THE ARMORED LAYER

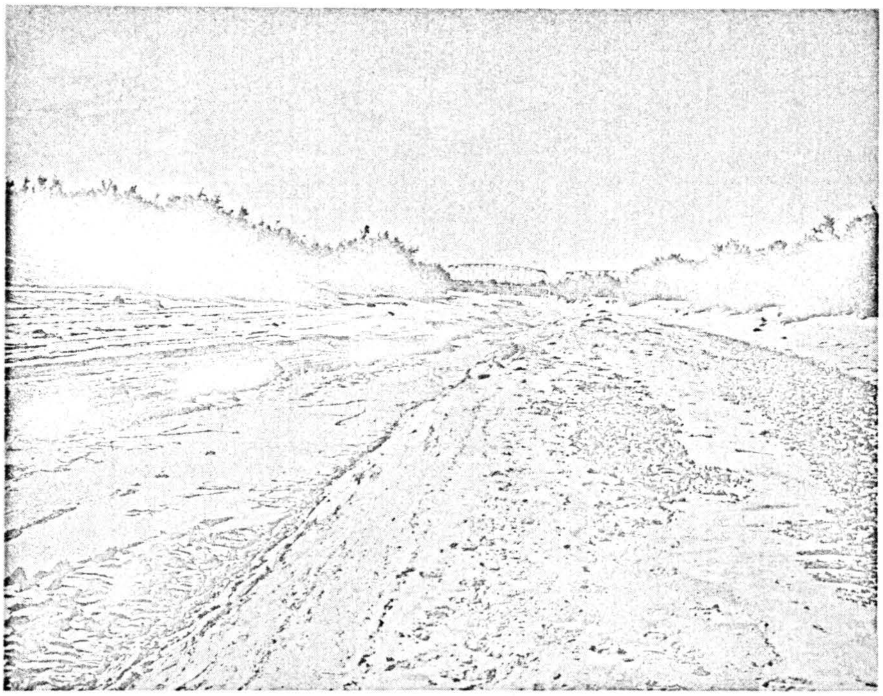


FIG. 4. --THE STUDY REACH, LOOKING UPSTREAM, OCT. 1961

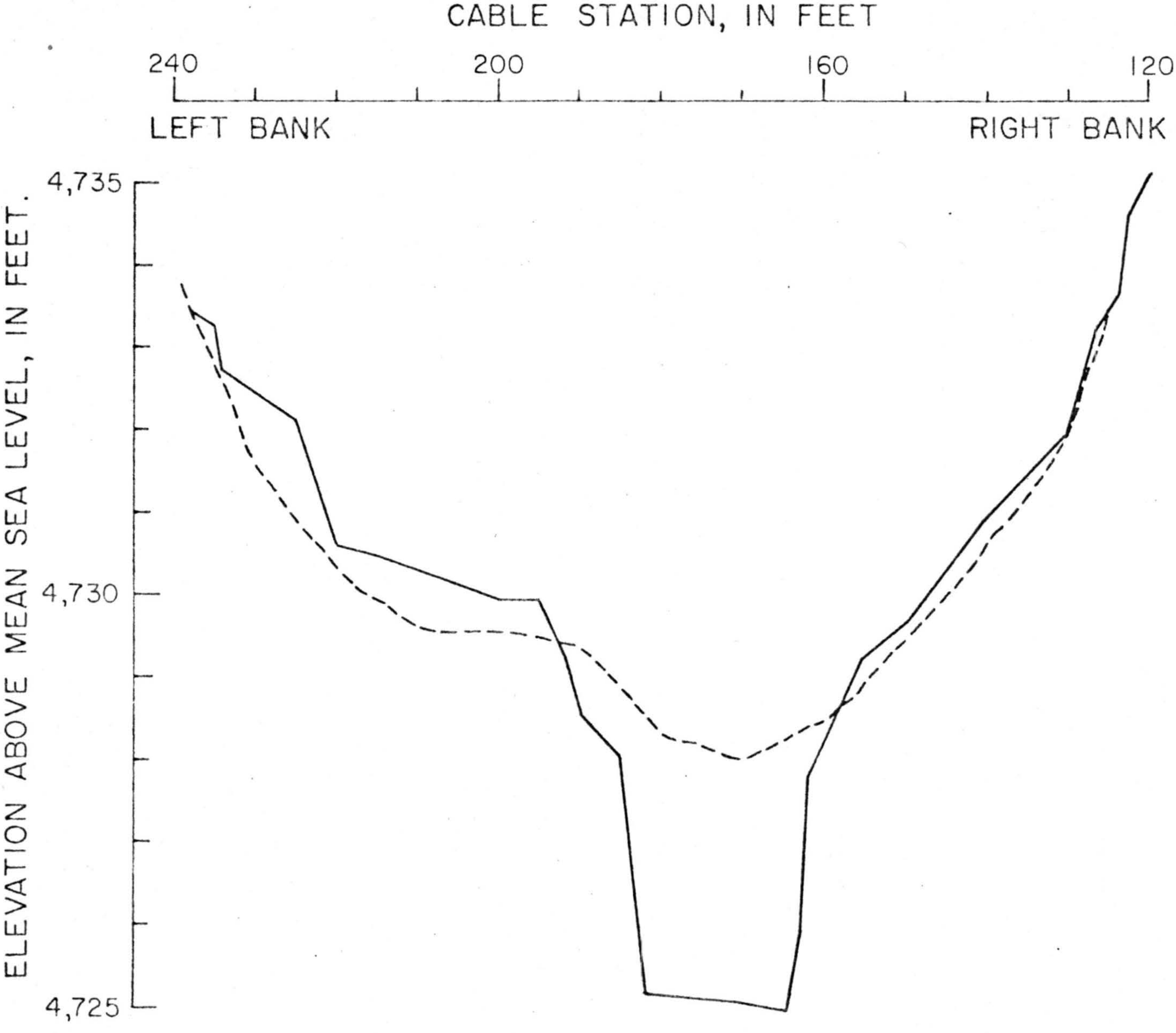


FIG. 5.--COMPARISON OF THE CROSS SECTION BEFORE AND AFTER THE HEADCUT

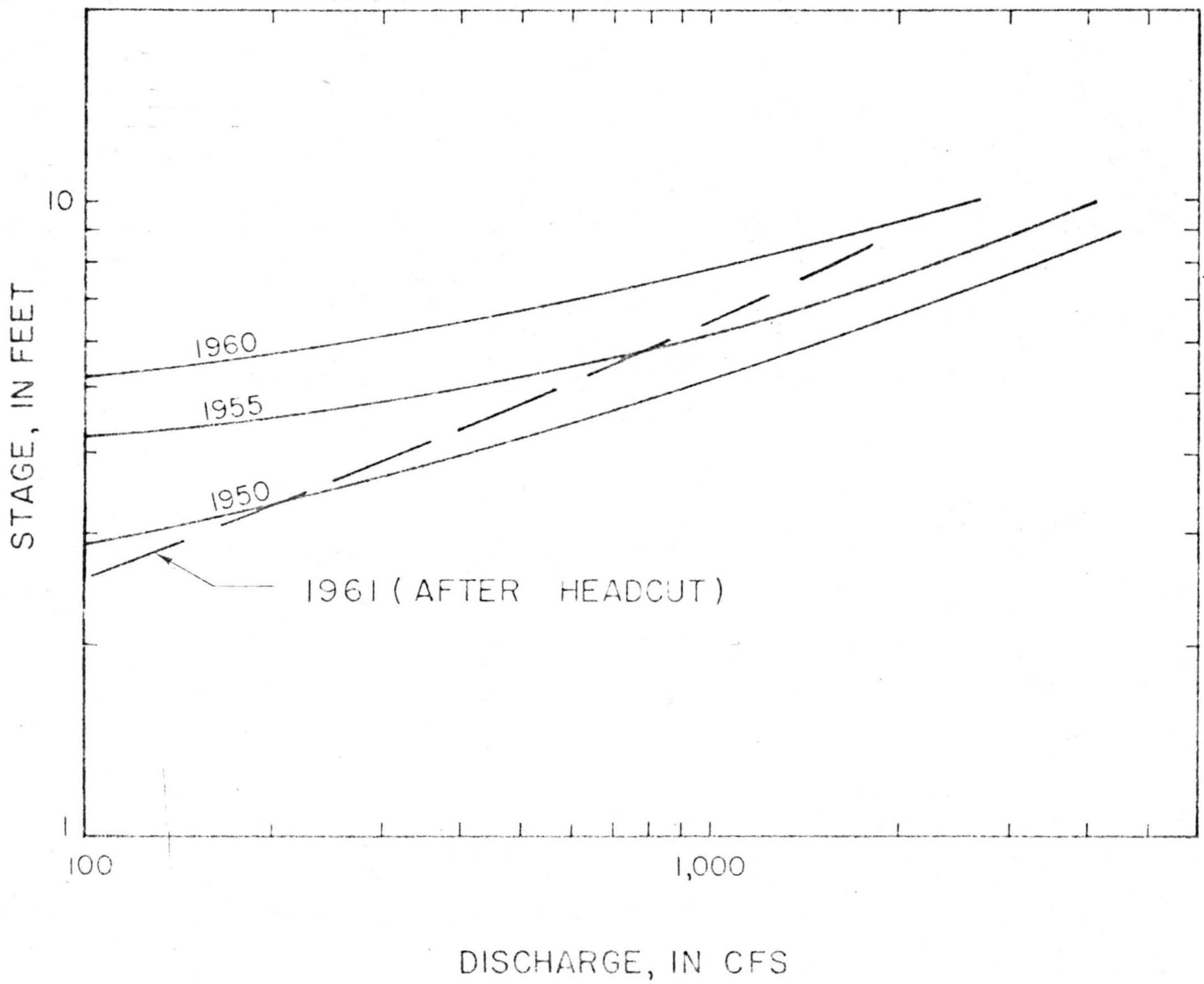


FIG. 6. --STAGE-DISCHARGE RELATIONS

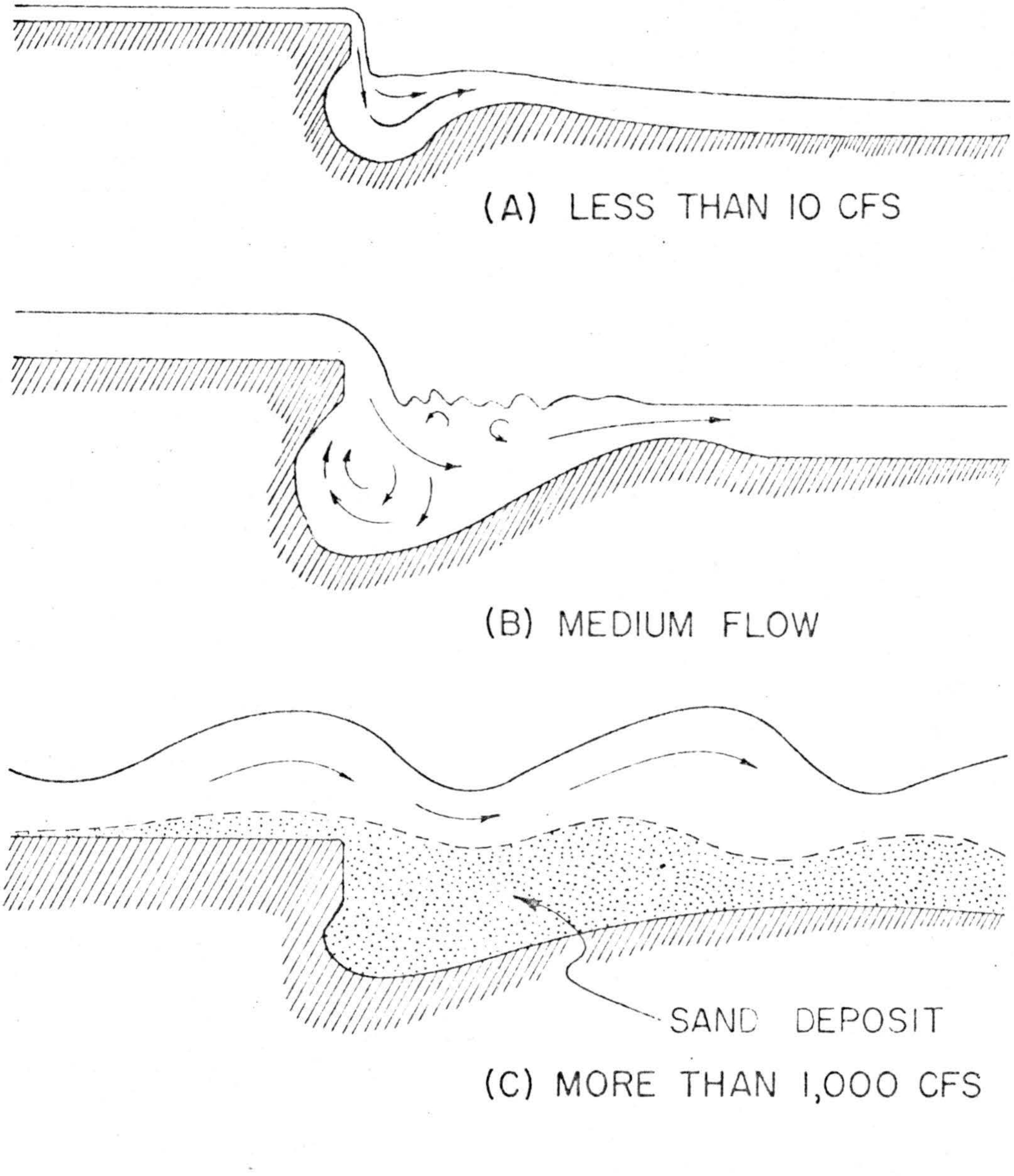
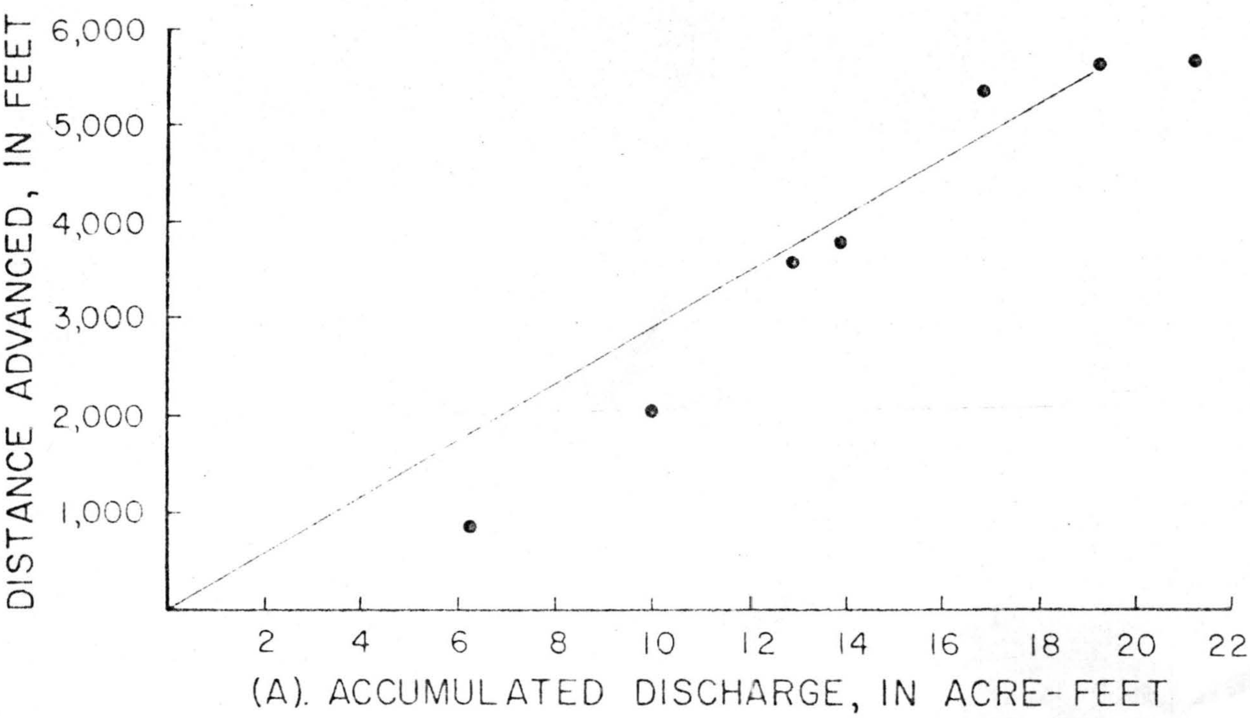


FIG. 7.--THE PLUNGE POOL UNDER VARIOUS FLOW CONDITIONS



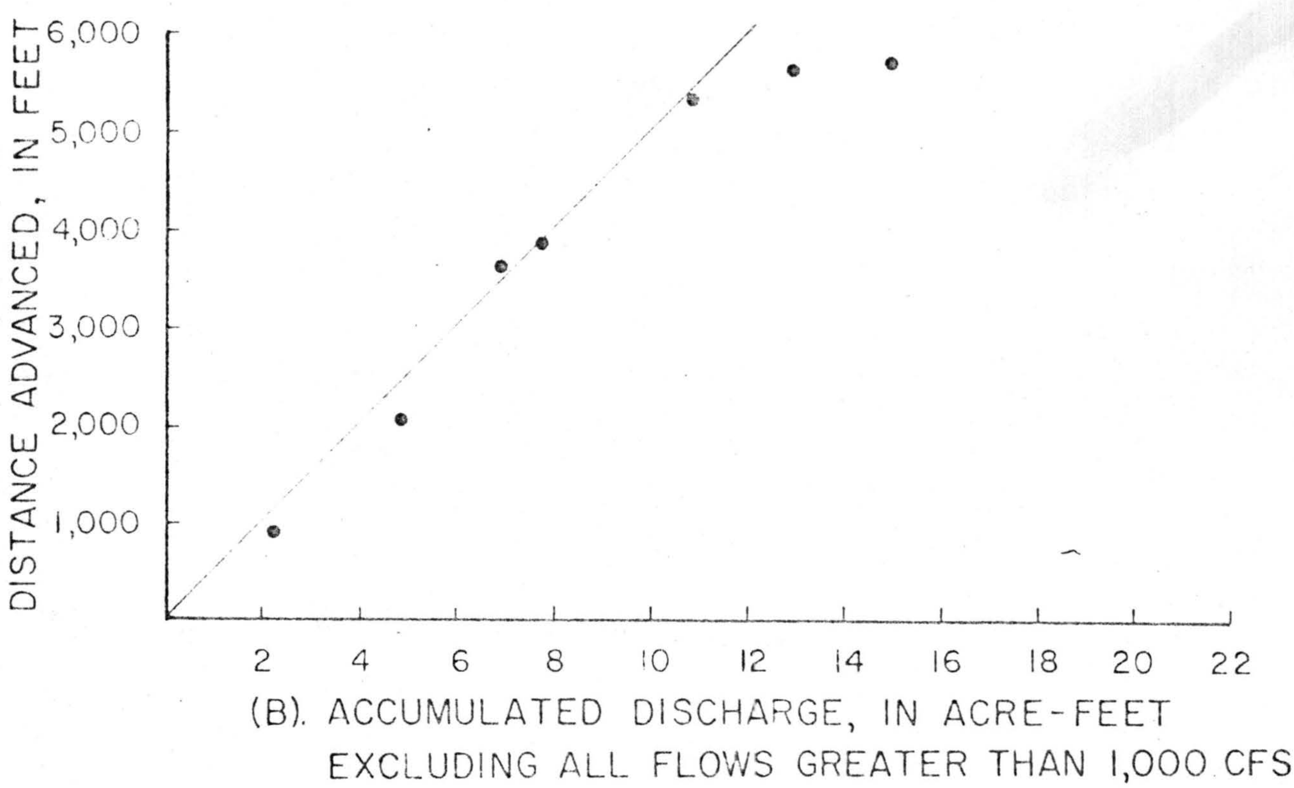


FIG. 8.--RATE OF ADVANCE OF THE HEADCUT

FIG. 9.--EFFECTS OF VEGETATION ON THE HEADCUT

FIG. 10.--DEPOSIT OF CLAY BALLS

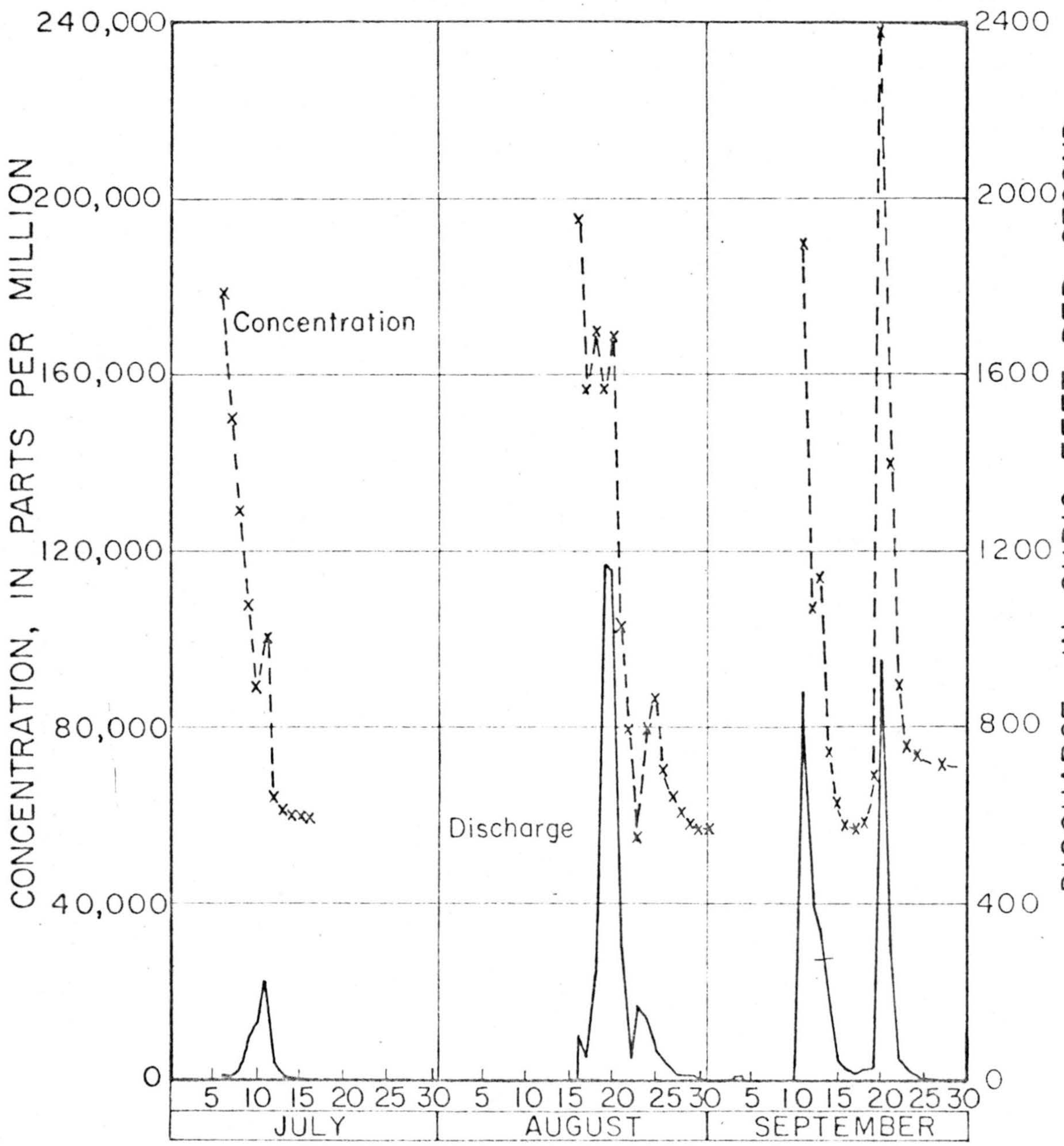


FIG. 11. --DAILY MEAN DISCHARGE AND CONCENTRATION

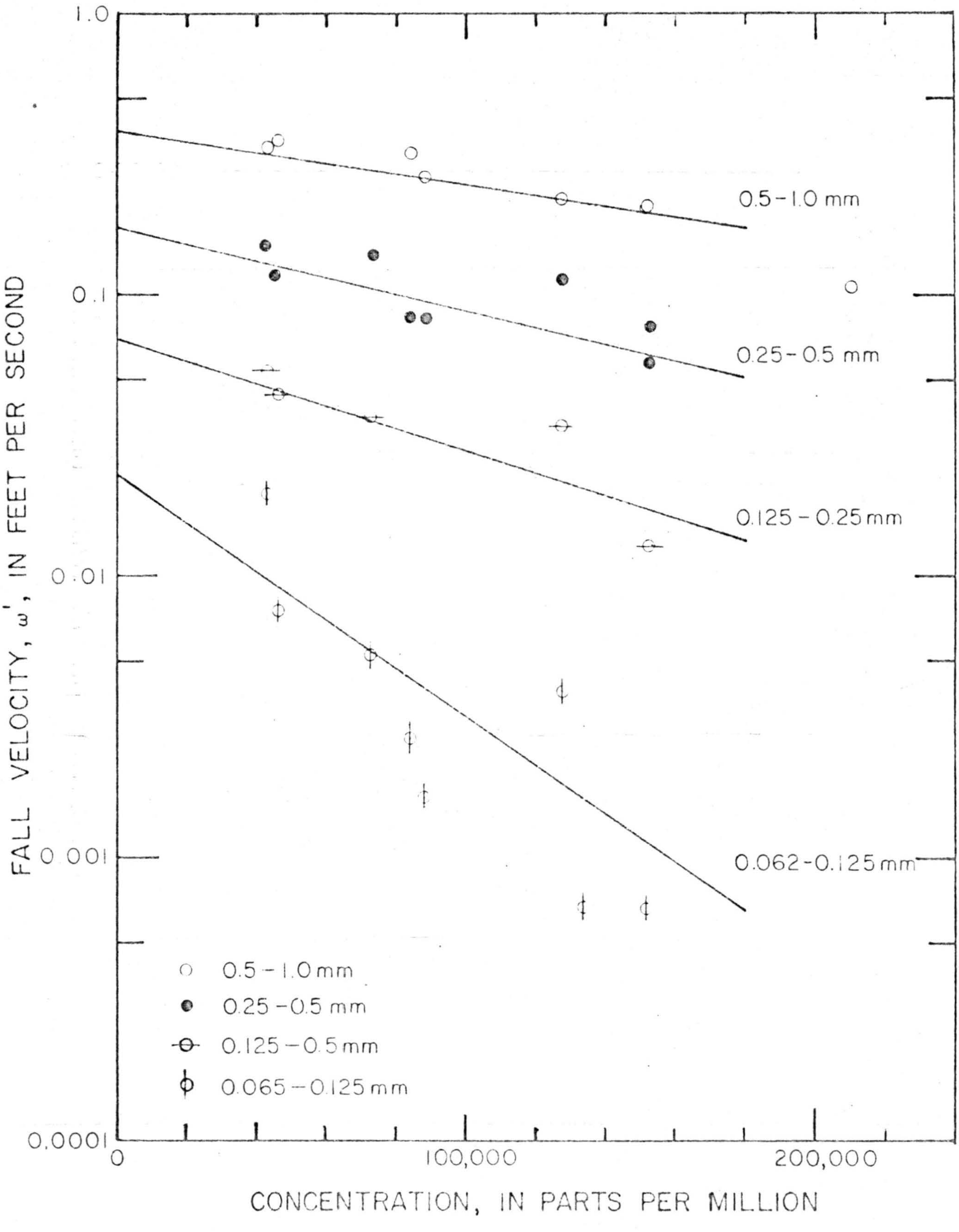
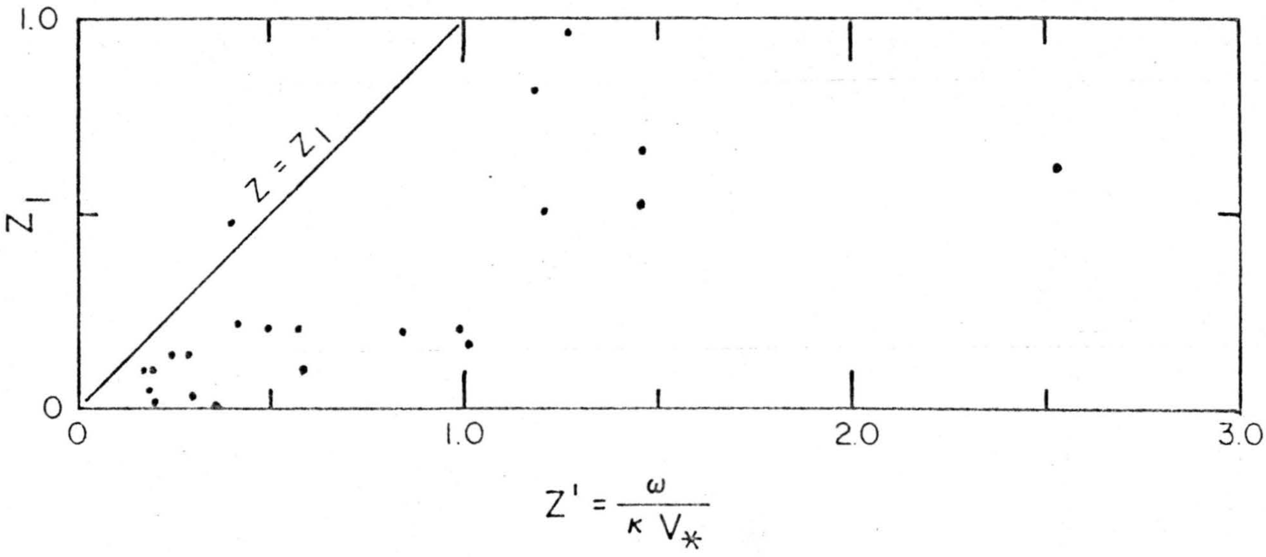


FIG. 12. --RELATION OF FALL VELOCITY TO CONCENTRATION OF FINE MATERIAL



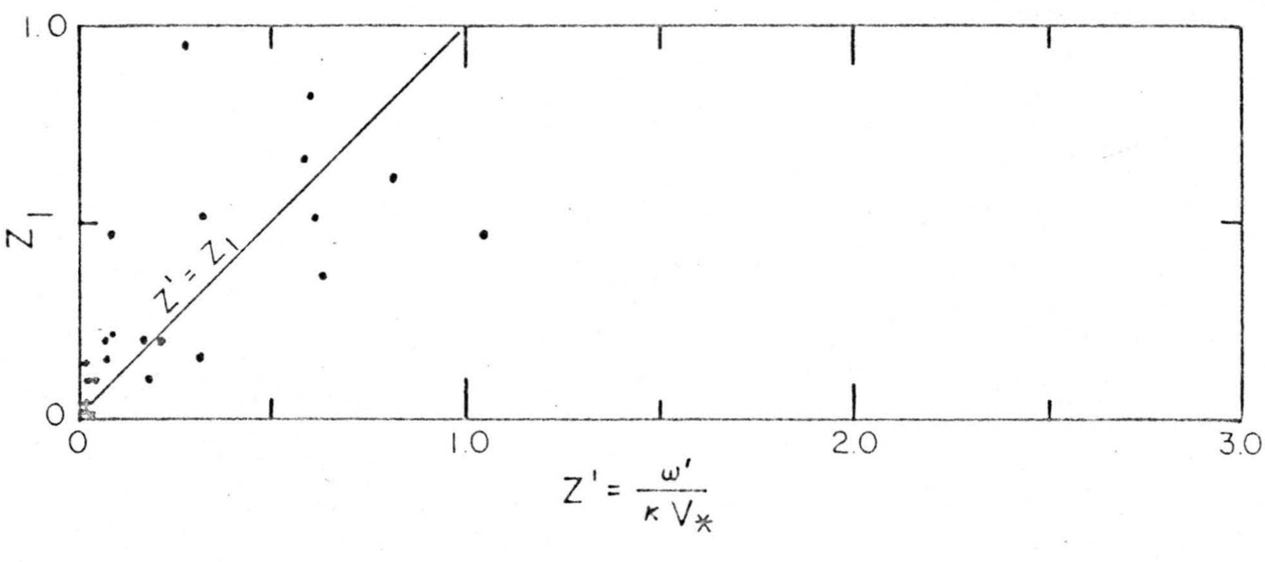


FIG. 13.--COMPARISON OF OBSERVED AND COMPUTED VALUES OF Z

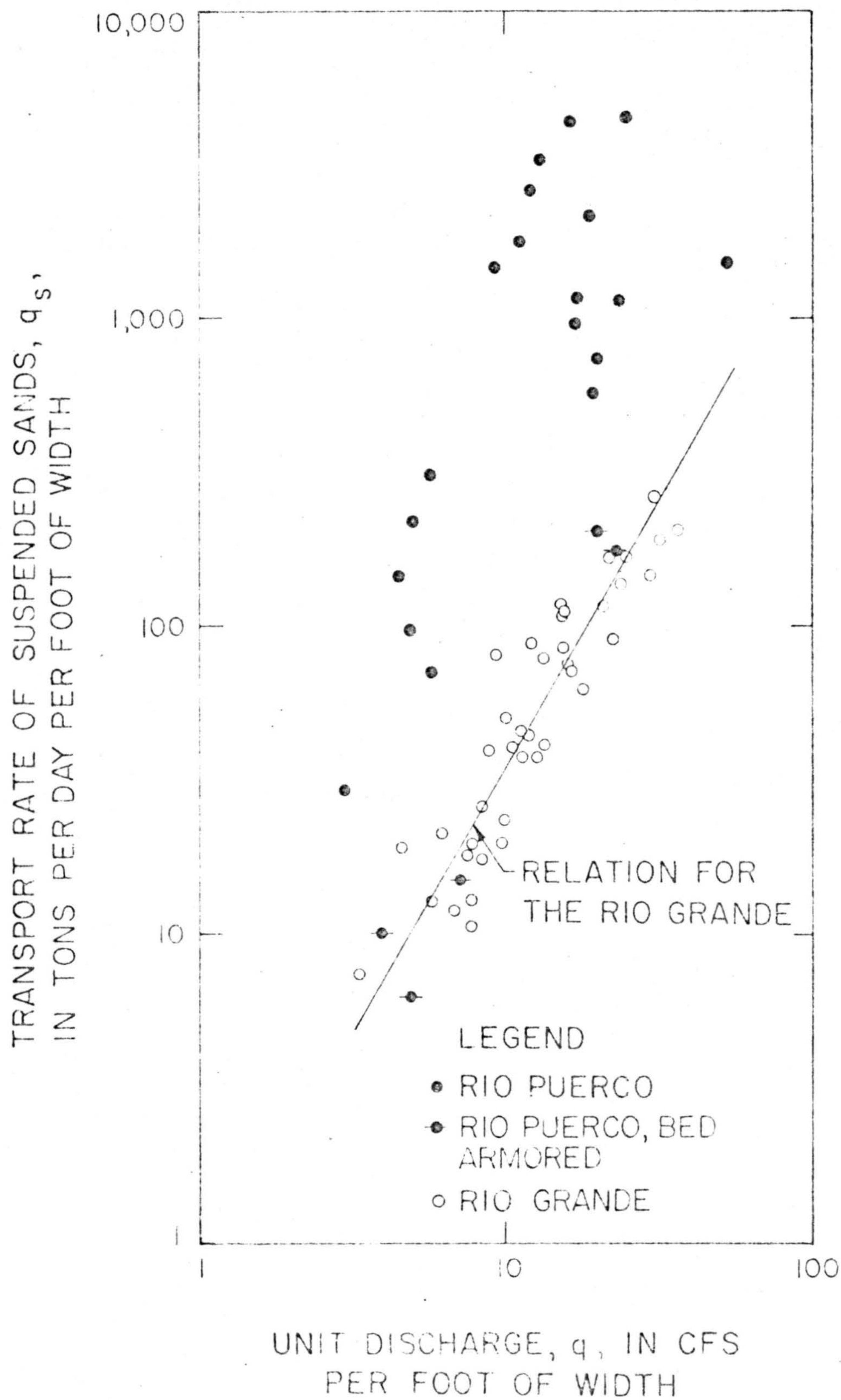


FIG. 14. --RELATION OF THE TRANSPORT RATE OF SUSPENDED SAND TO DISCHARGE