A Preliminary Study of Sediment Transport Parameters Rio Puerco Near Bernardo New Mexico

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SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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GLOSSARY OF TERMS

Bed material. Material that makes up the channel bed.

Clay. Sediment finer than 0.004 millimeters (mm), regardless of mineralogical composition.

Concentration. Sediment concentration, except where specified otherwise, is the ratio of the dry weight of sediment to the weight of the water-sediment mixture, expressed in parts per million (ppm). In general, this definition of concentration may refer to any material, dissolved or suspended, in a stream.

Fine material. Material finer than 0.062 mm.
High concentrations. Arbitrarily taken as any concentration greater than 50,000 ppm.
Sand. "Sand" and "sand sizes" are used interchangeably to refer to sediment between 0.062 mm and 2.0 mm in size, regardless of mineralogical composition.
Sediment. Fragmental material that originates from weathering of rocks and is transported by, suspended in, or deposited by water.
Silt. Sediment between 0.004 mm and 0.062 mm in size.

SYMBOLS

		Units
a	Reference distance above the bed	ft
A	Unit horizontal area	ft ^{2}
c	Concentration, in weight per unit volume	lb per ft ^{3}
C	Concentration	ppm
C_v	Volume concentration	0
$C_c/\sqrt{g}$	Dimensionless Chezy coefficient	0
C_1	A constant	0
d	Median diameter	mm
d_{65}	Particle size for which 65 percent by weight is finer	mm
D	Depth at a vertical	ft
$\overline{D}$	Mean depth of flow at a cross section	ft
F	Froude number	0
g	Acceleration of gravity	fps ^{2}
k	The coefficient of turbulent exchange	0
K_s	A length parameter	ft
m	Slope of the semilogarithmic plot of velocity versus depth above the streambed	fps
n	Manning's resistance coefficient	ft $^{1/6}$
P_f	Power to overcome friction	ft-lb per sec
P_s	Power to support the sediment	ft-lb per sec
P_s'	Power added by the sediment	ft-lb per sec
q	Discharge per foot of width	ft ^{3} per sec per ft
q_s	Transport rate of observed suspended sand	tons per day per ft
R	Hydraulic radius	ft
S	Water-surface slope	ft per ft
V	Velocity at a point	fps
$\overline{V}$	Mean velocity in a cross section	fps
V_*	Shear velocity	fps
y	Distance above the streambed	ft
Z	Computed exponent for the vertical distribution of suspended sediment	0
Z_1	Observed exponent for the vertical distribution of suspended sediment	0
β	Angle of inclination between the streambed and the horizontal	degrees
γ	Specific weight of water	lb per ft ^{3}
γ_s	Specific weight of sediment	lb per ft ^{3}
ϵ_m	Momentum transfer coefficient	0
ϵ_s	Sediment transfer coefficient	0
μ	Coefficient of viscosity	centipoise
ω	Fall velocity	fps

A PRELIMINARY STUDY OF SEDIMENT TRANSPORT PARAMETERS, RIO PUERCO NEAR BERNARDO, NEW MEXICO

By CARL F. NORDIN, JR.

ABSTRACT

Preliminary findings of a study of sediment transport in streams with high concentrations of suspended fine sediment indicate that for the Rio Puerco near Bernardo, N. Mex., the velocity varies logarithmically with depth, and the concentration distribution for several size classes of sand may be described by a conventional distribution equation if the fall velocity of the sand is corrected for the influence of the fine sediment. A corrected fall velocity, empirically defined for a temperature of 24° C and for concentrations of as much as about 150,000 parts per million, is given.

Through the period of the study, the channel of the Rio Puerco changed rapidly. The bed material varied from cohesive fine material to coarse sand. At the beginning of the study, the sand bed of the channel was impregnated with clay, and the clay-impregnated layer acted as an effective "armoring" which persisted for several weeks, forming a cohesive boundary for the flow and limiting the availability of sand for transport. For the last several observations, a "headcut" in the armored layer had progressed upstream into the study reach. The influence of the headcut was reflected in an increase in the water-surface slopes and in the concentrations of suspended sand.

Flow resistance, as measured by Manning's n, was approximately constant and was independent of the condition of the bed (cohesive or noncohesive) and of the average size distribution of the bed material.

Some observations of extreme sediment concentration are cited, and some of the problems involved in attempting to explain or to predict sediment transport rates for extreme conditions are discussed briefly.

The rapid changes in the channel geometry and in the characteristics of the bed material, and the extreme sediment concentrations that were observed, reflect conditions which, in general, are not described adequately by conventional sediment transport relations.

Observations in this report point out the extreme complexity of the natural processes operating in the Rio Puerco watershed and indicate the need for a better understanding of the factors controlling the flow and the sediment transport in ephemeral streams.

INTRODUCTION

Arid and semiarid regions are characterized by spectacular erosion features that have developed over short periods of time. Along with the erosion features, and equally spectacular, are the vast quantities of sediments delivered by the ephemeral streams to the major watercourses. Suspended-sediment loads in streams have been observed for many years, and something of the magnitude of the loads carried by the streams in arid or semiarid environments is known. However, there is little or no information on the mechanics of flow in streams carrying extreme concentrations of fine suspended material, and there exist no suitable methods for estimating the rates of sediment transport or for describing the flow and sediment characteristics which control the rates of transport.

This report presents preliminary findings of a study of sediment transport in streams with high concentrations of fine suspended sediment.

PURPOSE AND SCOPE

The purpose of this study was to investigate some aspects of the sediment-transport parameters and the mechanics of flow in streams transporting high concentrations of suspended fine material. Field observations were conducted on a reach of the Rio Puerco near Bernardo, N. Mex. The data obtained were supplemented by existing records of the Rio Puerco and other streams where applicable.

Specifically, the investigation included a study of the following: (a) Vertical-velocity distributions; (b) flow resistance; (c) vertical suspended-sediment concentration distributions; (d) channel-bed material and its effect on sediment-transport rates and related flow phenomena; and (e) extreme sediment concentrations.

PREVIOUS INVESTIGATIONS

The Rio Puerco in New Mexico is a notorious example of accelerated erosion, and several references to the channel and to the watershed are found in the literature. Bryan (1928, 1940) discussed some of the historical evidence of erosion in the Rio Puerco, and Leopold [1] presented some aspects of the erosion problem

[1] Leopold, L. B., 1950, The erosion problem of Southwestern United States: Ph. D. Dissertation, Harvard University.

over a wide area of the Southwest, including the Rio Puerco basin. Several reports deal with observations of other streams in semiarid environments, and many of the conclusions drawn probably apply to the Rio Puerco. Leopold and Miller (1956) indicated that certain hydraulic factors such as width, depth, velocity, and suspended-sediment load are related to the discharge as simple power functions. Schumm (1960, 1961) related the shape of alluvial channels (the width to depth ratio) to the types of sediment in the bed and banks and suggested that the relation between the channel shape and the weighted mean percent silt-clay can be used as a criterion for channel stability in ephemeral streams.

These and many other studies provide considerable insight into the nature of erosion and channel morphology, but none of the references deals specifically with the mechanics of sediment transport. Haushild (oral communication, 1960) and Simons and others (1963) used high concentrations of bentonite and kaolin as fine sediments in a series of flume experiments. They found that the fine material had a definite effect on the viscosity and specific weight of the fluid. Changes in the fall velocities of the bed material, caused by the variations in the fluid properties, influenced the form of bed roughness, the flow resistance, and the sediment transport. Earlier studies of transportation of fine sediments were given by Hsia [2] and Kalinske and Hsia (1945), who related the concentration of fine sediment to the composition of the bed, the ratio of fall velocity to shear velocity, and the shear velocity Reyonold's number. Some limited information on velocity and concentration distributions for field conditions was discussed by Nordin and Dempster (1963).

RIO PUERCO DRAINAGE BASIN AND THE STUDY REACH

The Rio Puerco drains approximately 6,200 square miles in central New Mexico (fig. 1). The drainage basin is bounded on the east by the Rio Grande drainage basin, on the west by the Continental Divide, on the north by the Jemez Mountains, and on the south by the Ladrone Mountains. Altitudes 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 about 10 inches over a major part of the basin (Dorroh, 1946).

In the past, some irrigated agriculture was practiced in the Rio Puerco valley. In more recent times, the major land use has been for grazing cattle and sheep. Over most of the watershed, vegetation is sparse, consisting mostly of pinon, juniper, and rough range grasses.

Large quantities of readily erodible sediments are available over most of the watershed. Observed suspended-sediment samples for the Rio Puerco near Bernardo contain, on the average, more than 50 percent clay-sized material. 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 carries large quantities of sand, of which there is an abundant supply generally available for transport. Deposits of fine wind-blown sands are present over much of the watershed, but the Santa Fe Formation of middle(?) Miocene to Pleistocene(?) age is exposed in many places along the lower 50 or 60 miles of the Rio Puerco and probably serves as a source for much of the sand transported by the stream. 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, N. Mex., shows alternate layers of fine sand and clay to a depth of about 70 feet and layers of sand and coarse gravel to 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 figure 1. Streamflow and suspended-sediment records for the Rio Puerco near Bernardo are published annually in Geological Survey Water-Supply Papers covering the hydrologic division, Part 8, Western Gulf of Mexico Basins.

The study reach for the observations presented in this report is approximately one-quarter of a mile downstream from the gaging station on the Rio Puerco near Bernardo, N. Mex. Figure 2 is a sketch map of the study reach, and figure 3 shows the reach as it appeared in July 1961. Section B is the site of the permanent cable installed for stream gaging and is approximately midway between the two bridges, which are about 1,900 feet apart.

OBSERVED DATA

Field observations and sampling included the following: Measuring water discharge, water-surface slope, water temperature, and water velocities at several points in one or more verticals in the section; collecting bed- and suspended-material samples; and taking photographs of the reach.

[2] Hsia, C. H., 1943, A study of transportation of fine sediments by flowing water: Ph. D. Dissertation, Iowa State University.

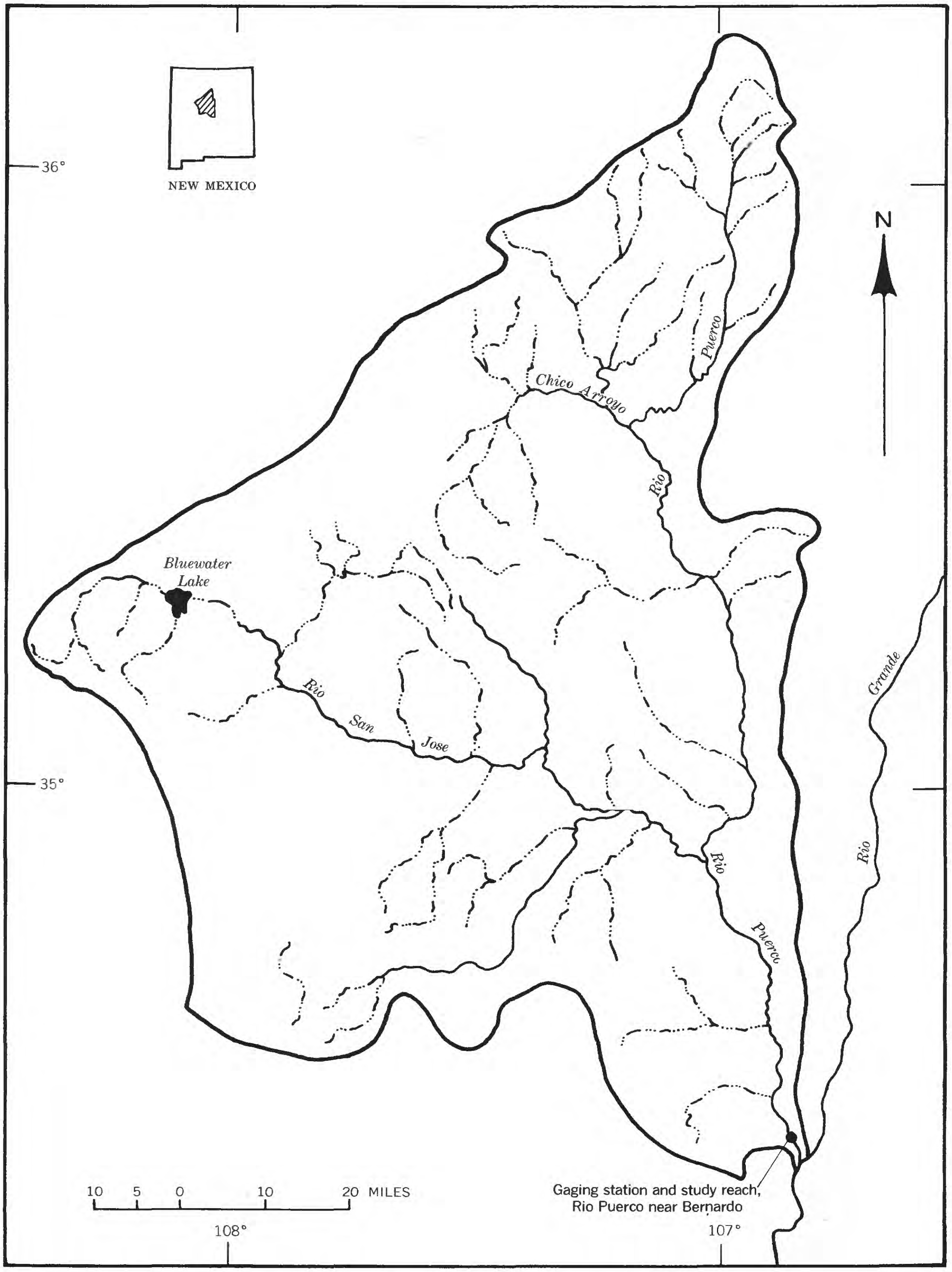


FIGURE 1.—The Rio Puerco drainage basin, showing the location of the study reach.

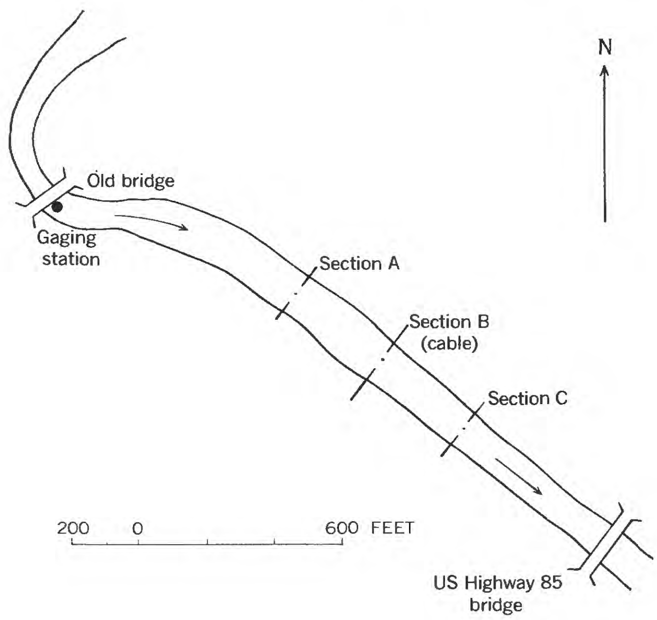


FIGURE 2.—Sketch map of the study reach.

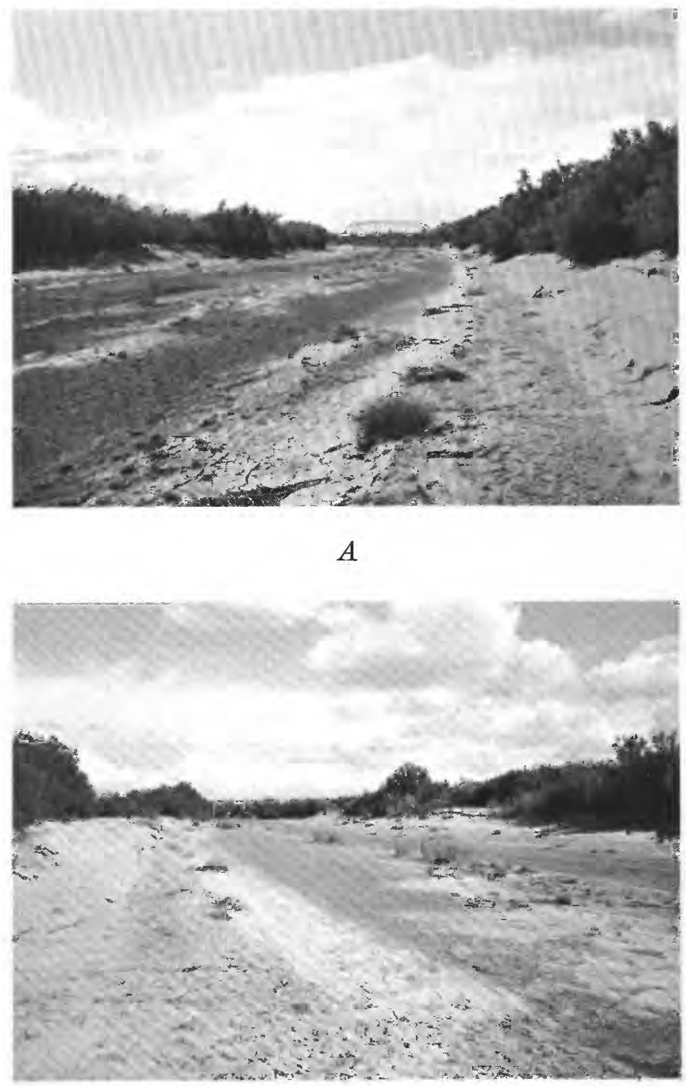
Velocities at points in the verticals were measured with a Price current meter, and water discharge was computed. Water-surface slopes were determined by staff gages at sections A, B, and C, referred to the datum of mean sea level. Bed material was sampled with a BM-54 bed-material sampler, which collects material from the top 1 or 2 inches of the bed. Suspended sediment was sampled with a US P-46 point-integrating sampler or with a modified US DH-48 hand sampler. These samplers collect material to within about 0.3 to 0.5 foot from the streambed.

Suspended-sediment samples were collected at several points in one or more verticals in the cross section to define vertical sediment concentration distributions. Depth-integrated samples collected at equal centroids of flow or depth-integrated samples collected at a series of equally spaced verticals of the cross section were analyzed to determine average concentrations and particle-size distributions of the suspended sediment in the sampled zone.

Particle-size distributions of bed material and of suspended sediments were determined by the pipette method for sizes smaller than 0.062 millimeter (Kilmer and Alexander, 1949) and by the visual-accumulation method for sand sizes (U.S. Inter-Agency Committee on Water Resources, 1957a).

Basic data for the hydraulic characteristics of the reach for the several observations in 1961 are given in table 1. Tables 2 and 3 show point velocity measurements and concentration distributions for various size classes of the point sediment samples, respectively, in 1961. All observations were at section B, and the stations shown in tables 2 and 3 correspond to the stationing of the permanent cable. Table 4 gives the average particle-size distributions for samples of suspended sediment and of bed material.

Water discharges and mean daily concentrations for July through September 1961 are shown in figure 4. Typically, the flow rose rapidly over the dry bed from runoff of short duration that resulted from high-intensity storms occurring upstream from the study reach. Discharge measurements and samples were difficult to obtain on rising stages because of the debris carried by the flow. Observations and sampling for the data in tables 1 through 4 were conducted during periods of receding flow.



A

B

FIGURE 3.—The study reach, July 1961. *A*, View upstream from section B; *B*, view downstream from section B.

TABLE 1.—*Basic data*

[Water surface altitudes are referred to the datum of mean sea level]

Date	Q (cfs)	T (°F)	b (ft)	$\bar{D}$ (ft)	$\bar{V}$ (fps)	S (ft per ft)	Water surface altitude	$V_* = \sqrt{gDS}$ (fps)	$C_f/\sqrt{g} = \bar{V}/\sqrt{g\bar{D}S}$	n (ft$^{1/6}$)	F
July 10	403	72	82.0	1.71	2.88	0.000385	4,730.76	0.145	19.9	0.0144	0.39
Aug. 18	31.4	82	24.0	.74	1.76	.00073	----------	.132	13.3	.0180	.36
Do	636	75	90.0	2.08	3.40	.00049	4,731.30	.181	18.8	.0159	.42
Aug. 19	2,380	74	119	4.47	4.46	.00024	4,734.60	.192	23.2	.0140	.37
Aug. 30	5.46	79	16.0	.29	1.14	.00105	----------	.099	11.5	.0185	.37
Sept. 11	1,110	66	91	2.08	5.87	.00122	4,731.81	.286	20.5	.0144	.72
Sept. 20	1,430	63	89	2.48	6.48	.00148	4,731.49	.344	18.9	.0162	.73

TABLE 2.—*Velocity distributions*

Date	Station	D (ft)	y (ft)	V (fps)	y (ft)	V (fps)	y (ft)	V (fps)	y (ft)	V (fps)	y (ft)	V (fps)
July 10	170	2.6	0.3	2.92	0.7	3.28	1.1	3.80	1.6	3.97	2.2	3.97
	170	2.5	.3	2.86	.7	3.43	1.2	3.72	1.7	3.97	2.1	3.97
Aug. 18	170	3.6	.5	3.20	1.0	3.88	2.0	4.25	3.0	4.54	------	------
	185	2.6	.5	3.43	1.1	3.97	1.6	4.15	2.1	4.15	------	------
Aug. 19	170	5.8	.5	3.80	1.0	4.25	2.2	4.84	3.4	5.18	4.6	5.18
	200	4.8	.5	4.45	.8	4.48	1.8	4.69	2.8	4.89	3.8	5.12
Sept. 11	155	2.6	.5	4.86	1.1	5.74	1.6	6.38	2.1	6.85	------	------
	170	3.1	.6	5.80	1.1	6.85	1.6	7.23	2.1	8.18	2.6	8.02
	185	3.0	.5	5.33	1.0	5.96	1.5	6.99	2.0	7.46	2.5	7.59
Sept. 20	155	2.5	.5	4.90	1.0	5.95	1.5	6.76	2.0	7.14	------	------
	170	3.6	.5	7.38	1.6	9.12	2.6	9.79	------	------	------	------
	185	3.8	.5	6.83	1.4	7.75	2.5	9.66	3.2	9.79	------	------

The reach of the Rio Puerco near Bernardo has been steadily aggrading for a number of years. At the beginning of the observations in the summer of 1961, the sand bed of the channel was impregnated with clay to a depth of about 0.6 foot. This clay armoring of the bed persisted through the observations of July 10 and August 18 and 19, 1961, and was reflected in extremely low concentrations of suspended sands for these dates (table 4). For the observations on September 11 and 20, at least a part of the bed was sand, and the concentrations of suspended sands were much higher.

Because the bed material varied from cohesive fine material to coarse sand with a median diameter of 0.5 mm, the results discussed below may not be generally applicable to all streams carrying high concentrations of suspended material. Nonetheless, differences in the characteristics of flow and of sediment transport for the different bed conditions lead to some significant conclusions that should prove useful to understanding the mechanics of flow and the sediment transport in similar streams.

In the following discussion of the results of this investigation it is assumed that the flow is uniform for

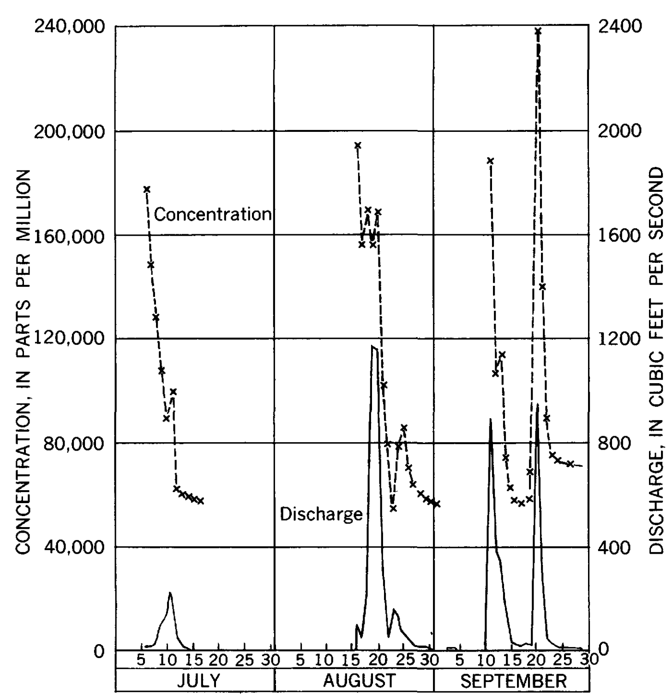


FIGURE 4.—Daily water discharge and concentration of suspended sediment, July-September 1961.

TABLE 3.—*Concentration distribution*

Date	Station	D (ft)	Y (ft)	$\frac{D-y}{y}$	Concentration in parts per million, for indicated size class, in millimeters: <0.002	0.002–0.004	0.004–0.008	0.008–0.016	0.016–0.031	0.031–0.062	0.062–0.125	0.125–0.25	0.25–0.50	Total
July 10	170	2.6	0.3	7.67	47,000	4,310	10,900	5,590	495	495	608	1,220	57	70,660
			.7	2.71	41,300	8,810	11,100	5,160	1,170	688	323	248	----------	68,810
			1.1	1.36	41,000	9,030	10,100	5,270	1,570	889	287	191	----------	68,360
			1.6	.625	41,800	8,690	9,850	5,090	1,970	475	48	20	----------	67,890
			2.2	.182	47,700	4,670	8,120	4,540	1,620	677	230	95	----------	67,690
Do	170	2.5	.3	7.33	41,500	7,530	8,340	5,560	2,170	1,360	502	841	----------	67,800
			.7	2.57	41,600	10,300	7,760	4,380	928	663	332	298	----------	66,320
			1.2	1.08	41,600	8,610	9,330	4,500	1,060	596	265	192	----------	66,160
			1.7	.471	40,800	8,620	8,420	4,770	1,500	784	215	137	----------	65,280
			2.1	.190	40,500	9,240	9,240	4,580	1,110	524	203	118	----------	65,520
Aug. 18	185	2.6	.5	4.20	95,400	15,700	11,700	26,300	24,000	3,920	410	344	36	178,200
			1.1	1.36	93,300	14,600	13,900	31,500	21,400	2,670	357	357	18	178,500
			1.6	.625	98,100	10,300	19,200	25,800	19,200	4,630	391	355	18	177,500
			2.1	.238	91,500	13,400	20,500	20,600	23,100	8,370	268	250	18	178,400
Aug. 19	170	5.8	.5	10.6	73,400	6,070	10,800	19,500	13,200	4,880	2,080	1,620	424	132,400
			1.0	4.80	68,600	17,000	7,200	15,900	12,600	6,160	1,930	1,400	197	131,100
			2.2	1.64	63,900	16,100	13,900	14,100	14,500	4,980	1,880	1,340	158	131,400
			3.4	.706	68,600	13,400	14,800	12,800	13,500	4,580	1,960	1,200	105	130,900
			4.6	.261	70,200	11,400	11,700	15,700	14,400	4,720	2,010	903	----------	130,800
Do	200	4.8	.5	8.60	66,800	8,980	15,800	13,600	16,000	7,390	1,950	1,330	119	131,800
			.8	5.00	66,300	10,400	13,000	13,800	16,900	6,630	1,780	1,210	52	130,200
			1.8	1.67	66,500	13,100	13,100	14,100	14,300	6,810	1,750	1,200	92	130,800
			2.8	.714	71,400	7,730	11,800	14,700	16,100	6,420	1,760	1,080	26	131,200
			3.8	.263	66,400	6,050	11,600	13,500	17,400	8,320	1,730	993	13	125,700
Sept. 11	200	2.0	.3	5.67	61,700	7,990	10,200	13,300	21,600	21,600	22,500	10,200	1,020	170,300
			.6	2.33	62,500	6,720	8,360	11,600	20,000	26,400	21,100	6,800	589	163,600
			1.0	1.00	59,000	8,860	9,020	12,300	18,000	28,000	22.000	6,430	426	164,000
			1.5	.333	63,000	11,100	4,350	12,400	21,700	22,400	20,500	5,590	97	161,000
Sept. 20	170	3.4	.4	7.50	55.900	16,300	8,750	13,900	34,700	34,300	50,300	27,200	1,700	243,100
			1.0	2.40	55,400	4,920	5,410	38,600	10,100	41,800	56,800	30,700	2,210	245,700
			2.2	.545	70,200	14,600	8,320	13,200	22,600	40,700	45,000	16,100	231	236,000
			3.0	.133	75,300	11,400	6,050	16,400	22,000	40,500	39,400	13,000	----------	223,700
Do	185	3.3	.4	7.25	64,800	7,480	11,900	14,400	24,800	39,500	52,600	36,600	5,930	258,000
			1.3	1.54	63,900	8,260	10,200	17,700	23,300	41,800	51,700	24,300	1,700	242,600
			2.1	.571	51,400	16,600	8,320	17,100	24,700	45,500	46,300	19,200	926	231,400
			2.7	.222	82,100	9,680	1,580	17,100	25,900	32,000	38,300	17,600	902	225,500

TABLE 4.—*Particle-size distribution of suspended sediment and bed material*

[Methods of analysis: P, pipette; W, in distilled water; C. chemically dispersed; M, mechanically dispersed; V, visual-accumulation tube]

Date	Type of sample	Water discharge (cfs)	Concentration sample (ppm)	Percent finer than indicated size, in millimeters: 0.002	0.004	0.008	0.0156	0.0312	0.0625	0.125	0.250	0.500	1.00	2.00	4.00	Methods of analysis
July 19	Suspended	403	75,800	63.0	73.4	87.7	98.7	99.2	99.4	99.8	99.9	100	--------	--------	------	VPWCM
Aug. 18	do	636	178,000	50.8	61.7	71.0	84.4	96.7	99.6	99.8	100	--------	--------	--------	------	VPWCM
Aug. 19	do	2,380	132,000	52.0	59.2	66.8	80.5	92.5	97.3	99.1	100	--------	--------	--------	------	VPWCM
Sept. 11	do	1,110	175,000	33.6	38.5	41.1	49.9	60.5	75.5	93.8	99.8	100	--------	--------	------	VPWCM
Sept. 20	do	1,430	240,000	26.6	30.3	35.1	42.3	51.8	64.9	88.6	99.6	100	--------	--------	------	VPWCM
July 10	Bed material	403	----------	24.2	28.4	34.4	39.6	45.3	53.3	70.8	92.3	99.8	100	--------	------	VPWCM
Aug. 18	do	636	----------	------	------	------	------	------	84.8	88.7	96.9	99.7	100	--------	------	V
Aug. 19	do	2,380	----------	------	------	------	------	------	65.6	69.3	81.1	98.2	100	--------	------	V
Sept. 11	do	1,110	----------	21.9	25.7	27.4	31.6	36.2	44.8	55.0	80.5	95.1	99.7	100	------	VPWCM
Sept. 20	do	1,430	----------	11.6	14.1	16.4	20.4	24.2	29.5	43.0	68.7	85.9	97.8	99.6	99.9	VPWCM

the time of the observations; that the water-surface slope equals the slope of the energy gradient through the reach; and that the hydraulic radius, R, approximately equals the mean depth of flow, $\overline{D}$.

VELOCITY DISTRIBUTIONS

Plots of velocity, V, against the distance, y, from the streambed for the various points in the verticals (fig. 5) indicate that the velocity is proportional to the logarithm of the depth. The figure suggests that the velocity distribution perhaps can be described by some form of the von Karman-Prandtl logarithmic velocity equation.

The logarithmic velocity equation, as given by Kuelegan (1938) for two-dimensional open-channel flow over a rigid wholly rough boundary, is

$$\frac{V}{V_*}=\frac{2.303}{k}\log\frac{y}{K_s}+C_1. \tag{1}$$

where

y=the distance from the streambed, in feet;
V=the velocity at the distance y from the streambed, in feet per second;
V_*=the shear velocity=$\sqrt{gRS}$, in feet per second;
k=the dimensionless coefficient of turbulent exchange;
K_s=a length parameter, describing the roughness elements on the bed, in feet;
C_1=a dimensionless constant;
R=the hydraulic radius, in feet;
S=the slope of the energy gradient, in feet per foot; and
g=the acceleration due to gravity, in feet per second squared.

For a sand-grain-type roughness, the length parameter, K_s, assumes the value of the representative size of the sand. For uniform sands, the representative size may be taken as the median diameter, d; whereas for naturally worn river sediments, the representative size is more closely given by the diameter for which 65 percent by weight of the mixture is finer, d_{65} (Einstein, 1950).

In general, equation 1 does not adequately describe the velocity distributions for flow over an alluvial bed. The values of K_s and C_1 which are found applicable for flow over a rigid boundary with a sand-grain roughness, are not applicable for flow over a mobile boundary where there is moving sediment, even though the channel bed be plane and free from irregularities. A recent study of vertical velocity distribution for flow in the Rio Grande showed that for flow over a plane bed, if the constant C_1 is assumed equal to the value 8.5 given by Kuelegan, the length parameter, K_s, has an average value of about 400 times d_{65} (Nordin and Dempster, 1963). On the other hand, if there are dunes and major bed configurations in the channel, the velocity is not proportional to the shear velocity, $\sqrt{gRS}$, but to some values less than the shear velocity (Einstein, 1950).

Regardless of the values which K_s and C_1 may assume, if a form of equation 1 applies for the velocity distributions in the individual verticals, it is possible to investigate the values of the von Karman coefficient of turbulent exchange from the observed vertical velocity distributions. Values of k can be computed from equation 1 as

$$\frac{V_1-V_2}{\log y_1-\log y_2}=\frac{2.303\ V_*}{k}=m, \tag{2}$$

where V_1 and V_2 are the velocities at distances y_1 and y_2, respectively, and m is the slope of the velocity profile, in feet per second, and is equal to the change in velocity for one log cycle of depth; thus,

$$k=\frac{2.303\ V_*}{m}. \tag{3}$$

Values of k were computed for each of the verticals plotted in figure 5 by measuring the slope, m, of the line fitted by eye through the plotted points and by assuming the value of V_* to be equal to $\sqrt{gDS}$, where D is the depth at the vertical. Values of m and k, so computed, are shown in figure 5.

Some of the velocity profiles are not well defined. The velocity profile for station 185 on September 20 was influenced by violent antidunes in the section and probably is not suited to the determination of k. The k value of 0.617 for station 200 on August 19 was probably due to three-dimensional flow effects or to secondary circulation. Sayre and Albertson (1961) reported k values ranging from 0.34 to 2.77, as determined by the velocity-profile method for clear-water flow over isolated roughness baffles. They attributed the large variation in k to three-dimensional flow effects and to large-scale vortices. Nordin and Dempster (1963) showed a similar large variation in k for flow over a dune bed in the Rio Grande, where k ranged from 0.35 to 1.2 and was generally greater than 0.4.

The values of k found in the Rio Puerco appear to be consistent with the values reported by other investigators (Vanoni and Nomicus, 1960; Nordin and Dempster, 1963). For those dates when the channel bed was armored with clay, the values of k varied from 0.32 to 0.62 and averaged 0.38; whereas for the observations when the bed was partly covered with sand and large quantities of sand were carried in suspension, the values of k varied from 0.22 to 0.31 and averaged 0.25.

Ismail (1951) suggested that sediment dampens the turbulence and reduces the momentum transfer, which

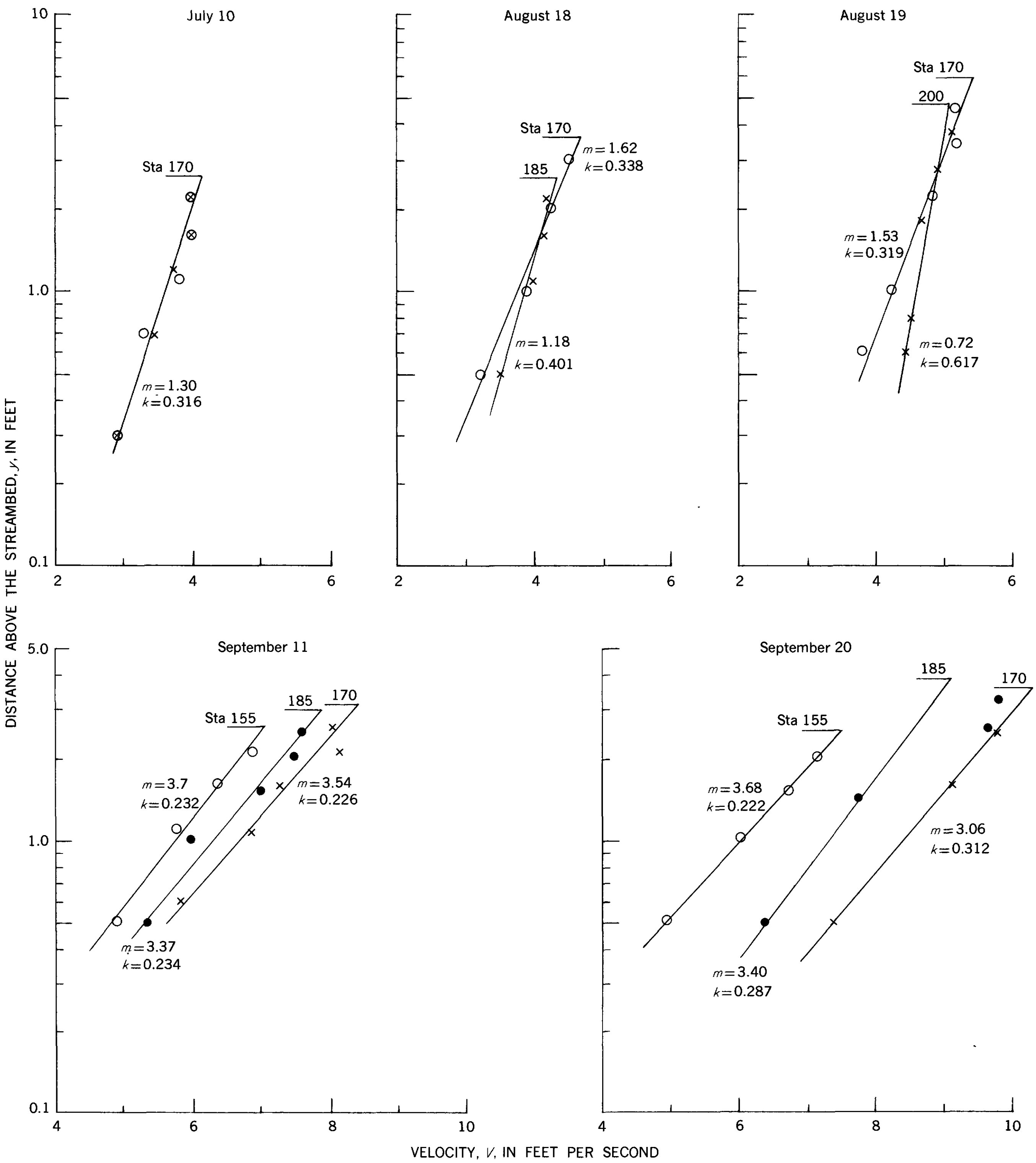


FIGURE 5.—Variation of velocity with the distance above the streambed.

results in a reduction in k. Einstein and Chien (1954) and Vanoni and Nomicus (1960) correlated the reduction in k with the ratio of energy required to support the sediment to the energy dissipated in overcoming friction. According to Vanoni and Nomicus, the power, P_s, to support the sediment in a water prism with unit horizontal area, A, and depth, D, equal to the stream depth is

$$P_s=\frac{\gamma_s-\gamma}{\gamma_s}\,Ac\omega D, \tag{4}$$

in which γ and γ_s are the specific weights of water and sediment, respectively; c is the mean concentration over the depth, in weight per unit volume; and ω is the settling velocity of the sediment. The power P_f to overcome the friction of the prism of water is

$$P_f=A\gamma DVS. \tag{5}$$

The ratio of the two powers is

$$\frac{P_s}{P_f}=\frac{(\gamma_s-\gamma)c\omega}{\gamma_s\gamma VS}. \tag{6}$$

The value of k was found to decrease with increasing values of the ratio P_s/P_f (Einstein and Chien, 1954).

The values of the ratio P_s/P_f were not computed for the data given in this report for two reasons. First, it is extremely difficult to determine what fall velocity should be used in equation 4 when high concentrations of fine material are present in the stream, due to the variable viscosity and mass density of the stream fluid; and second, equation 6 is not a good index to the reduction in k in streams transporting high concentrations of fine material, because the equation does not account for the energy added by the sediment.

According to Bagnold (1956), the sediment contributes to the total tractive force on the bed by an amount equal to the tangential component along the bed of the submerged weight of the sediment. In form analogous to equation 4, the power contributed by the sediment can be expressed as

$$P_s'=\frac{\gamma_s-\gamma}{\gamma_s}\,AcVD\ \mathrm{Sin}\ \beta, \tag{7}$$

where β is the postive angle of inclination between the bed and the horizontal. For the small angles usually found in natural channels, Sin β may be assumed equal to the slope, S. The ratio of the power to support the sediment to the power contributed by the sediment (equation 4 divided by equation 7) is given by

$$\frac{P_s}{P_s'}=\frac{\omega}{VS}. \tag{8}$$

Thus, the power added by the sediment to the flow will be greater than the power extracted from the flow in supporting the sediment when ω is less than the product VS. For the August 18 observation, the product $VS=3.40\times0.00049=0.00167$ fps (feet per second), and the median diameter of the suspended material is less than 0.002 mm (millimeter). The fall velocity from Stokes' equation for a sphere with a diameter of 0.002 mm and a specific gravity of 2.65 falling in distilled water at a temperature of 75° F is about 1.28×10^{-5} fps. The fall velocity of a similar particle in natural stream conditions would be even less. Thus, the energy added by the sediment is about 130 times as great as the energy required to support the sediment.

Equation 6 probably is not a good measure of the reduction in k where the energy added by the sediment is equal to or greater than the energy required to support the sediment.

If equation 8 is approximately correct, it can be seen that the concentration of fine sediment can be increased indefinitely; that is, there is no upper limit to the concentration which may be found in natural streams transporting fine materials other than the static limit imposed by some upper limiting concentration at which the mixture turns into a mudflow.

FLOW RESISTANCE

The overall resistance to flow, as measured by Manning's n and by the dimensionless Chezy coefficient $C_c/\sqrt{g}$, was determined for each of the observations in table 1. Excluding the two lowest discharges (August 18, 30), the flow resistance was remarkably constant. Values of Manning's n ranged from 0.0140 to 0.0162 and averaged 0.0150. The maximum deviation from the average value was +8 percent.

For the low discharges of August 18 and 30, values of Manning's n were about 0.018. The greater flow resistance may be attributed, in part, to sinuosity effects in the low flow channel.

Recent (1962) studies of flow resistance for the Rio Grande near Bernalillo, N. Mex., indicate that values of Manning's n vary from 0.035 to 0.012, depending upon the configuration of the channel bed. The average value of n is about 0.030 for a dune bed and 0.015 for a plane bed. The median diameter of the bed material for these observations was 0.29 mm.

The flow resistance for the Rio Puerco was comparable to the flow resistance over a plane sand bed for the Rio Grande. In general, bed configuration does not influence the flow resistance for the Rio Puerco except at low stages; most of the flows for discharges greater than about 300 cfs (cubic feet per second) are over a plane bed.

It is significant that the resistance coefficients for the Rio Puerco do not seem to be controlled by the condition of the channel bed or by the size distribtuion of the bed material. There was no appreciable difference between the flow resistance over the clay-armored bed and the flow resistance over the sand bed.

CONCENTRATION DISTRIBUTIONS

The equation for sediment suspension was introduced by O'Brian (1933) in the form of a standard diffusion equation:

$$\omega C = \epsilon_s \frac{dc}{dy}, \tag{9}$$

where $\epsilon_s dC/dy$ equals the rate of upward transfer of suspended sediment through turbulent exchange. Rouse (1937) showed that equation 9 could be integrated to yield an equation for the distribution of the relative concentration of the suspended sediment as

$$\frac{C_y}{C_a} = \left(\frac{D-y}{y}\,\frac{a}{D-a}\right)^Z, \tag{10}$$

where

C_y = the concentration of a grain size at the distance y above the bed, in parts per million;

C_a = the concentration of a grain size at reference level a above the bed, in parts per million; and

Z = the theoretical exponent of the distribution equation given by

$$Z = \frac{\omega}{kV_*}. \tag{11}$$

In the derivation of equations 10 and 11, it was assumed that the transfer coefficient for the sediment ϵ_s equals the momentum transfer coefficient ϵ_m.

Equation 10 plotted logarithmically is a straight line with a slope Z. If values of the observed concentration C_y at the depth y are plotted against the values of $(D-y)/y$ on a logarithmic scale, the slope of the line through the plotted points equals Z_1, the observed exponent of suspended-sediment distribution. Typical concentration distributions for some of the size classes given in table 3 are shown plotted in figures 6 through 8. In general, the slope, Z_1, of the line which was fitted by eye to the plotted points is not well defined.

Values of the observed exponent Z_1 usually do not agree with the values of Z, the computed exponent from equation 11. One reason for the difference is that the fall velocity, ω, used to compute Z is usually taken as the terminal fall velocity of a particle falling alone in quiescent distilled water of temperature equal to the stream temperature, whereas the fall velocity in the actual stream may assume a value of a completely different order of magnitude.

It is impossible to determine the fall velocity of a sediment particle in the natural condition of a stream, but it is possible to determine some of the effects of the concentrations of fine sediment upon the fall velocity of the sand-size particles. Simons and others (1963) determined apparent viscosities of suspensions of varying concentrations of bentonite and kaolin in water and computed fall velocities based upon the mass densities

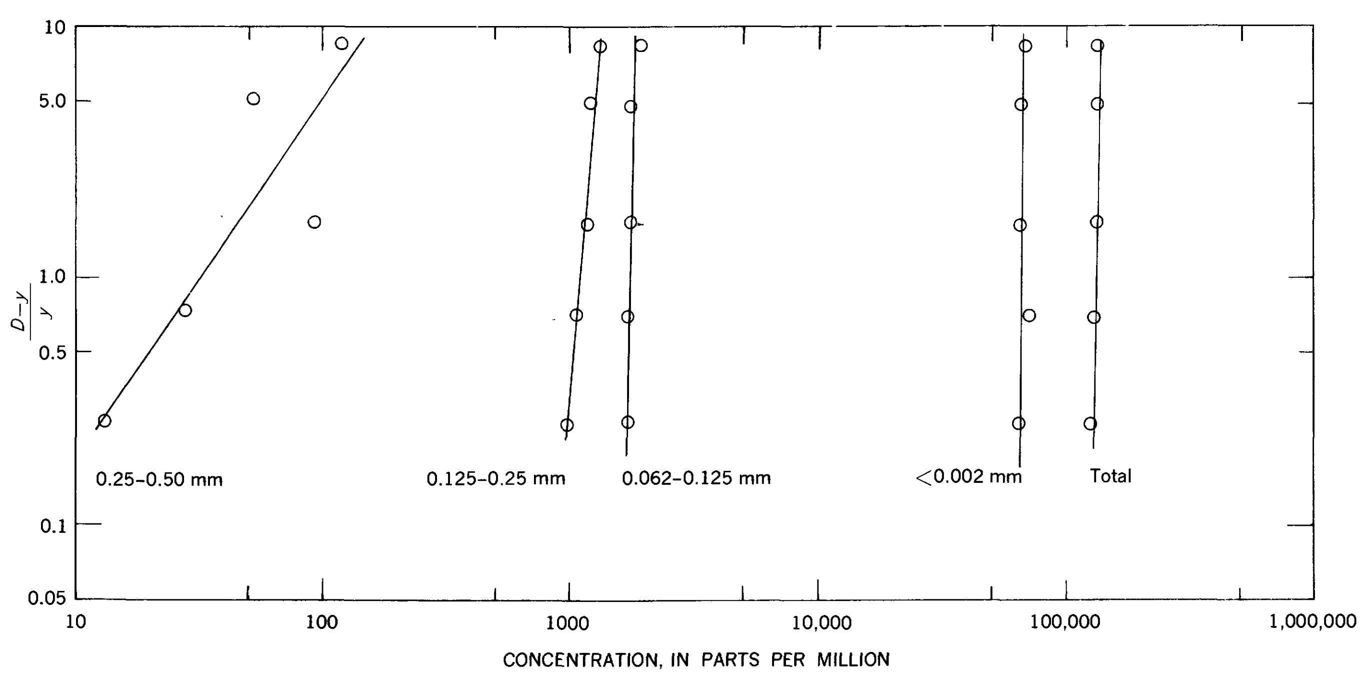


FIGURE 6.—Variation of concentration with $(D-y)/y$, station 200, August 19, 1961.

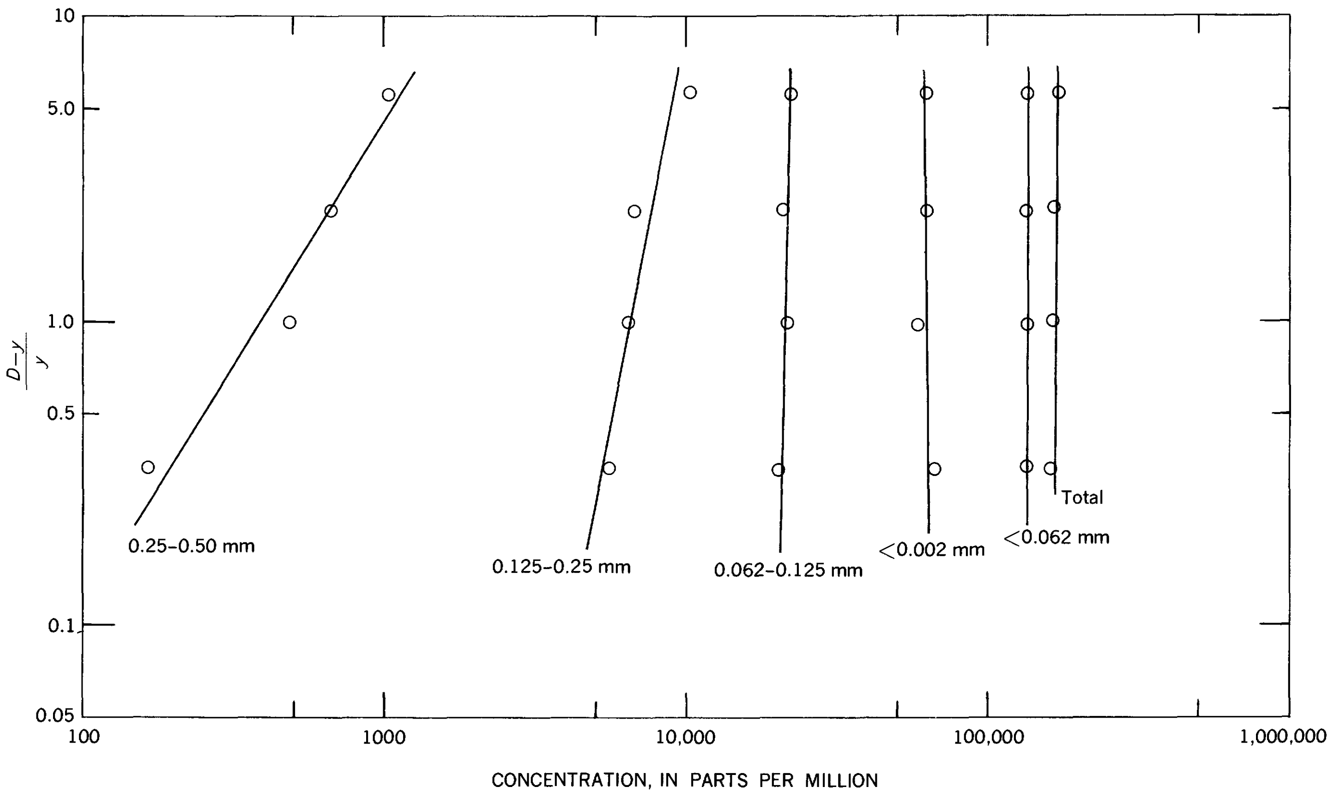


FIGURE 7.—Variation of concentration with $(D-y)/y$, station 200, September 11, 1961.

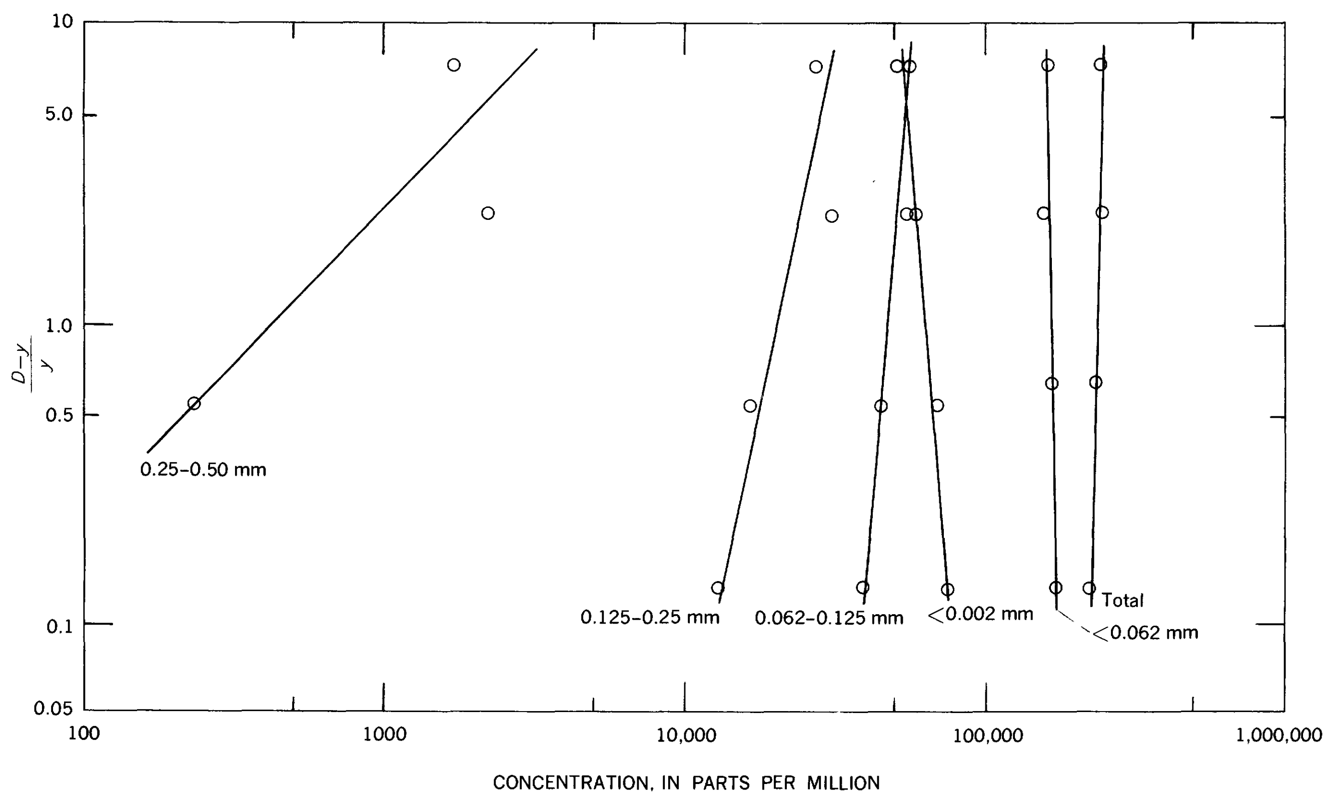


FIGURE 8.—Variation of concentration with $(D-y)/y$, station 170, September 20, 1961.

and the apparent viscosities of the fluids, using theoretical considerations and empirical relations given in Inter-Agency Committee on Water Resources (1957b). The computed fall velocities compared favorably with fall velocities determined by analyzing a sand of known distribution in the visual-accumulation tube, using suspensions of known concentrations of fine material as a sedimentation fluid.

The determination of the effects of concentrations of suspensions of fine sediment upon fall velocities using the visual-accumulation tube is simple. Figure 9 shows the particle-size distribution of a sample of sand from the bed of the Rio Puerco analyzed in distilled water (curve *A*) and in a suspension of fine sediment (curve *B*). The median diameter in distilled water is 0.33 mm, which has a standard fall velocity of 4.9 cm per sec (centimeters per second) at 24° C. The median diameter of the sample in the native water is 0.16 mm, which has a standard fall velocity of about 1.84 cm per sec. If values of fall velocity determined in this manner are plotted along the ordinate against concentrations of fine sediment in the sedimentation fluid, plotted on the abscissa, the plotted points define a trend which is indicative of the effects of concentrations of fine material upon fall velocity.

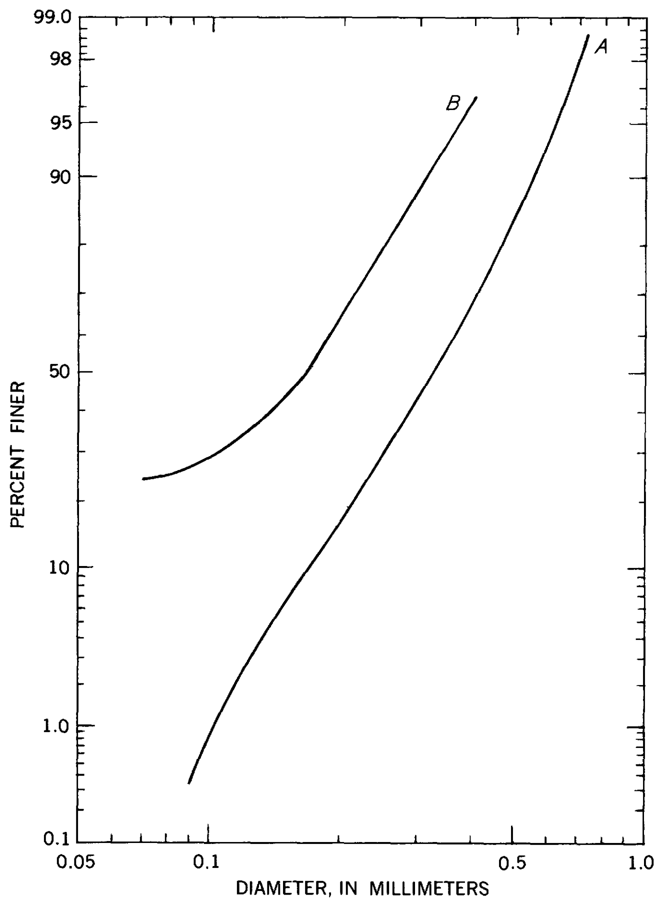


FIGURE 9.—Particle-size distributions from visual-accumulation-tube analysis in distilled water (curve *A*) and in native water with 150,000 ppm suspended sediment finer than 0.053 mm (curve *B*).

Figure 10 shows the trends defined by the method described above for the geometric mean of several size classes of sands. The sedimentation fluids used were (a) suspensions of fine material (<0.053 mm) from the Rio Puerco in native water, mechanically dispersed; and (b) suspensions in distilled water, mechanically and chemically dispersed. The ratio of the weight of the dispersing agent (sodium hexametaphosphate) to the weight of the fine sediment was 1 to 100. Some flocculation of the clays occurred in the native water. The flocculation did not have any major effects on the size distributions for low concentrations of fine material, but at concentrations of about 100,000 ppm or greater the flocculation of the clay appeared to cause a clogging of the sand grains in the visual-accumulation tube. Several of the points in figure 8 with extremely low fall velocities are the results from analysis where the clogging occurred. No weight was given these points in drawing the trend lines in the figure. The fall velocity defined by figure 10 will be designated ω'.

Values of Z', the sediment distribution exponent computed from equation 11 using ω' from figure 10, show better agreement with Z_1 than do the values Z com-

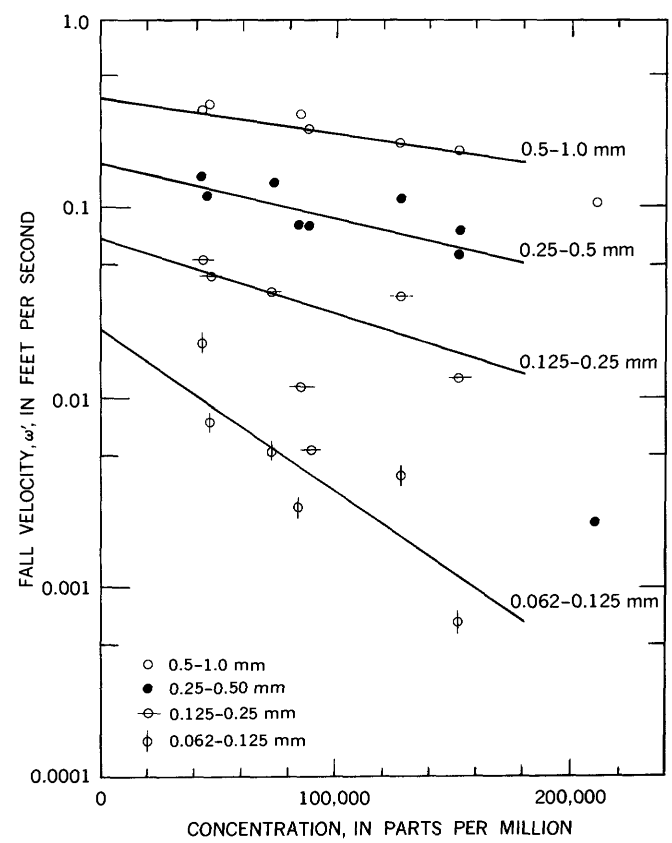


FIGURE 10.—Variation of fall velocity with concentration.

puted using the standard fall velocities, ω. Computations of values Z and Z' for given dates in 1961 are given in table 5, and values of Z and Z' are plotted against Z_1 in figure 11.

As might be expected, there is considerable scatter in the relation of Z' to Z_1. Part of this scatter may be attributed to variations in the stream temperature, which ranged from 17° C to 24° C. The relation of fall velocity to concentration was defined for only one temperature, 24° C, and was applied to all the Z values regardless of the temperature of the stream.

The effect of temperature on the fall velocities for a given sand size and concentration of fine material was not defined from the data in this investigation. However, something of the magnitude of the temperature effects may be indicated. Figure 12 shows the variation of the apparent viscosity with temperature of dispersed fine sediments in native water for the Rio Puerco near Bernardo, N. Mex., for a range of temperature from 2° C to 40° C at a constant concentration of 127,000 ppm. The apparent viscosities were determined with a Stormer Viscometer. Simons and others (1963) found that for a given fine material dispersed in distilled water, the ratio of the viscosity of the dispersion to the viscosity of water was independent of temperature. Therefore, some of the scatter in figures 10 and 12 probably is due to variations in viscosity of the dispersions other than the variations caused by concentration and temperature.

Other major factors which influence the viscosity of a clay-water system are the mineralogical composition of the clay, the nature and amount of adsorbed ions, and the electrolytes present in solution (Houwink, 1952).

Partial chemical analyses of the native water of the Rio Puerco for two of the observation dates in 1961 are given in table 6. The mineralogic composition of the suspended sediment finer than 0.004 mm for September 11, 1961, is shown in table 7. This information was fur-

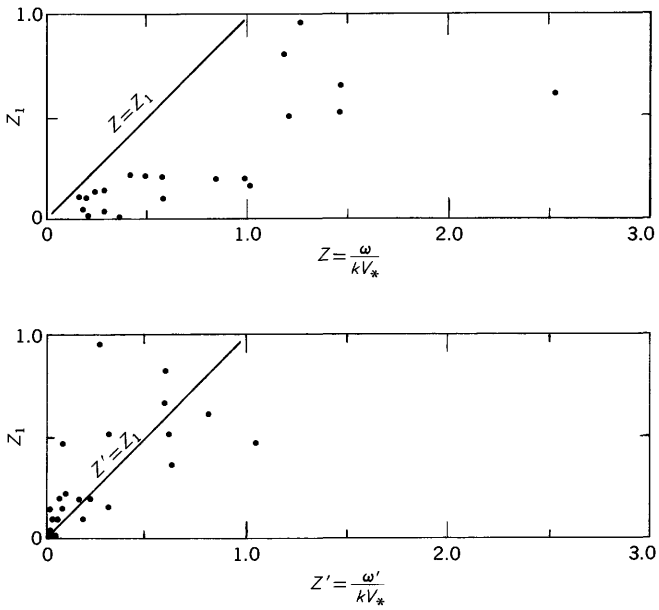


FIGURE 11.—Z and Z' plotted against Z_1.

nished by Mr. V. C. Kennedy, U.S. Geological Survey, Denver, Colo. (oral communication, 1962). The cation exchange capacity for this sample was not available for this report. Without knowing the exchange capacity, it is impossible to predict the effects of the chemical constituents in the native water upon the properties of the suspension.

Because illite and montmorillonite plus mixed-layer clay constitute more than 50 percent of the clay-sized material, it is assumed that the exchange capacity is high and that the chemical constituents of the native water have considerable effect upon the properties of the suspension.

The general shape of the viscosity curves for clay-water systems with various amounts of added base is shown qualitatively in figure 13. Where both monovalent and divalent ions are present (table 6), the general shape of the viscosity curve would probably fall somewhere between the extremes shown in figure 13.

TABLE 5.—*Measured and computed exponents of sediment distribution*

Date	Station	D (ft)	$V_*=\sqrt{gDS}$ (fps)	k	T (°C)	ω, in feet per second			ω', in feet per second			Z_1			$Z=\omega/kV_*$			$Z'=\omega'/kV_*$		
						0.062–0.125 (mm)	0.125–0.25 (mm)	0.250–0.50 (mm)	0.062–1.25 (mm)	0.125–0.25 (mm)	0.250–0.50 (mm)	0.062–0.125 (mm)	0.125–0.25 (mm)	0.250–0.50 (mm)	0.062–0.125 (mm)	0.125–0.25 (mm)	0.250–0.50 (mm)	0.062–0.125 (mm)	0.125–0.25 (mm)	0.250–0.50 (mm)
July 10	170	2.6	0.179	0.317	22	0.0226	0.0669	-------	0.005	0.034	-------	0.48	0.82	-------	0.400	1.18	-------	0.088	0.600	-------
	170	2.5	.176	.316	22	.0226	.0669	-------	.005	.034	-------	.22	.51	-------	.406	1.20	-------	.090	.612	-------
Aug. 18	185	2.6	.205	.401	24	.0233	.0699	0.174	.00066	.014	0.052	.14	.20	0.36	.283	.837	2.12	.008	.170	0.63
Aug. 19	170	5.8	.212	.319	23	.0230	.0684	.172	.0017	.021	.070	0	.16	.47	.340	1.01	2.54	.025	.311	1.04
	200	4.8	.192	.617	23	.0230	.0684	.172	.0017	.021	.070	.02	.10	.67	.195	.580	1.46	.014	.178	.593
Sept. 11	200	2.0	.280	.23	19	.0207	.0633	.163	.0007	.014	.052	.03	.20	.62	.321	.983	2.53	.011	.217	.807
Sept. 20	170	3.4	.402	.312	17	.0203	.0623	.159	.0002	.0077	.034	.10	.21	.96	.162	.498	1.27	.002	.062	.272
	185	3.3	.383	.287	17	.0203	.0623	.159	.0002	.0077	.034	.10	.20	.52	.185	.566	1.45	.002	.070	.309

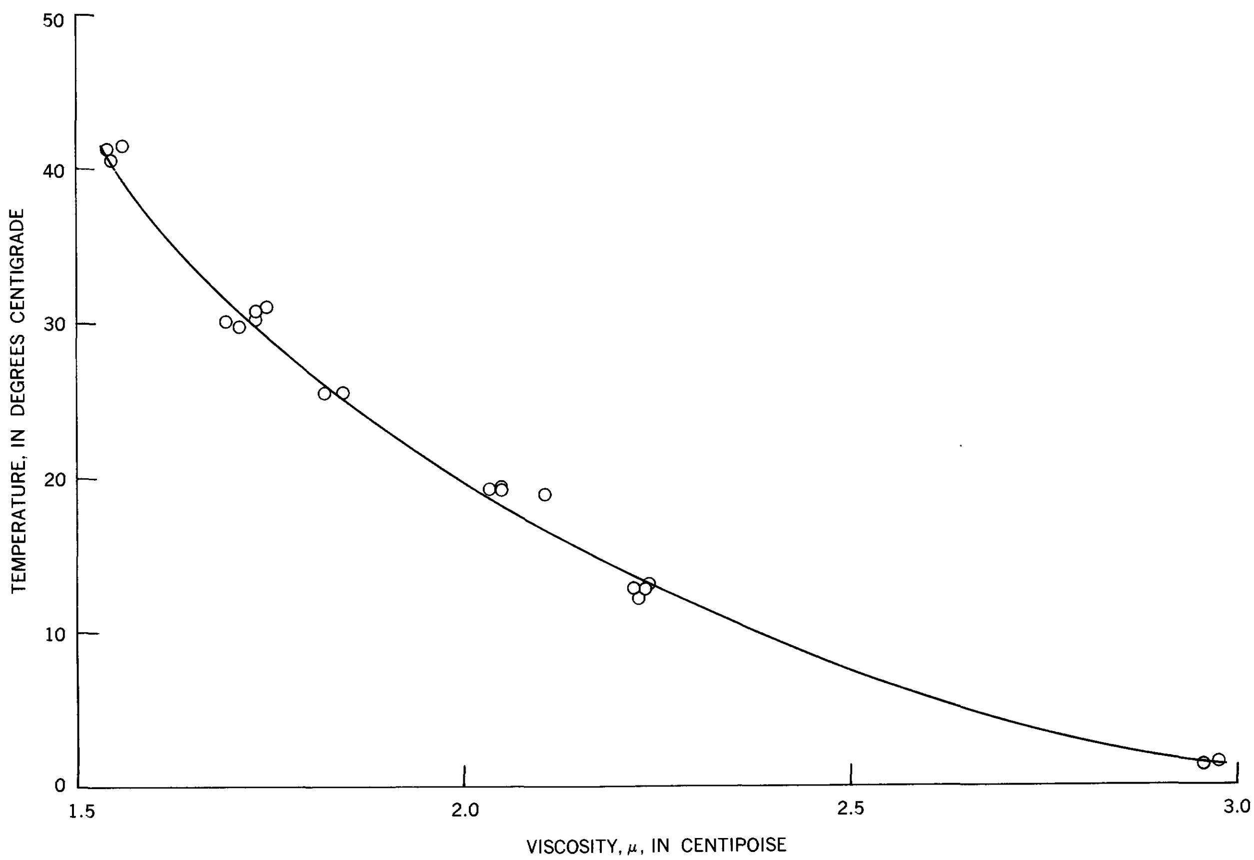


FIGURE 12.—Variation of apparent viscosity with temperature for dispersed fine sediment in native water, Rio Puerco near Bernardo. N. Mex.

TABLE 6.—*Partial chemical analysis of native water*

Date	Specific conductance (micromhos at 25°C)	pH	Concentration (parts per million)					
			Total	Ca	Mg	Na	K	Na+K
July 10	3,050	7.2	2,200	198	36	473	15	------
Sept. 11	1,730	7.3	1,270	158	17	------	------	228

TABLE 7.—*Mineralogical composition of suspended sediment finer than 0.004 mm, September 11, 1961*

Material	*Percent*
Amorphous material	2–3
Kaolinite (hydromica)	25–30
Illite	10–15
Montmorillonite plus mixed-layer clay	40–45
Quartz	9–12
Calcite	2–3

Previous records show appreciable variations in the concentrations of the chemical constituents in the Rio Puerco flow. The physical properties of the fine sediments—such as the color, size distribution, and plasticity—are known to vary, depending upon the source of the sediment. It may be assumed that the mineralogical composition of the material finer than 0.004 mm also varies. Obviously, on the Rio Puerco the clay-water systems become extremely complex, and the viscosities of the dispersions cannot be predicted with any degree of certainty. It is generally conceded that the effects of the factors influencing the viscosity of heterogeneous fluids containing ionized particles are beyond explanation at the present time (Houwink, 1952).

So far as sediment transport is concerned, the effects of fine material upon the fall velocities and concentration distributions of sand-sized particles must be defined from empirical relations, such as those in figures 10

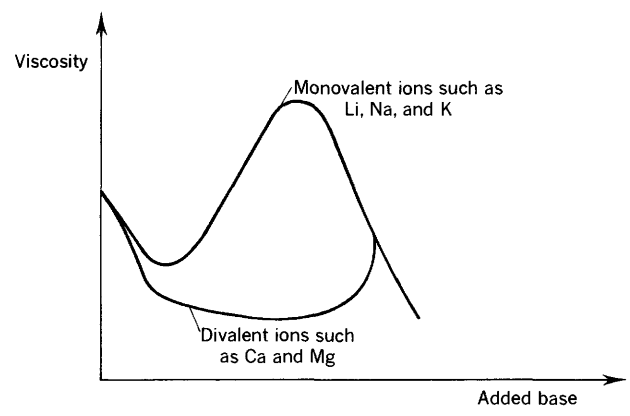


FIGURE 13.—General shape of the viscosity curves for clay-water systems with various amounts of added base. From Simons and others (1963).

and 12. As shown by figure 11, these empirically defined relations cannot be expected to yield accurate results.

From a practical viewpoint, however, it is probably not necessary to determine accurately the concentration distributions in streams such as the Rio Puerco, because the total concentration distribution is so nearly uniform through a vertical that samples taken anywhere in the vertical give a reasonable representation of the average concentration and particle-size distribution of the sediment transported by the stream. From figures 6 through 8 and table 3, it can be seen that in almost all instances the slope of the line through the points representing total concentrations is not much different from the slope of the line through the points for the very finest fraction. (Some of the fine fractions show a reverse concentration gradient; that is, the concentration appears to be greater near the surface than near the bed. This is probably due to errors inherent in the sampling and laboratory procedures.) Also, the total concentration distribution depends to some extent upon the concentrations of sands in the flow; as will be shown in the next section, the concentration of the sands is unpredictable over a considerable range of conditions.

CHANNEL BED

The characteristics of the channel-bed material effect both the flow and the sediment transport.

When this investigation began in July 1961, the sand bed of the channel was impregnated with clay to a depth of about 0.6 foot (fig. 14). Analyses of core samples for particle-size distribution showed the clay-armored layer to have a median particle diameter of 0.067 mm and to contain about 50 percent sand, 23 percent silt, and 27 percent clay. The underlying sand contained 10 percent fine material and had a median particle diameter of 0.20 mm (fig. 15).

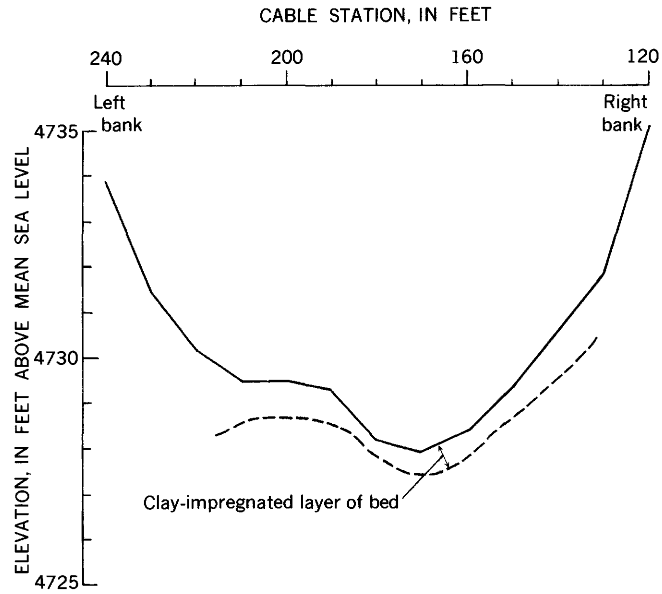


FIGURE 14.—Section B, showing the thickness of the clay-impregnated layer of the bed.

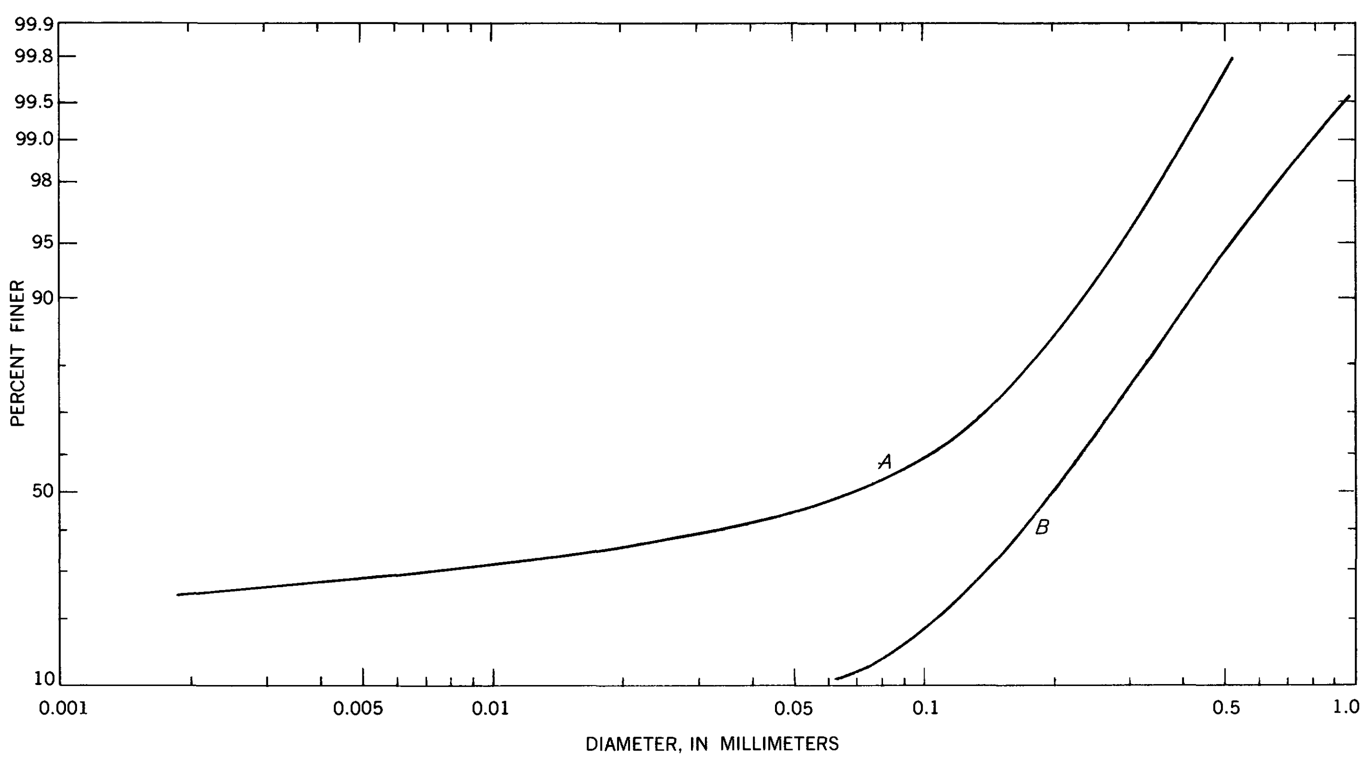


FIGURE 15.—Particle-size distribution of the clay-impregnated layer of the bed (curve A) and of the underlying sand (curve B).

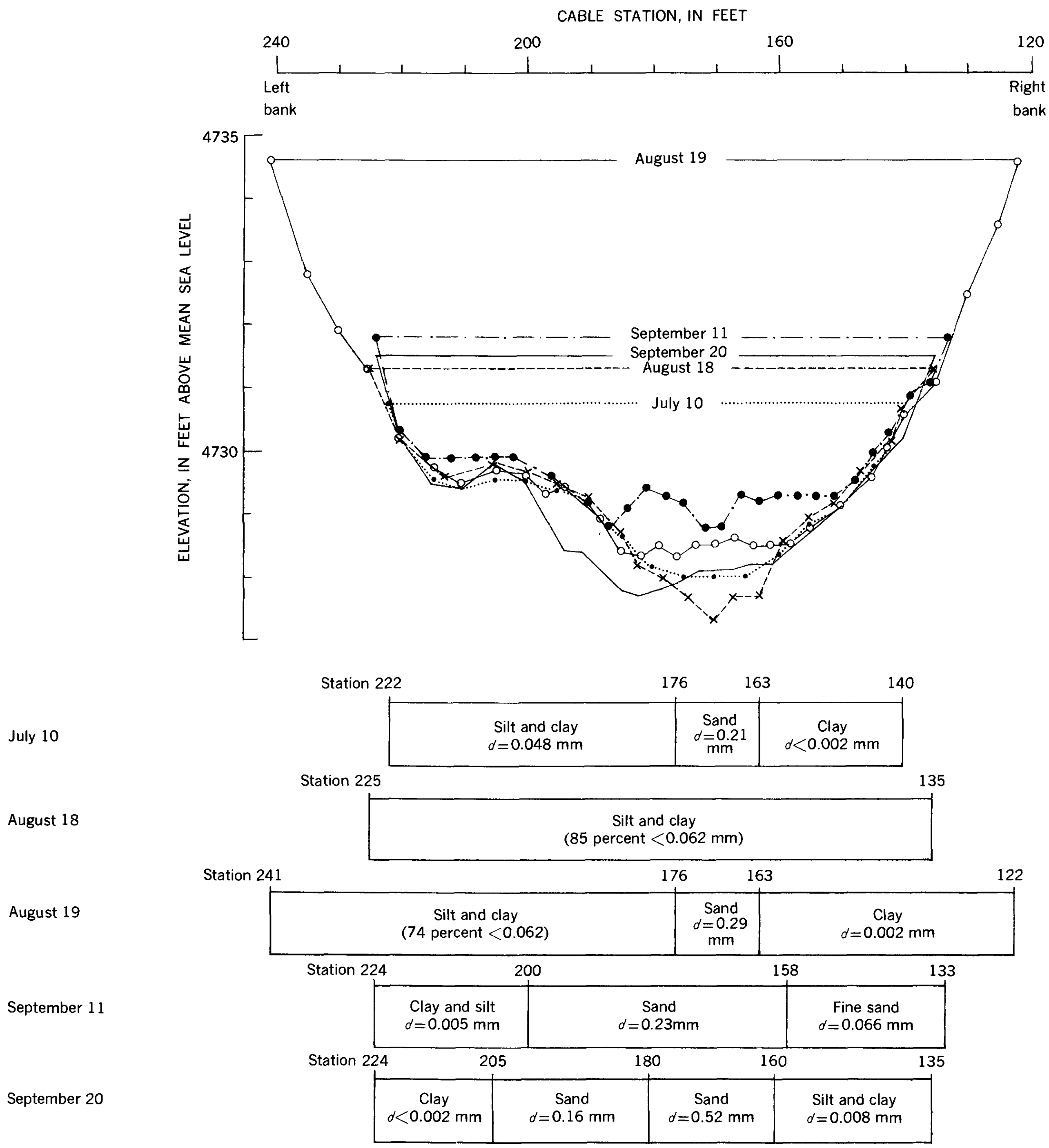


FIGURE 16.—Cross sections defined from water-discharge measurements, and lateral distribution of bed material, 1961.

The conditions which caused the bed to armor are not known. Probably, the armoring was the result of a combination of (a) the deposition of sand, silt, and clay during receding flows; and (b) the infiltration of flow into the channel bed, carrying clay into the pore spaces between the sand grains. The clay served as a matrix to bind the top few inches of the bed when the material dried.

Streamflow records show that the July and August flows originated above the confluence of the Rio Puerco and the Chico Arroyo. From the extremely low concentrations of suspended sand in these flows (table 4), it is concluded that the channel bed was armored through the entire 100-mile reach. Thus, although there are vast quantities of sand in the Rio Puerto watershed, under some conditions this sand is not available for transport.

Figure 16 shows the cross sections of the channel defined from the water-discharge measurements. The bar graphs plotted below the cross sections give an indication of the bed material across the wetted perimeter at the time of the observations. The graphs were constructed from the size analyses of the individual samples of bed material collected with the BM–54 sampler. The stations listed at the top of each bar graph indicate the approximate boundaries of the different types of bed material. The graphs show, for example, that on July 10, 1961, sand with a median particle diameter of 0.21 mm was present on the bed of the channel between stations 163 and 176, whereas on August 18, the entire wetted perimeter (station 135 to station 225) was covered with silt and clay. The average size distribution of the bed material is given in table 4. Of special interest are the wide variations in the size distributions of the bed material and the presence of the coarse sand (d=0.52 mm) on September 20.

Trains of standing waves were present through the reach during both of the September observations (fig. 17); on September 20, violently breaking antidunes were noted. The coarse sand was found on the bed in the area of the channel where trains of these waves were forming, breaking, and reforming at regular intervals of about 2 to 3 minutes. Standing waves were not observed to form over the clay-impregnated bed.

During July through September, the period of these observations, the channel of the Rio Puerco was undergoing relatively rapid changes. A "headcut" in the clay armoring of the bed, commencing at the confluence of the Rio Puerco and the Rio Grande, had progressed upstream by August 19 to the bridge at U.S. Highway 85. On August 30, it was about 50 yards downstream from the cable (fig. 18). There was no evidence from the cross sections in figure 15 to indicate that the headcut had moved upstream from section B on September 11 or 20. Probably, the headcut was upstream from section B, and the cut channel had refilled with sand. There was no discontinuity in the water-surface profile to indicate the presence of the headcut, because at discharges greater than about 300 cfs, the plunge pool would drown out. Figure 19 shows the cross section of the channel measured under the cable on October 5, 1961. On this date the headcut was upstream from the old Highway 85 bridge. In the channel above the headcut the bed was still armored with clay; in the cut channel the bed material was composed of sand with a median diameter of 0.35 mm. The core samples taken prior to the headcut showed the material at the same elevation to have a median diameter of about 0.2 mm, hence there was an appreciable change in the bed material as the headcut moved upstream.

A

B

FIGURE 17.—Standing waves and antidunes in the reach, September 11, 1961.

The presence of the headcut in the study reach is reflected in the increased water-surface slopes for the September observations. The cut channel through the reach was uniform in cross section, averaging 25 feet wide and 3 feet deep (fig. 20). Changes in the channel

FIGURE 18.—Headcut in the clay-armored bed.

geometry induced by the headcut can be seen by comparing the plotted cross sections (figs. 16, 19), and from the appearance of the reach preceding and after the headcut (figs. 3, 20). The headcut exposed numerous deposits of clay balls, which have been described in detail elsewhere (Nordin and Curtis, 1962).

Headcuts and discontinuous gullies are characteristic of streams in semiarid environments, and although the changes in the channel reported here are more intense than those that have been observed for this reach in the past, these phenomena are not unique. In fact, such changes are to be expected in streams such as the Rio Puerco. Some of the conditions necessary for the formation of discontinuous gullies and headcuts were dis-

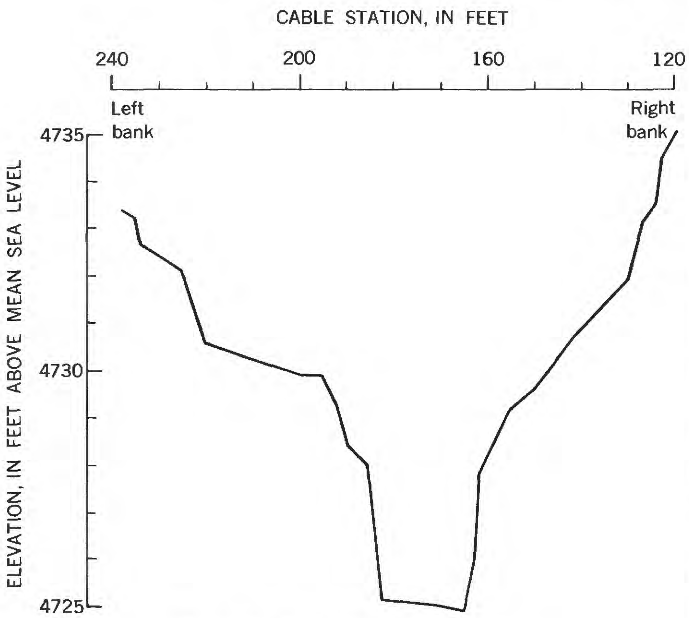


FIGURE 19.—Section B on October 5, 1961.

A

B

FIGURE 20.—The study reach, October 5, 1961. *A*, View upstream from section B; *B*, view downstream from section B.

cussed by Leopold and Miller (1956) and by Schumm and Hadley (1957).

It is beyond the scope of this study to discuss channel morphology, but the observations given above emphasize the complexity of the natural processes operating in the Rio Puerco watershed and indicate the urgent need for a better understanding of these processes.

In terms of sediment-transport parameters, the observed changes in the channel of the Rio Puerco are reflected in the geometry of the cross section, the hydraulic characteristics of the reach, the nature of the boundary (cohesive or noncohesive) the composition of the bed material, and the availability and, hence, the concentration and size distribution of the suspended sediment.

EXTREME CONCENTRATIONS IN EPHEMERAL STREAMS

Streams with high concentrations of fine sediment have a tremendous capacity for transporting sand. Figure 21 shows the relation of the transport rate of suspended sand per foot of width, q_s, to unit discharge, q, for the Rio Grande near Bernalillo and for the Rio Puerco. The concentrations of fine sediment in the Rio Grande were relatively low—about 500 to 1,000 ppm. The slope of the Rio Grande is approximately 0.001, or about the same as the slope of the Rio Puerco. For a given unit discharge, the Rio Puerco may transport 10 or more times as much sand as the Rio Grande, provided the sand is available for transport. Note that the points for the July and August observations, when the bed was armored and sand was not available, plot along the line for the Rio Grande.

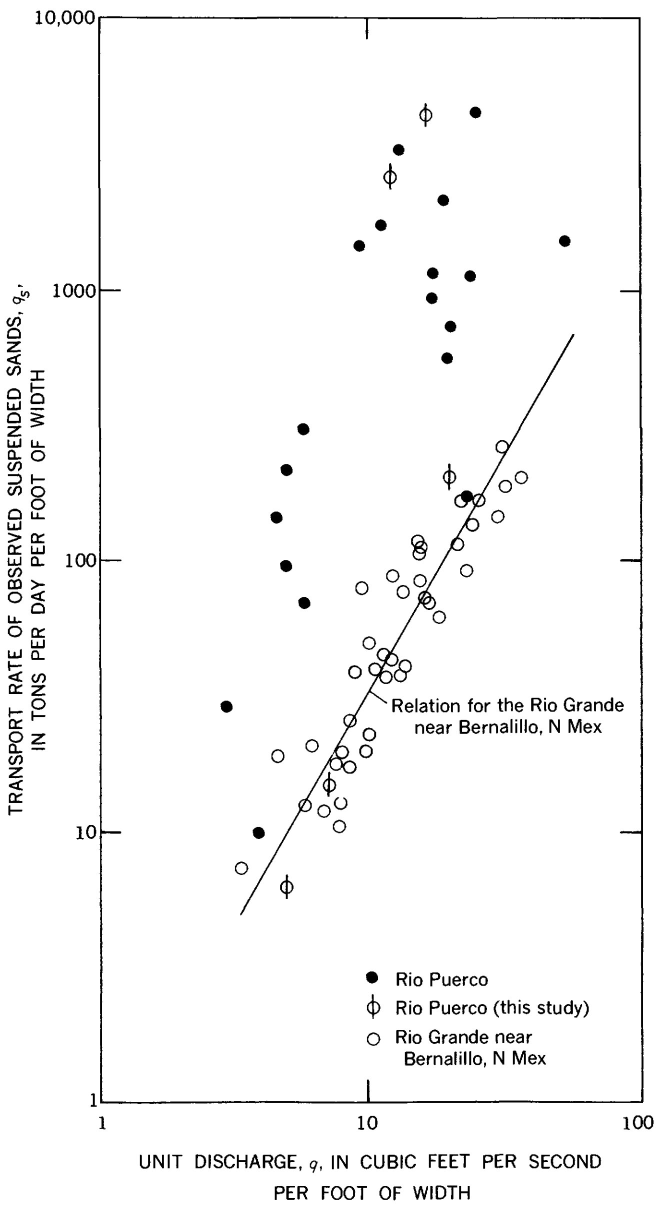


FIGURE 21.—Relation of the transport rate of suspended sand per foot of width to unit discharge.

The increased transport capacity for streams such as the Rio Puerco is partly due to the increased viscosity and mass density of the transporting media and to the reduced fall velocity of the sand particles. Presumably, at sufficiently high concentrations of fine material, the fall velocities of the sand would be so reduced that the rate of sand transport would be similar to the transport of fine material; that is, the transport rate would be limited either by the availability of the sand or, at the upper limit, by the concentration at which the sand particles are in actual contact. Again, as in the instance of fine sediment with extremely low fall velocities, the upper limit would be a "mudflow."

Bagnold (1956) gave a volume concentration, C_v, of 0.6 as the upper limiting "fluid" concentration of uniform spheres in a Newtonian fluid; at higher concentrations the mixture behaved as a granular paste. "Volume concentration" is defined as the grain-occupied volume divided by the total volume. For a specific gravity of 2.65, the volume concentration of 0.6 equals a concentration by weight of 800,000 ppm. Probably the upper limiting "fluid" concentration for sediments in natural channels should be of this same order of magnitude. Documentation of such high concentrations in natural streams has not been accomplished. The highest recorded concentration appears to be 680,000 ppm for the Rio Puerco, reported by D. C. Bondurant (1951). About 75 percent of the sample was sand. (See Lane and Borland, 1954.) Some examples of high concentrations determined from samples collected with standard U.S. Geological Survey sampling equipment are given in table 8 (J. P. Beverage, oral communication, 1962).

Obviously, to be applicable in streams transporting such high concentrations of suspended sediment, the conventional transport equations require considerable modification. This study has shown that the velocity follows a conventional logarithmic distribution with depth; and for the range of sizes and concentrations considered, the concentration distributions may be described by equation 10 if the fall velocity is corrected for the effects of the fine sediment. Simons and others (1963) concluded from their flume experiments that the total transport rate can be predicted if, where fine sediment is involved, the concentration of fine sediment is determined by sampling and the effects of fine sediment on the properties of the stream liquid are taken into account. In Simons' experiments, the highest

TABLE 8.—*Extreme sediment concentrations observed in ephemeral streams*

Station	Date	Discharge (cfs)	Concentration (ppm)	Concentration of sand (ppm)
Rio Puerco below Cabezon, N. Mex.	Aug. 6, 1951	----------	414,000	----------
	July 22, 1954	1,080	327,000	131,000
Rio Puerco near Bernardo, N. Mex.	July 24, 1949	----------	418,000	117,000
Paria River at Lees Ferry, Ariz.	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
	do	----------	451,000	262,000
Little Colorado River at Cameron, Ariz.	Aug. 20, 1957	----------	620,000	----------
	Aug. 25, 1957	3,080	299,000	111,000

total concentration was 102,000 ppm, of which 50,000 ppm was sand. It is probable that at the high concentrations given in table 8, the presence of the sand as well as the fine material will influence the properties of the fluid, and additional studies are needed to determine the combined effects of a wide range of sizes on fluid properties.

When extreme concentrations of sand, say 300,000 ppm or more, are present in a stream, fall velocities probably have no meaning. It is difficult to visualize how turbulence, if it existed at all, could be an effective mechanism in supporting the sediment. A more plausible explanation has been advanced by R. A. Bagnold (1954), who postulated a dispersive stress arising from the mutual encounters between the grains. Bagnold was able to measure this stress for dispersions of uniform, solid, spherical grains sheared in Newtonian fluids in the annular space between two concentric drums, and he applied the results to predict the velocity of dry sand flowing down an inclined slope and to explain an observed gravel flow. The case of heterogeneous grains sheared in a non-Newtonian fluid, such as a clay-water system, has not been investigated. Simons and others (1963) discussed the applicability of the Bagnold shear and transport functions (Bagnold, 1956) for concentrations of as much as 102,000 ppm.

It should be emphasized that most extreme concentrations in natural streams are observed during rapid changes in stage and in concentration. Under these conditions, the assumptions of uniform flow and of an equilibrium relation between a shear and a transport function become untenable, and a sediment-transport rate cannot be predicted.

If the bed is armored or partly armored with clay, equilibrium transport rates cannot be predicted, because the transport of sand would be controlled by the availability of the sand, and because there exist no methods for describing an equilibrium condition between flow parameters and a cohesive bed.

SUMMARY

This report presents some limited findings for an investigation of sediment transport in the Rio Puerco near Bernardo, N. Mex.

The velocity of sediment transport in a vertical varies logarithmically with depth, and the concentration distribution for the geometric mean of several size classes of sand can be described by a conventional distribution equation if the fall velocity of the sand is corrected for the influence of fine sediment. Flow resistance, measured by Manning's n, is approximately constant and is independent of the condition of the bed (cohesive or noncohesive) and of the average size distribution of the bed material.

Through the period of this study, the channel of the Rio Puerco was undergoing some relatively rapid changes. At the beginning of the study, the bed of the channel was armored with a layer of sand, silt, and clay about 0.6 to 1.0 foot thick. This layer contained about 25 percent clay, which served as a matrix to bind the material. A headcut in the clay-impregnated layer of the bed moved upstream into the study reach and resulted in changes in the channel geometry and in the composition of the bed material. The bed material ranged from a cohesive fine material to a coarse sand. When the bed of the channel is composed of cohesive material, the availability of sand for transport is limited; and the standard equations for predicting the rate of sediment transport are not applicable.

Some observations of extreme sediment concentrations indicate concentrations of sand ranging from 117,000 to 447,000 ppm. Conventional sediment transport relations generally are not applicable for extreme conditions, because most high concentrations occur for periods of rapidly changing stage, and because the effects of high concentrations of sand upon fluid properties have not been defined.

Finally, the data presented herein point out the complexity of the natural processes that are operating in the Rio Puerco watershed and indicate the need for additional study of sediment transport and related flow phenomena in ephemeral streams transporting high concentrations of suspended sediment. Further investigations should be oriented to provide information on the following:

1. The effects of the physiochemical properties of the fine material upon fluid properties.
2. The relation of the source of sediment to the physiochemical properties of the fine sediment and to the chemical quality of the water.
3. The effects of high concentrations of sand upon fluid properties.

4. The conditions which lead to the armoring of the bed.
5. The conditions which influence the cycle of deposition and incision in existing channels.

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