Aspects of Flow Resistance and Sediment Transport Rio Grande Near Bernalillo New Mexico

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1498-H

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By CARL F. NORDIN, Jr.

STUDIES OF FLOW IN ALLUVIAL CHANNELS

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GLOSSARY OF TERMS

Bed material: The material which composes the channel bed. For this study, bed material was considered to be all sediment coarser than 0.062 mm.

Fine material: Sediment finer than 0.062 mm.

Sand: Sediment between 0.062 mm and 2.0 mm in size, regardless of minerological composition. The terms "sand", "sand sizes" and "bed material" are used interchangeably.

Sediment: Fragmental material that originates from weathering rocks and is transported by, suspended in, or deposited by water.

Wash load: Material finer than any size of sediment found in appreciable quantities in the stream bed. The terms "wash load" and "fine material" are used interchangeably.

LIST OF SYMBOLS

Symbol	*Description*	*Units*
A	Area of cross section of stream	ft^2
B	Channel width	ft
C	Chezy discharge coefficient	$ft^{1/2}$ per sec
$C/\sqrt{g}$	Dimensionless Chezy coefficient	
Cm	Measured suspended sediment concentration	ppm
D	Depth at a vertical	ft
$\bar{D}$	Mean depth at a cross section	ft
d	Median diameter of bed material	mm
d_{16}	Diameter of bed material for which 16 per cent, by weight, is finer	mm
d_{35}	Diameter of bed material for which 35 per cent, by weight, is finer	mm
d_{65}	Diameter of bed material for which 65 per cent, by weight, is finer	mm
d_{84}	Diameter of bed material for which 84 per cent, by weight, is finer	mm
$\mathbf{F}$	Froude number	
f	Friction factor	
f'	Friction factor from a pipe-friction diagram	
f/f'	Relative friction factor	
g	Acceleration due to gravity	ft per sec^2
h	Height of standing waves, crest to trough	ft
k_s	Representative grain roughness, d_{65}	ft

L	Wave length of standing waves	ft
n	Manning resistance coefficient	fty6
P_w	Wetted perimeter	ft
Q	Water discharge	ft^3 per sec
Q_s	Discharge rate of measured suspended sand	tons per day
Q_t	Discharge rate of bed material	tons per day
R	Hydraulic radius ($R \sim \overline{D}$)	ft
R'	Hydraulic radius with respect to the sand grains	ft
R''	Hydraulic radius with respect to dunes and bars	ft
S	Water surface slope	
S_e	Energy gradient slope	
T	Temperature	°F
V_*'	Shear velocity with respect to the sand grains, $\sqrt{gR'S_e}$	ft per sec
V_*''	Shear velocity with respect to the bars and dunes, $\sqrt{gR''S_e}$	ft per sec
V	Mean velocity at a vertical	ft per sec
$\overline{V}$	Mean velocity at a cross section	ft per sec
x	A correction factor for transition from smooth to rough boundary	
γ	The unit weight of water	lbs per ft^3
δ	Theoretical thickness of the laminar sublayer	ft
ν	Kinematic viscosity	ft^2 per sec
π	3.1416	
ρ_f	Density of the fluid	slugs per ft^3
ρ_s	Density of the sediment	slugs per ft^3
σ	Measure of gradation of the bed material	
τ	Shear stress or tractive force on the bed, γRS_e	lbs per ft^2
τ'	Shear stress resisted by the sand grains, $\gamma R'S_e$	lbs per ft^2
τ''	Shear stress resisted by the bars, dunes, and other bed features, $\gamma R''S_e$	lbs per ft^2
ψ'	A flow intensity parameter.	

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ASPECTS OF FLOW RESISTANCE AND SEDIMENT TRANSPORT, RIO GRANDE NEAR BERNALILLO NEW MEXICO

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ABSTRACT

Twenty-one roughly concurrent observations of hydraulic variables at the partially confined section A–2 and the wider section *F* for a reach of the Rio Grande near Bernalillo, N. Mex., form the basis for this study of flow resistance and sediment transport. In addition, the averages of the hydraulic properties of 13 cross sections for the reach are used to determine bar resistance and bed-material transport rates by the Einstein procedure. Some miscellaneous observations on standing waves and on flows with high sediment concentrations are given.

Because bed configurations change, flow resistance for the Rio Grande varies widely. For lower regime flow, the bed configuration is dunes, and the flow resistance is high. Values of the dimensionless Chezy coefficient, $C/\sqrt{g}$, range from about 9 to 12. For upper regime flow, the bed is relatively plane, the flow resistance is low, and $C/\sqrt{g}$ varies approximately from 19 to 24. Flow in the transition region between lower and upper regime is characterized by variable bed configurations, flow resistance, velocity and depth, both laterally at a cross section and from section to section along the reach. Width adjustments are effected by channelization. Both width adjustments and minor variations in characteristics of the bed material reflect a tendency for the channel to maintain continuity of bed-material transport.

Flow resistance is consistently greater at the narrow section *A*–2 than at section *F*. The Einstein bar-resistance curve does not adequately describe the flow resistance for either of these cross sections. However, data for the average of 13 cross sections in the reach fit the bar-resistance curve reasonably well.

High concentrations of suspended sediment have more effect on the values of overall resistance coefficients for lower regime flow and flow in the transition region than for upper regime flow.

Transport rates of bed material are estimated by several methods and compared with the transport rates of measured suspended sand.

High concentrations of bed material accompany high velocity and low flow resistance. The interrelation of sediment transport and flow resistance is complicated by the extreme variability of water and sediment discharge and by the time-dependency of sediment concentration during flood events.

INTRODUCTION

Studies of flow phenomena in alluvial channels have been conducted mostly in carefully controlled laboratory experiments. It is sometimes difficult to extend the results of such studies to natural channels

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because field data often are inadequate or incomplete. Comparable field studies are difficult to conduct, and the interpretation of field data is complicated by the indeterminacy introduced from nonuniform flow conditions and from the inherent inaccuracies in measuring, estimating, or sampling some of the factors involved.

Nonetheless, it is of interest to consider field data in the light of carefully controlled laboratory investigation and, with due consideration of the limitations of field measurements, to examine some of the observed similarities and differences in the experimental and natural conditions.

PURPOSE AND SCOPE

This paper presents the results of a series of observations of the Rio Grande near Bernalillo, N. Mex. The characteristics of flow resistance are described qualitatively in terms of flow regime and bed configuration, and quantitatively in terms of standard resistance coefficients and of the Einstein bar-resistance curve (Einstein and Barbarossa, 1952). Some limited data for flows with high concentration of suspended fine material are given. The magnitude of the resistance coefficients, the regimes of flow, and the general forms of the bed configurations are compared to those reported in several flume investigations.

Sediment transport rates are computed by the modified Einstein method (Colby and Hubbell, 1961) and by the method proposed by E. M. Laursen (1958). For several observations, transport rates are estimated using the Einstein bed-load function (Einstein, 1950).

OBSERVED DATA

The analysis which follows is based principally upon data from a reach of the Rio Grande near Bernalillo, N. Mex. (fig. 1). The right bank of the upstream part of the reach is a high bluff composed of calcareous sandstone, which partially confines the flow at section *A*–2. Throughout the rest of the reach, the banks are composed of a mixture of sand, silt, and clay, and are partially stabilized by vegetation. Section *A*–2 is the site of a U.S. Geological Survey gaging station. Permanent cables are installed at sections *A*–2 and *F*. Other sections are equipped to accommodate temporary cables for boat measurements. The stationing shown in figure 1 represents the distance, in feet, along the center of the channel.

Tables 1 and 2 present observed data and computed parameters for 21 observations at sections *A*–2 and *F*. The observations were approximately concurrent, except in 1960, when water discharge was measured only at section *A*–2. For these dates, the cross-sectional area at section *F* was determined by sounding, and the

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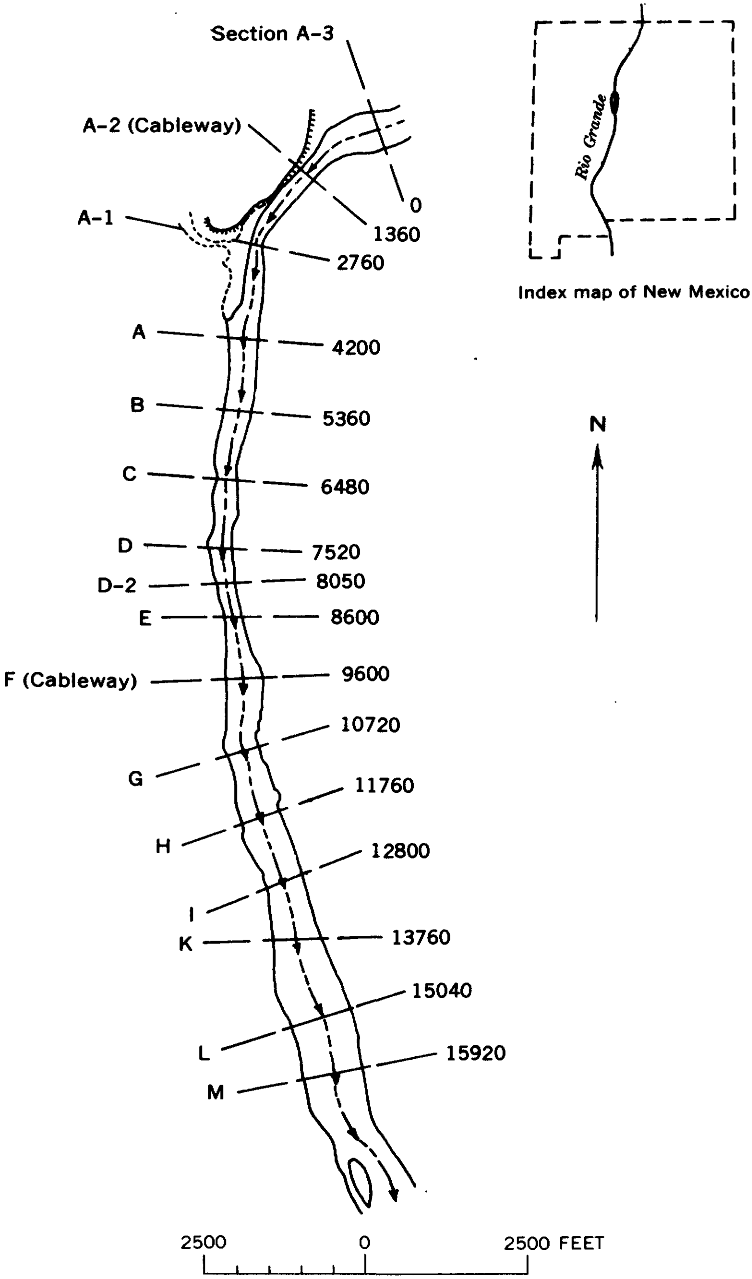

FIGURE 1.—Sketch map of the study reach.

TABLE 1.—*Observed data and computed parameters for section A–2*

Date	Q (cfs)	B (ft)	$\overline{V}$ (ft per sec)	$\overline{D}$ (ft)	T (°F)	Water-surface elevation (ft above MSL)	S_e (ft per ft)	Bed material d (mm)	Bed material σ	F	V_* (ft per sec)	n (ft$^{1/6}$)	f	f/f' [a]	R' (ft)	V_*' (ft per sec)	$\overline{V}/V''_*$ [a]	ψ' [a]	Flow regime
4-25-52	2,730	272	4.06	2.47	58	5,034.64	0.00089	0.23	1.65	0.455	0.266	0.0200	0.0344	2.9	0.97	0.167	19.6	1.50	Transition.
5-12-52	6,490	272	6.57	3.63	62	5,035.07	.00084	.39	1.65	.606	.314	.0155	.0182	1.7	2.39	.254	36.1	.65	Upper.
6-17-52	6,140	272	5.96	3.79	70	5,034.95	.00083	.28	1.53	.539	.318	.0175	.0184	1.7	2.07	.235	27.7	.76	Do.
6-20-52	4,830	272	5.09	3.49	72	5,034.38	.00079	.32	1.55	.480	.298	.0189	.0274	2.5	1.61	.202	23.2	1.02	Transition.
6-26-52	2,760	269	3.71	2.76	70	5,033.88	.00076	.30	1.57	.394	.260	.0218	.0393	3.3	.96	.153	17.8	1.80	Do.
7-24-52	2,060	270	2.84	2.69	75	5,034.00	.00080	.27	1.66	.306	.263	.0287	.0687	5.7	.59	.123	12.2	2.78	Lower.
5- 8-58	6,860	270	6.91	3.68	58	5,034.52	.00080	.32	1.89	.635	.308	.0146	.0159	1.4	2.68	.263	43.2	.61	Upper.
5-13-58	8,320	271	6.88	4.46	60	5,034.81	.00080	.29	1.73	.576	.339	.0166	.0194	1.8	2.66	.262	32.1	.61	Do.
5-21-58	8,680	270	7.82	4.11	67	5,034.89	.00079	.37	1.48	.680	.323	.0138	.0137	1.2	3.36	.292	55.9	.49	Do.
5-27-58	10,100	273	7.71	4.80	74	5,035.10	.00080	.29	1.54	.619	.352	.0155	.0166	1.5	3.24	.289	38.6	.50	Do.
6-4 -58	8,160	272	6.92	4.34	67	5,034.55	.00083	.28	1.42	.584	.341	.0165	.0194	1.8	2.63	.265	32.3	.60	Do.
6-10-58	5,800	270	6.27	3.43	65	5,033.86	.00074	.34	1.49	.596	.290	.0147	.0166	1.5	2.44	.241	40.7	.72	Do.
6-13-58	4,340	266	6.10	2.67	63	5,033.55	.00076	.35	1.67	.658	.256	.0129	.0140	1.2	2.27	.236	61.9	.76	Do.
6-18-58	4,000	267	5.06	2.96	67	5,033.49	.00076	.27	1.88	.519	.269	.0167	.0226	1.9	1.63	.200	28.1	1.06	Do.
6-25-58	6,040	273	6.50	3.40	73	5,034.09	.00080	.35	1.44	.621	.296	.0147	.0166	1.5	2.44	.251	41.4	.67	Do.
4-6 -60	2,100	269	3.04	2.56	59	5,034.00	.00083	------	------	.335	.262	.0264	.0592	4.6	.64	.131	13.5	2.44	Lower.
5-24-60	1,240	133	2.71	3.44	65	5,033.64	.00083	------	------	.258	.303	.0361	.100	8.3	.49	.114	9.68	3.22	Do.
6-22-60	2,030	268	2.89	2.93	74	5,034.11	.00082	------	------	.297	.278	.0303	.0741	6.2	.60	.126	11.6	2.65	Do.
4-27-61	2,230	267	3.16	2.64	57	5,034.12	.00083	.22	1.56	.343	.266	.0259	.0564	4.7	.69	.136	13.9	2.27	Transition.
5-3 -61	3,360	270	3.99	3.12	66	5,034.50	.00083	.23	1.53	.398	.289	.0231	.0419	3.5	1.02	.165	16.9	1.54	Do.
5-19-61	2,260	268	3.62	2.33	63	5,034.33	.00085	.22	1.46	.419	.253	.0213	.0390	3.0	.83	.151	17.8	1.84	Do.

[a] Average bed-material size distribution from figure 2 used in calculations.

TABLE 2.—*Observed data and computed parameters for section F*

Date	Q (cfs)	B (ft)	$\overline{V}$ (ft per sec)	$\overline{D}$ (ft)	T (°F)	Water-surface elevation (ft above MSL)	S_e (ft per ft)	Bed material		F	V_* (ft per sec)	n ($ft^{1/6}$)	f	f/f' [a]	R' (ft)	V_*' (ft per sec)	$\overline{V}/V''_*$ [a]	ψ' [a]	Flow regime
								d (mm)	σ										
4-25-52	2,910	640	3.86	1.18	64	5,027.31	0.00089	0.29	1.61	0.630	0.183	0.0129	0.0182	1.3	0.90	0.161	43.2	1.63	Upper.
5-12-52	6,390	570	5.42	2.07	65	5,028.32	.00084	.34	1.73	.663	.237	.0129	.0152	1.2	1.67	.213	53.1	.92	Do.
6-17-52	6,100	489	5.73	2.18	74	5,028.17	.00083	.31	1.53	.682	.242	.0126	.0142	1.1	1.91	.226	67.6	.82	Do.
6-20-52	4,720	350	5.50	2.45	73	5,027.84	.00079	.33	1.72	.617	.250	.0138	.0165	1.4	1.85	.217	44.7	.89	Do.
6-26-52	2,850	370	3.20	2.41	70	5,027.64	.00076	.31	1.52	.364	.243	.0231	.0461	3.6	.74	.134	15.8	2.32	Transition.
7-24-52	2,030	580	2.20	1.58	80	5,027.44	.00080	.33	1.60	.308	.202	.0260	.0673	4.8	.39	.100	12.6	4.18	Lower.
5-8-58	6,730	557	5.61	2.15	61	5,028.2	.00080	.24	1.53	.673	.236	.0126	.0141	1.1	1.88	.220	67.5	.87	Upper.
5-13-58	8,310	541	6.02	2.55	63	5,028.4	.00080	.28	1.56	.663	.257	.0131	.0145	1.2	2.11	.233	56.8	.77	Do.
5-21-58	8,700	645	6.17	2.19	68	5,028.7	.00079	.22	------	.735	.236	.0115	.0117	.90	2.06	.228	107	.78	Do.
5-27-58	9,970	637	5.93	2.64	68	5,028.9	.00080	.25	2.35	.645	.261	.0136	.0155	1.3	2.08	.231	49.4	.78	Do.
6-4-58	7,790	508	5.64	2.72	71	5,028.0	.00083	.30	1.67	.603	.270	.0148	.0183	1.5	1.85	.222	36.9	.85	Do.
6-10-58	5,450	520	4.91	2.13	69	5,028.0	.00074	.32	1.51	.592	.225	.0137	.0168	1.3	1.58	.194	43.1	1.11	Do.
6-13-58	4,380	498	4.60	1.91	66	5,027.5	.00076	.45	2.25	.587	.216	.0137	.0177	1.4	1.40	.185	41.4	1.23	Do.
6-18-58	4,730	518	4.01	2.28	72	5,027.4	.00076	.29	3.34	.468	.236	.0177	.0278	2.1	1.10	.164	23.7	1.56	Transition.
6-25-58	5,960	532	5.36	2.09	77	5,027.7	.00080	.32	1.68	.651	.232	.0128	.0150	1.2	1.75	.212	57.4	.93	Upper.
4-6-60	2,100	632	3.03	1.09	62	5,027.17	.00083	.30	1.52	.514	.170	.0150	.0254	1.7	.64	.131	27.8	2.45	Transition.
5-24-60	1,240	459	2.05	1.32	65	5,026.86	.00083	--------	------	.314	.188	.0252	.0672	4.5	.34	.0949	12.7	4.62	Lower.
6-22-60	2,030	357	2.23	1.44	73	5,027.41	.00082	--------	------	.327	.195	.0244	0612	4.4	.39	.101	13.4	4.08	Do.
4-27-61	2,280	552	3.02	1.37	58	5,027.26	.00083	.19	1.58	.455	.191	.0176	.0321	2.3	.64	.131	21.7	2.45	Transition.
5-3-61	3,890	638	3.49	1.75	65	5,027.75	.00083	.22	1.51	.466	.216	.0178	.0307	2.4	.81	.147	22.1	1.94	Do.
5-19-61	2,260	335	3.60	1.87	66	5,027.31	.00085	.21	1.49	.463	.226	.0183	.0316	2.4	.83	.151	21.4	1.84	Do.

[a] Average bed material size distribution from figure 2 used in calculations.

area so determined was used with the discharge from section *A*–2 to obtain mean velocity.

Water-surface elevations were obtained from staff gages referred to a datum of mean sea level. Slopes of the energy gradients were determined as the drop in elevation of the energy gradients divided by the distance, 8,240 feet, between sections *A*–2 and *F*, and were assumed applicable to both sections.

Suspended-sediment samples were collected with a US D–49 sampler. These samples were analyzed for particle-size distribution by the pipette method for sizes smaller than 0.062mm (Kilmer and Alexander, 1949) and by sieving or by the visual accumulation method (U.S. Inter-Agency Rept. 11, 1957) for sand sizes. The D–49 suspended-sediment sampler collects samples from the water surface to about 0.3 foot above the stream bed. The measured suspended-sediment concentrations, C_m, and the particle-size distributions for samples at sections *A*–2 and *F* are given in tables 3 and 4. All concentrations are given in parts per million (ppm) by weight.

The particle-size distributions of bed-material samples are given in tables 5 and 6. Usually, 3 to 15 samples of bed material were collected from the top inch or two of the bed. The samples were analyzed separately by sieves, and the arithmetic average of the separate samples was plotted on log-probability paper to define the median diameter, *d*, and the measure of the gradation, σ, shown in

TABLE 3.—*Particle-size analysis of suspended-sediment samples, section* A–2

[Methods of analysis: C, chemically dispersed; M, mechanically dispersed; P, pipet; S, sieve; V, visual accumulation tube; W, in distilled water]

Date	Water discharge (cfs)	Concentration of sample (ppm)	Percent finer than indicated size (mm)							Methods of analysis
			0.004	0.016	0.062	0.125	0.250	0.500	1.000	
4-25-52	2,730	3,320	14	20	44	78	97	100		SPWCM
5-12-52	6,490	3,160	12	19	33	58	88	99	100	SPWCM
6-17-52	6,140	1,990	7	9	22	35	68	98	100	SPWCM
6-20-52	4,830	1,690	5	10	22	46	85	99	100	SPWCM
6-26-52	2,760	1,040	6	9	18	44	81	99	100	SPWCM
7-24-52	2,060	2,490	16	22	65	82	95	99	100	SPWCM
5- 8-58	6,860	4,420	15	23	44	61	92	99	100	VPWCM
5-13-58	8,320	4,740	13	19	33	58	92	100		VPWCM
5-21-58	8,680	3,400	13	18	34	58	87	96	100	VPWCM
5-27-58	10,100	3,040	10	16	32	54	88	100		VPWCM
6- 4-58	8,160	2,580	8	12	28	50	84	99	100	VPWCM
6-10-58	5,800	3,480	4	7	18	34	64	92	100	VPWCM
6-13-58	4,340	2,080	6	6	18	45	91	99	100	VPWCM
6-18-58	4,000	5,980	25	38	51	63	78	96	100	VPWCM
6-25-58	6,040	5,410	8	13	27	30	44	89	100	VPWCM
4- 6-60	2,100	1,900	20	27	50	83	97	100		VPWCM
5-24-60	1,240	1,200	18	24	36	55	89	100		VPWCM
6-22-60	2,030	781			33	64	94	100		V
4-27-61	2,230	1,790	15	22	36	68	92	100		VPWCM
5- 3-61	3,360	2,670	18	28	51	74	97	100		VPWCM
5-19-61	2,260	1,250	13	20	39	66	96	100		VPWCM

TABLE 4.—*Particle-size analysis of suspended-sediment samples, section* F

[Methods of analysis: C, chemically dispersed; M, mechanically dispersed; P, pipet; S, sieve; V, visual accumulation tube; W, in distilled water]

Date	Water discharge (cfs)	Concentration of sample (ppm)	Percent finer than indicated size (mm)							Methods of analysis
			0.004	0.016	0.062	0.125	0.250	0.500	1.000	
4-25-52	2,910	2,820	15	21	45	79	94	99	100	SPWCM
5-12-52	6,390	2,690	14	21	43	67	95	100	-------	SPWCM
6-17-52	6,100	1,500	8	14	25	51	88	100	-------	SPWCM
6-20-52	4,720	1,460	5	10	22	45	83	99	100	SPWCM
6-26-52	2,850	852	8	12	26	57	89	100	-------	SPWCM
7-24-52	2,030	1,740	18	27	67	85	97	100	-------	SPWCM
5- 8-58	6,730	4,700	16	23	43	66	95	99	100	VPWCM
5-13-58	8,310	4,220	14	21	39	69	94	100	-------	VPWCM
5-21-58	8,700	3,350	13	19	36	63	95	100	-------	VPWCM
5-27-58	9,970	3,060	12	18	34	60	94	100	-------	VPWCM
6- 4-58	7,790	2,500	8	13	30	53	80	96	100	VPWCM
6-10-58	5,450	2,070	8	13	30	53	88	97	100	VPWCM
6-13-58	4,380	1,990	-------	-------	16	37	80	99	100	V
6-18-58	4,730	5,420	13	22	40	56	77	96	100	VPWCM
6-25-58	5,960	2,800	18	28	55	64	88	100	-------	VPWCM
4- 6-60	2,100	1,870	22	29	55	80	95	100	-------	VPWCM
5-24-60	1,240	828	29	38	55	72	93	100	-------	VPWCM
6-22-60	2,030	1,090	-------	-------	23	41	67	94	98	V
4-27-61	2,280	1,540	18	26	46	72	96	100	-------	VPWCM
5- 3-61	3,890	2,690	19	29	52	77	97	100	-------	VPWCM
5-19-61	2,260	1,140	-------	-------	43	67	93	100	-------	V

tables 1 and 2. The measure of gradation, σ, was calculated from the equation

$$\sigma = 1/2(d/d_{16} + d_{84}/d) \tag{1}$$

in which

d is the median diameter
d_{16} is the size, by weight, for which 16 percent is finer
d_{84} is the size for which 84 percent is finer.

For some of the computations, the average size distribution of bed material shown in figure 2 was assumed applicable. This distribution is based upon a previous analysis of 139 observations, wherein it was concluded that particle-size distribution of bed material for the Rio Grande near Bernalillo is approximately constant (Nordin and Culbertson, 1961a).

The data presented for the period from 1952 through 1958 were collected as part of a cooperative program between the U.S. Geological Survey and the U.S. Bureau of Reclamation.

FLOW REGIME AND BED CONFIGURATION

Flow in the Rio Grande may be classified into lower and upper flow regime, with a transition zone between. This classification is described in detail by Simons and Richardson (1961) and is based upon magnitude of resistance to flow, bed and water surface configurations, and mode and magnitude of sediment transport.

Lower regime is characterized by a large resistance to flow and a low transport rate of bed material. The bed roughness is ripples or

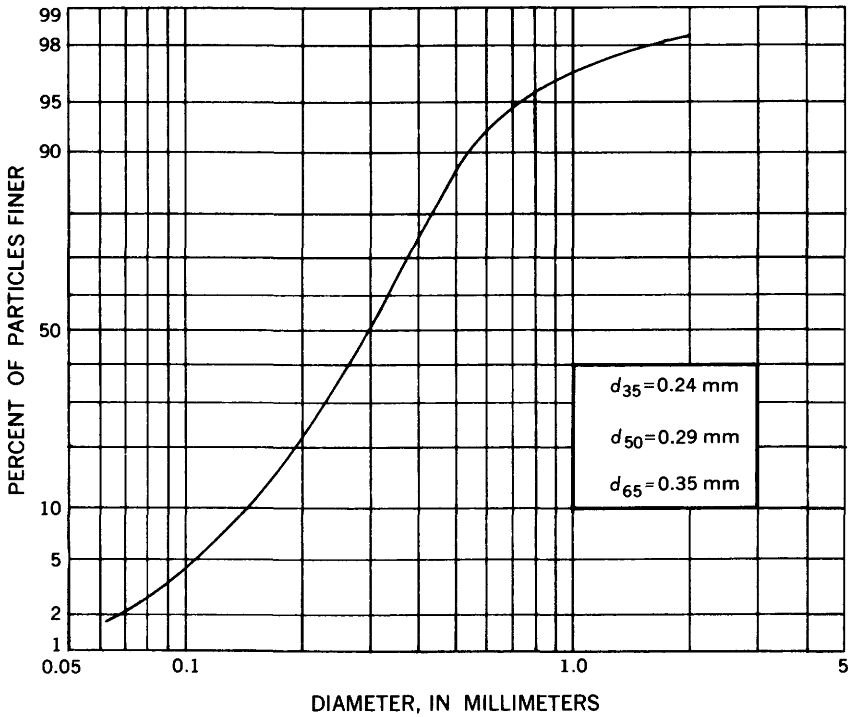

FIGURE 2.—Average size distribution of bed material.

TABLE 5.—*Particle-size analysis of bed-material samples, section A–2*

Date	Number of samples	Percent finer than indicated size, (mm)									
		0.062	0.125	0.250	0.500	1.000	2.000	4.000	8.000	16.00	32.00
4-25-52	3	2.1	10.8	56.5	93.4	98.2	98.8	99.2	99.2	100	------
5-12-52	3	0.2	1.5	15.2	70.6	93.7	97.8	99.1	99.3	100	------
6-17-52	6	0.4	3.0	37.4	93.0	98.9	99.4	99.5	99.6	100	------
6-20-52	3	0.4	2.8	26.7	86.4	95.3	97.3	98.2	99.2	99.9	------
6-26-52	3	0.3	2.8	32.7	87.4	97.7	99.2	99.6	100	--------	------
7-24-52	3	1.0	5.6	45.5	86.9	98.2	99.5	99.7	100	--------	------
5- 8-58	4	0.7	3.2	34.2	77.9	91.4	94.5	95.7	96.3	96.6	100
5-13-58	3	0.8	6.1	39.0	83.0	97.0	98.4	98.8	99.2	100	------
5-21-58	3	0.2	1.3	12.8	78.9	98.5	99.6	99.8	99.8	100	------
5-27-58	3	0.3	2.4	38.0	88.6	97.1	98.8	99.6	99.7	100	------
6- 4-58	3	0.4	3.3	33.4	97.3	99.9	100	--------	--------	--------	------
6-10-58	3	0.2	2.2	20.9	86.1	94.6	96.7	97.7	98.6	100	------
6-13-58	3	0.3	2.4	22.4	78.0	93.9	97.9	98.9	99.7	100	------
6-18-58	3	0.9	7.3	45.2	80.5	94.8	98.1	99.1	99.6	100	------
6-25-58	3	0.3	1.4	16.1	83.1	98.1	99.2	99.4	99.7	100	------
4- 6-60	[1] 18	0.5	3.7	32.2	84.7	95.6	97.4	98.2	99.0	100	------
5-24-60	[2] 9	0.3	3.3	35.6	89.4	96.9	98.4	99.4	99.9	100	------
6-22-60	[3] 12	0.2	4.3	42.6	86.8	96.9	98.8	99.4	99.8	100	------
4-27-61	6	0.4	9.8	61.1	97.4	99.6	100	--------	--------	--------	------
5- 3-61	6	0.4	6.4	58.8	96.6	99.8	100	--------	--------	--------	------
5-19-61	6	0.2	4.1	67.2	97.8	99.9	100	--------	--------	--------	------

[1] Average of samples from sections A, B, C, D, E, F.
[2] Average of samples from section A, C, E.
[3] Average of samples from sections A, C, E, G.

TABLE 6.—*Particle-size analysis of bed-material samples, section* F

Date	Number of samples	Percent finer than indicated size (mm)									
		0.125	0.125	0.250	0.500	1.000	2.000	4.000	8.000	16.00	32.00
4-25-52	3	1.1	6.5	34.2	90.5	99.7	99.0	99.6	99.8	100	------
5-12-52	3	0.4	2.8	26.6	76.7	95.7	98.1	98.5	98.6	100	------
6-17-52	3	0.3	2.0	31.0	87.3	97.1	98.7	99.2	99.4	100	------
6-20-52	3	0.3	1.4	30.6	79.3	94.5	97.1	98.2	99.1	100	------
6-26-52	3	0.4	3.0	29.4	89.2	96.8	97.3	97.5	98.4	100	------
7-24-52	3	0.7	2.6	25.9	82.0	95.4	97.5	98.7	99.5	100	------
5- 8-58	4	1.2	8.4	52.8	96.5	99.8	99.9	100	--------	--------	------
5-13-58	4	0.8	5.7	39.4	93.0	98.6	99.2	99.5	99.8	100	------
5-21-58	4	22.6	25.6	54.7	93.4	98.7	99.4	99.8	99.9	100	------
5-27-58	4	10.2	29.4	49.5	93.4	99.3	99.8	100	--------	--------	------
6- 4-58	3	1.0	8.0	34.6	87.7	97.5	99.1	99.7	100	--------	------
6-10-58	3	0.2	1.6	27.8	88.2	94.7	96.3	97.3	98.2	100	------
6-13-58	3	0.1	0.9	11.3	59.4	79.3	90.6	94.6	96.6	99.3	100
6-18-58	3	0.7	5.2	42.2	74.6	82.6	85.1	86.7	88.5	90.1	100
6-25-58	3	0.3	2.4	31.1	81.9	91.9	95.0	96.8	98.2	99.4	100
4- 6-60	[1] 18	0.5	3.7	32.2	84.7	95.6	97.4	98.2	99.0	100	------
5-24-60	[2] 9	0.3	3.3	35.6	89.4	96.9	98.4	99.4	99.9	100	------
6-22-60	[3] 12	0.2	4.3	42.6	86.8	96.9	98.8	99.4	99.8	100	------
4-27-61	7	2.2	16.9	72.2	98.7	99.8	100	--------	--------	--------	------
5- 3-61	7	0.4	7.0	62.9	96.6	100	--------	--------	--------	--------	------
5-19-61	4	0.6	7.8	69.2	95.4	99.8	100	--------	--------	--------	------

[1] Average of samples from sections *A, B, C, D, E, F.*
[2] Average of samples from sections *A, C, E.*
[3] Average of samples from sections *A, C, E, G.*

dunes or both, and the water surface typically shows boils downstream from the crests of the dunes or in the vicinity of potholes. For upper regime flow, the bed is relatively flat, the flow resistance is low, and the transport rate of bed material is high. The water surface generally is quite smooth; under some conditions standing waves or antidunes may be present.

Figure 3 shows a simple but convenient method for classifying flow regime and bed configuration for the Rio Grande near Bernalillo. It has been determined from field observations that flow with values of mean velocity, $\overline{V}$, and mean depth, $\overline{D}\sim R$, which plot along the lower regime line, is over a bed that has a dune configuration, whereas flow along the upper regime line is over a bed that is relatively plane. In the transition zone, between the two regimes of flow, the bed configuration is unpredictable, but it is generally a composite of dunes over portions of the bed and of plane bed or washed-out dunes and bars over other portions. The importance of this transition zone will be discussed subsequently. Bed configurations shown in tables 1 and 2 were classified into dune, transition, and plane bed by use of field notes and the relation in figure 3. These classifications are rough and necessarily overlapping at times, but they appear to give a fair qualitative indication of the bed condition.

Details of the geometry of the bed configurations for lower regime flow have not been observed for the Rio Grande, but some general features have been determined. The major form of bed roughness is

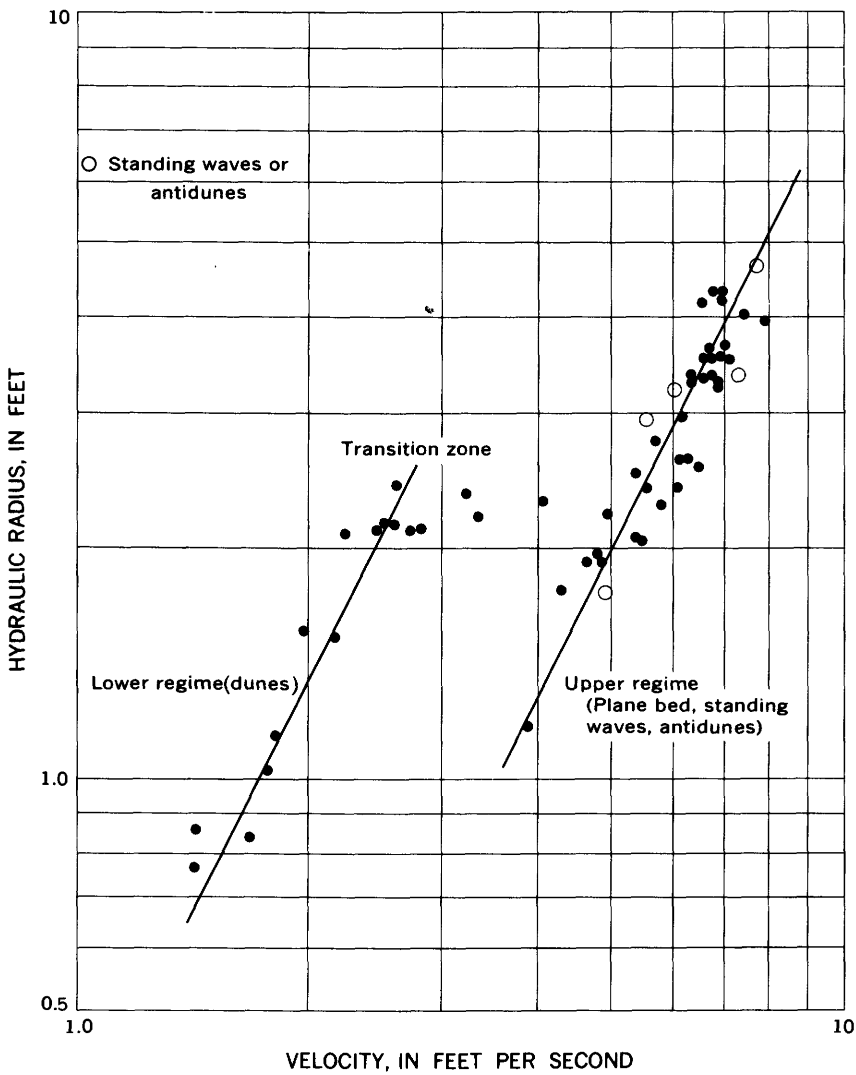

FIGURE 3.—Relation of hydraulic radius to velocity for Rio Grande near Bernalillo, N. Mex.

dunes. Dunes with ripples superposed have been observed in some reaches of the Rio Grande upstream from Bernalillo, where the sediment transport rate is extremely low, but there is no evidence to indicate that this form of bed roughness is present in the Bernalillo reach. Ripples are not especially important and generally occur at very shallow depths.

The approximate ratios of the length of the dune, from crest to crest, to the height of the dune range from 10 to 24, and average about 16. This compares with approximate ratios from 12 to 20 in irrigation canals (Bender, 1956), and ratios from 14 to 28 reported by Simons and others (1961) for flume studies with a sand of 0.45 mm median diameter. E. M. Laursen (1958) reported ratios ranging approximately from 4 to 7 for flume studies with 0.1 mm sand. The shorter dune length may be related in some way to the scale of the flume system or the size distribution of the bed material.

The height of dunes for the Rio Grande varies widely, and has been observed in many cases to exceed the mean depth of flow. Dunes in the Rio Grande appear to grow to greater height, relative to the mean flow depth, than do the dunes in channels of small width-depth ratios. R. A. Bagnold (1956) has pointed out that in flow of unrestricted width, the fluid can divert and rejoin around a bed feature, while in channels that are narrow relative to the scale of the dune, the entire flow must pass over the bed feature. Because the fluid boundary drag on the upstream face of the dune is decreased in the three-dimensional case, the dunes grow steeper and higher than in the case of restricted width.

For upper regime flow, the bed is usually firm; under some conditions, it may become so hard packed that sampling of the bed material by conventional techniques is difficult or impossible. Standing waves may be present. Trains of waves will build and die out in a regular cyclic pattern. Relative to a fixed point in the channel, the trains of waves may be stationary, or they may move upstream or (rarely) downstream. Violently breaking waves are not uncommon.

Generally, the standing waves have a wave length L from crest to crest of 3 to 6 times the mean flow depth, and the width of the waves, measured perpendicularly to the direction of flow, averages about 1½ times the wave length and has never been observed to exceed 3 times the wave length.

Some quantitative information for standing waves in the Rio Grande and several tributaries is given in table 7. The velocities and depths listed in the table are local values which were observed in the regions where the standing waves occurred. Most of the observations were made from boats, and the data are admittedly crude. Figure 4 shows wave length, L, plotted against velocity, V. The solid line represents the wave length criterion established by Kennedy (1961a), namely:

$$V=\sqrt{gL/2\pi}. \tag{2}$$

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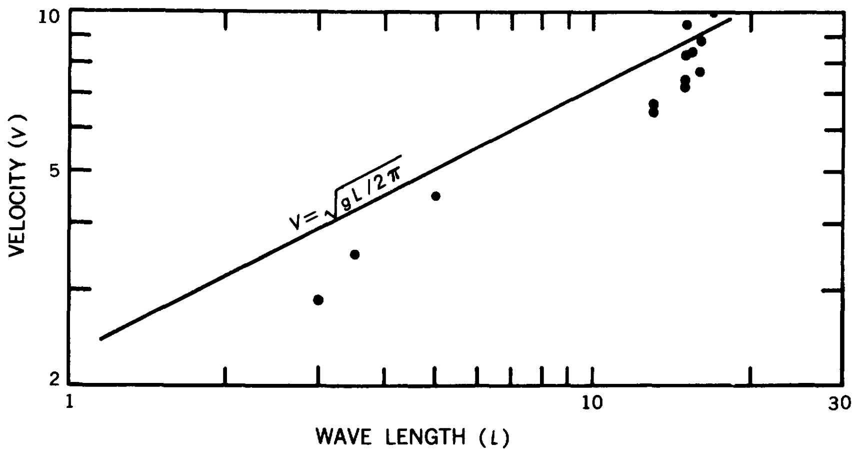

FIGURE 4.—Relation of velocity to the wave length of standing waves.

The field data indicate generally greater wave lengths for a given velocity than equation 2 would predict. When the difficulties of accurately measuring velocity and wave length under field conditions are considered, the scatter from the predicted relation is not excessive.

Figure 5 shows wave length plotted against depth, D, where the solid line represents the equation:

$$L=4.2\ D. \tag{3}$$

Kennedy concluded that the wave length, L, was independent of flow depth. Figure 5 does not reject this contention, but merely indicates that the velocity-depth relation was reasonably stable, for the range

TABLE 7.—*Observed data for standing waves*

Location	Date	V (ft per sec)	D (ft)	L (ft)	h (ft)	Bed material		Cm (pm)	Remarks
						d (mm)	σ		
Rio Grande	8-17-54	7.4	3.2	15.0	2.0	0.28	1.43	114,000	Breaking.
	8-17-54	8.3	2.9	15.0	1.8	0.32	1.51	129,000	Do.
	8-17-54	8.8	3.6	16.0	2.0	0.18	1.78	115,000	Do.
	5-27-58	7.7	4.6	16.0	------	0.24	1.54	3,040	------
	6-25-58	6.5	3.3	13.0	1.6	0.35	1.24	2,080	------
	4-6-60	3.5	1.2	3.5	0.5	0.30	1.52	1,870	------
	5-10-61	6.7	2.5	13.0	1.5	------	------	------	Breaking.
	5-10-61	9.5	4.5	15.0	2.5	------	------	------	Do.
	5-11-61	10.0	5.4	17.0	2.0	------	------	------	------
Galisteo Creek	8-16-60	2.9	0.5	3.0	0.3	0.29	1.90	47,000	------
	8-16-60	4.5	1.0	5.0	0.4	0.54	1.71	47,000	------
Rio Puerco	9-11-61	7.2	2.8	15.0	2.5	0.23	1.86	175,000	Breaking.
	9-20-61	8.4	3.8	15.4	2.8	0.51	2.21	240,000	Do.
	9-20-61	8.4	3.7	14.0	2.8	0.20	2.44	240,000	Do.

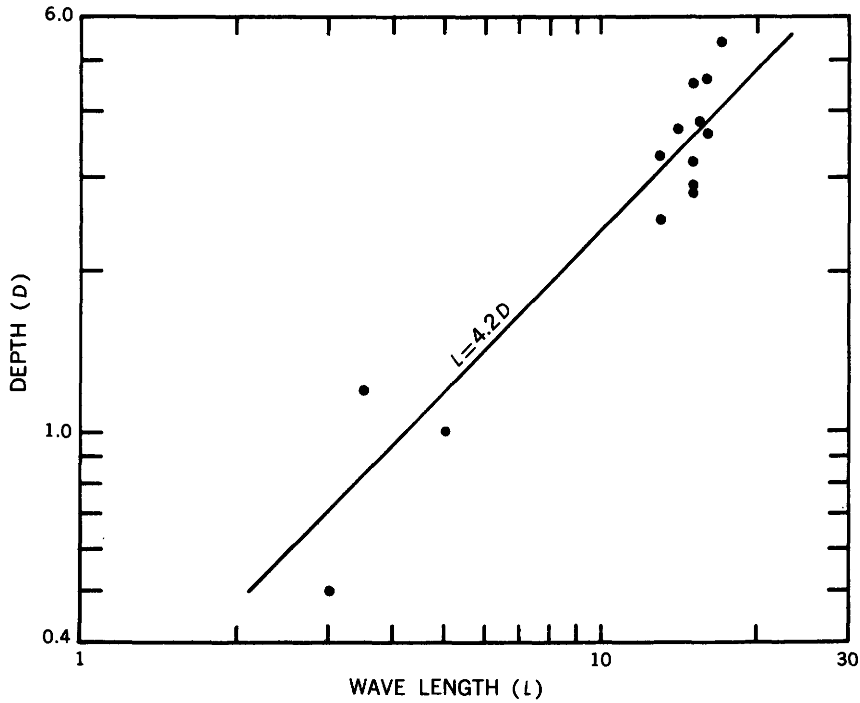

FIGURE 5.—Relation of depth to wave length of standing waves.

of conditions in table 7, and was similar to the relation for upper regime flow shown in figure 3. From equations (2) and (3),

$$L=2\pi V^2/g=4.2D \tag{4}$$

and

$$V=\sqrt{4.2Dg/2\pi}=4.64D^{1/2}. \tag{5}$$

The upper regime line in figure 3 may be represented by the equation $\overline{V}=3.5\,\overline{D}^{1/2}$.

The ratio of the wave height h from crest to trough to the wave length L for the breaking waves varied from 0.12 to 0.20 and averaged about 0.15. The values agree reasonably well with the theoretical value of 0.142 for deep water waves and with the observed values given by Kennedy (1961a).

The presence or absence of standing waves makes no impression on the overall flow resistance in the Rio Grande near Bernalillo, N. Mex.

Several criteria for predicting bed configurations in alluvial channels have been advanced (Liu and Hwang, 1959; and Garde, 1960). It has been shown (Culbertson and Dawdy, 1964) that these criteria do not adequately define the bed configuration for the Rio Grande.

RESISTANCE TO FLOW

CHEZY EQUATION

In many natural channels it is sufficiently accurate for preliminary analyses to assume that the slope of the energy gradient, S_e, equals the water-surface slope, S, and is constant (Dawdy, 1961). If this assumption is introduced in the interpretation of figure 3, the lines of lower and upper regime represent the Chezy equation with constant coefficients:

$$V = C\sqrt{RS}. \tag{6}$$

Values of $C/\sqrt{g}$, the dimensionless Chezy coefficient, range approximately from 9 to 12 for lower regime flow and from 19 to 24 for upper regime flow. These values are in reasonable agreement with values computed from data presented by Simons and Richardson (1961), wherein $C/\sqrt{g}$ ranged from 10.1 to 11.4 for flow over a dune bed of 0.28 mm median diameter sand, and from 17.4 to 18.1 for flow over a plane bed.

The lower and upper regime lines of figure 3 also represent lines of constant Froude number, $\mathbb{F} = \overline{V}/\sqrt{g\overline{D}}$, where $\overline{D} \sim R$. It is significant that the limiting Froude number for dunes is about 0.3, the upper limit for channel stability given by Simons and Albertson (1960). The limiting Froude number for upper regime flow is about 0.6. Leopold and others (1960) have suggested that the upper limit for Froude number in a river is controlled by the onset of spill resistance, which represents a localized and concentrated dissipation of energy near the banks. Field observations show that spill resistance occurs in the Rio Grande with upper regime flow, and the presence of standing waves and antidunes also represents a concentrated dissipation of energy.

During sustained upper regime flow, general degradation occurs through the reach. Leopold and Wolman (1956) reported that the bed elevation of the entire reach was lowered by scour during spring floods. The decreasing bed elevation and velocity-depth ratio for the 1952 spring flow is evident from the data in tables 1 and 2. It is concluded that along with spill resistance, the tendency to scour is an important factor controlling the upper limit of the velocity-depth ratio in the Rio Grande.

MANNING EQUATION

Probably the most common approach to flow resistance in natural channels is the Manning equation:

$$\overline{V} = \frac{1.49}{n} R^{2/3} S_e^{1/2}. \tag{7}$$

Values of Manning's n computed using $\overline{D}=R$ are plotted against discharge in figure 6. The n values in the figure represent the data in tables 1 and 2, and some additional observations at section A–2 (table 8) where the concentration of suspended sediment was relatively high in the range of 10,000 to 75,000 ppm.

For upper regime flow, which occurs above 4,000 cubic feet per second, the n values range approximately from 0.012 to 0.018, while for flows over a dune bed, the values range from 0.024 to 0.036.

The resistance to flow at section A–2 is generally greater than the resistance at section F for either lower or upper regime of flow. Part of this difference is due to a side-wall effect at section A–2; but a side-wall correction, as outlined by H. A. Einstein (1942) with an assumed n value of 0.05 for the banks, is not sufficient to bring the n values for section A–2 down to the values for section F.

For lower regime flow, dunes persist on the channel bed during greater discharges at section A–2 than at section F, and the dunes are of greater height at section A–2. The height of dunes appears to be dependent on the depth of flow, and the higher dunes account for the greater flow resistance at section A–2.

For upper regime flow, where the bed is plane, the flow resistance should depend upon the grain roughness and upon the depth of flow, and the overall flow resistance should be greater at the wide shallow

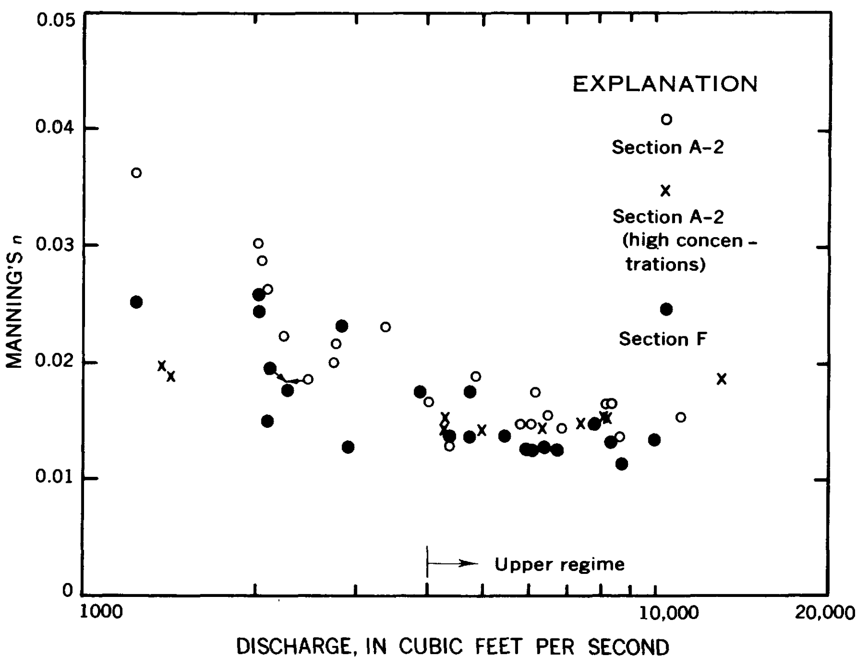

FIGURE 6.—Relation of Manning's n to discharge.

section than at the deeper section because of relative roughness effects. However, figure 6 indicates a higher resistance at section *A*–2, and it must be concluded that additional frictional losses at section *A*–2 are related in some way to local conditions which have not been determined. Probably, the changing cross section of the channel in the approach reach to section *A*–2 creates a form of spill resistance or an effect of sinuosity similar to that found by Leopold and others (1960) in a rigid-boundary flume study.

Figure 6 also shows values of n for section *A*–2 for flow transporting high concentrations of fine material in suspension. Most of the values were presented by Culbertson and Dawdy (1964). The measured data upon which the calculations were based are shown in table 8. Concentrations of suspended sediments range upward to about 75,000 ppm. Slopes were not observed, and an assumed average value of 0.00095 is probably on the conservative side, as most of the observations were on the falling side of the hydrograph.

The resistance for high concentration flows over a plane bed (table 8) is about the same as resistance for lower concentration flows. There is no consistent trend toward either an increase or decrease in resistance due to suspended-sediment concentrations. If a dampening of turbulence occurred because of the presence of suspended sediment, the effects on flow resistance probably are negligible for practical purposes. Vanoni and Nomicos (1960) reported a reduction in n of 13 percent due to sediment load. Changes in n of this magnitude could not be detected over the gross scatter in figure 6.

Simons and Richardson (1960) indicated that concentrations of fine sediment on the order of 40,000 ppm reduced resistance to flow by as much as 40 percent in the lower flow regime. This decrease in resistance was explained as due to the increased mass density and kinematic viscosity of the fluid, with a resulting decrease in fall velocity of the bed material. The decrease in fall velocity presumably allowed

TABLE 8.—*Observed data and computed parameters for flow with high concentrations of suspended sediment, section* A–2

Date	Q (cfs)	$\bar{V}$ (ft per sec)	$\bar{D}$ (ft)	C_m (ppm)	T (° F)	n (ft $^{1/6}$)	f	f/f'	Flow regime
7-18-53	1,370	3.18	1.60	42,400	73	0.0197	0.0388	3.0	Transition.
7-30-53	1,430	3.31	1.60	29,200	66	.0190	.0356	2.7	Do.
7-15-52	4,280	6.11	2.60	10,700	63	.0142	.0171	1.4	Upper.
8-27-55	4,300	5.80	2.75	59,500	63	.0155	.0200	1.8	Do.
8-30-57	5,000	6.48	2.86	20,400	70	.0143	.0167	1.5	Do.
8-23-61	6,340	6.82	3.43	51,600	70	.0145	.0180	1.6	Do.
8-27-55	7,360	7.34	3.70	48,100	63	.0150	.0168	1.5	Do.
7-18-53	8,020	7.46	3.95	74,700	70	.0154	.0174	1.6	Do.
8-12-52	8,200	7.52	4.01	63,400	64	.0154	.0173	1.6	Do.
9-25-55	13,000	8.50	5.60	71,600	61	.0170	.0190	1.9	Do.

the bed material to be transported at greater rates—that is, the bed becomes plane at lower flows than for conditions of lower concentrations. The data in table 8 for July 18 and 30, 1953 would tend to confirm the observations of Simons and Richardson.

In terms of overall resistance coefficients, high-concentration flow has more effect on lower regime flow or flow in the transition region than on flow over a plane bed. The changes in bed configuration occur at lower discharges for high-concentration flow than for the low-concentration flow. This interpretation appears to be in conflict with the findings of Vanoni and Nomicos (1960), who concluded that "the reduction in friction factor due to the suspended sediment is of importance only for streams carrying high suspended load over flat beds, and is of minor importance where there are dunes on the bed." However, in their flume study, Vanoni and Nomicos solidified the flume bed, and thus could not detect the interrelation of concentration to bed configuration. Their conclusion that changes in the friction factor due to variations in bed configuration are much larger than those due to the suspended load is well supported by the data in tables 1 through 4.

FRICTION FACTOR RATIO

Taylor and Brooks (1961) proposed that the ratio f/f' be used as a measure of bed configuration, where

$$f=\frac{8g\overline{D}S_e}{\overline{V}^2} \qquad (8)$$

and f' is determined from a standard Moody pipe-friction diagram by use of $4\overline{D}$ in place of pipe diameter and use of the median diameter of the bed material for the equivalent sand roughness. This value, f/f', represents the ratio of the actual overall resistance as measured by f to the resistance f' which would result from clear flow over a flat bed with grain roughness only, and thus should serve as an index to the energy dissipation due to form roughness of dunes, bars, and other irregularities on the bed. Taylor and Brooks found that an f/f' value of 2 separated the flow over a dune bed configuration from flow over a plane bed. Values of f/f' for section A–2 and F are plotted against discharge in figure 7. It may be seen that all the values of f/f' for upper regime flow are less than 2.

BAR RESISTANCE

Einstein and Barbarossa (1952) introduced an approach to the determination of flow resistance wherein the total resistance was divided into two parts, one due to the sand-grain roughness, and the

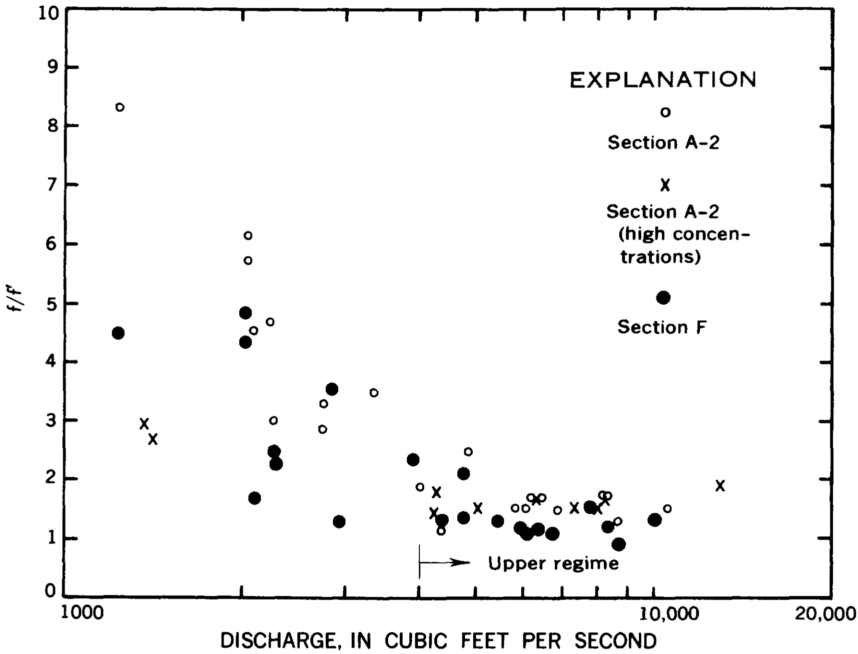

FIGURE 7.—Relation of f/f' to discharge.

other due to bars, dunes, and the general irregularities of the channel bed. The total shear stress on the bed, $\tau = \gamma R S_e$, was divided into two parts:

$$\tau = \tau' + \tau'' \tag{9}$$

where

$\tau' = \gamma R' S_e$ is the shear stress resisted by the sand grains,
$\tau'' = \gamma R'' S_e$ is the shear stress resisted by the form drag of the dunes and bars,
γ = the unit weight of water,
$R = R' + R''$.

For a given velocity, R' may be determined from the logarithmic velocity equation

$$\bar{V}/V'_* = 5.75 \log_{10} (12.27\, R'x/k_s) \tag{10}$$

where

$V'_* = \sqrt{gR'S_e}$
g is the acceleration due to gravity,
k_s is the representative grain roughness, d_{65},
x is a correction factor for transition from smooth to rough boundary, is given as a function of k_s/δ', and is applicable where $k_s/\delta' < 5$,
δ' is the theoretical thickness of the laminar sublayer, which is equal to $11.6\nu/V'_*$.
ν is the kinematic viscosity.

Reasoning that the shape, size, and frequency of bed irregularities should be a function of the bed-load transport rate, which is itself a function of flow intensity, ψ', Einstein and Barbarossa plotted a measure of the bar resistance, the dimensionless resistance factor $\overline{V}/V''_*$, against flow intensity ψ', where

$$\psi'=\frac{\rho_s-\rho_f}{\rho_f}\frac{d_{35}}{S_eR'}. \tag{11}$$

ρ_s is the density of the sediment,
ρ_f is the density of the fluid,
d_{35} is the representative grain diameter of the bed material and is the size for which 35 percent by weight is finer.

The functional relationship of $\overline{V}/V''_*$ to ψ' was defined from the average relation for reaches in several natural channels.

From the manner in which the bar-resistance curve was derived, it is apparent that it was not intended to be applicable to individual cross sections (Einstein, 1950). However, the application of the method to individual sections does give a means of comparing qualitatively the behavior of one section against another

Values of $\overline{V}/V''_*$ are plotted against ψ' for sections A–2 and F in figure 8. In these calculations, d_{35} and d_{65} were determined from figure 2, and the slopes used were values of S_e shown in tables 1 and 2. The behavior at section F, in spite of considerable scatter, is about as predicted by the curve, while for section A–2, the plotted points fall below the curve, and indicate that the dunes persist to greater shear stresses (low ψ' values) than predicted by the curve. Corrections for side-wall effects at section A–2, with n values of 0.05, do not appreciably change the relationship shown, and it is concluded that the difference in resistance at the two sections is not due to bank effects.

It is of interest to note that the behavior at section A–2, which is of almost constant width, is different from the behavior of many flumes, which are also of constant width. Flume data generally plot above the curve, which indicates that dunes will disappear from the bed at lower shear stresses than predicted by the curve, whereas for section A–2 the dunes persist to greater shear stresses. One reason for the differences might be in the effect of flow depth upon the height to which dunes will grow. Another reason probably lies in the method of operation of flume experiments—that is, a range of shear stresses in a flume requires a wide range of slope with a narrow range of depth, while in the field case, for a given reach, changes in shear stress result from wide variations in depth with a narrow range in slope. There exist some basic differences in behavior for the two cases.

Vanoni and Brooks (1957) have previously discussed the 1952 observations for sections A–2 and F in terms of the bar-resistance

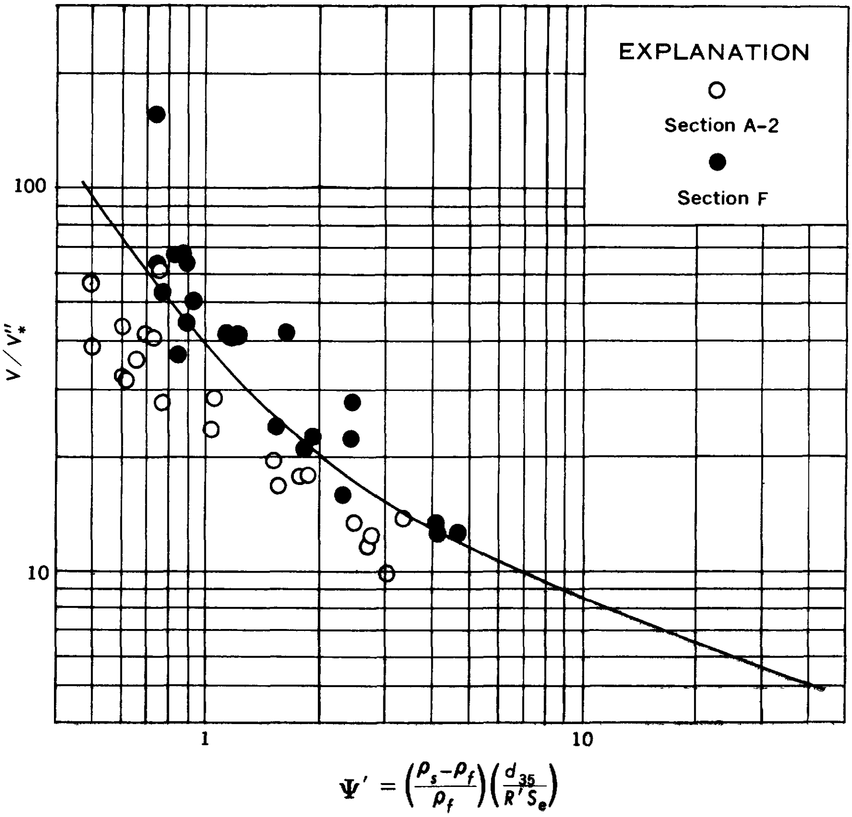

FIGURE 8.—Bar resistance for sections *A*-2 and *F*.

curve. In their analysis, they used the individual measurements for d_{35} and d_{65}, as well as the local water-surface slope for each section. Their values of $\overline{V}/V''_*$ and ψ' show the same general trend shown in figure 8, but with considerably more scatter and with a definite time sequence. They concluded that the 1952 Rio Grande data do not "lend confidence to the bar-resistance curve."

As indicated above, application of the curve to individual cross sections probably is not justified. In fact, when average conditions through the Bernalillo reach are applied to the bar-resistance curve (fig. 9), the computed values of $\overline{V}/V''$ and ψ' show excellent agreement with the predicted relation (Nordin and Dempster, 1963). The 1952 Rio Grande data would not detract from the bar-resistance curve but would tend to confirm the relation.

Basic data for figure 9 are given in table 9. The areas and wetted perimeters are the average of 13 cross sections through the reach, and water surface slopes were determined by fitting a line by the method

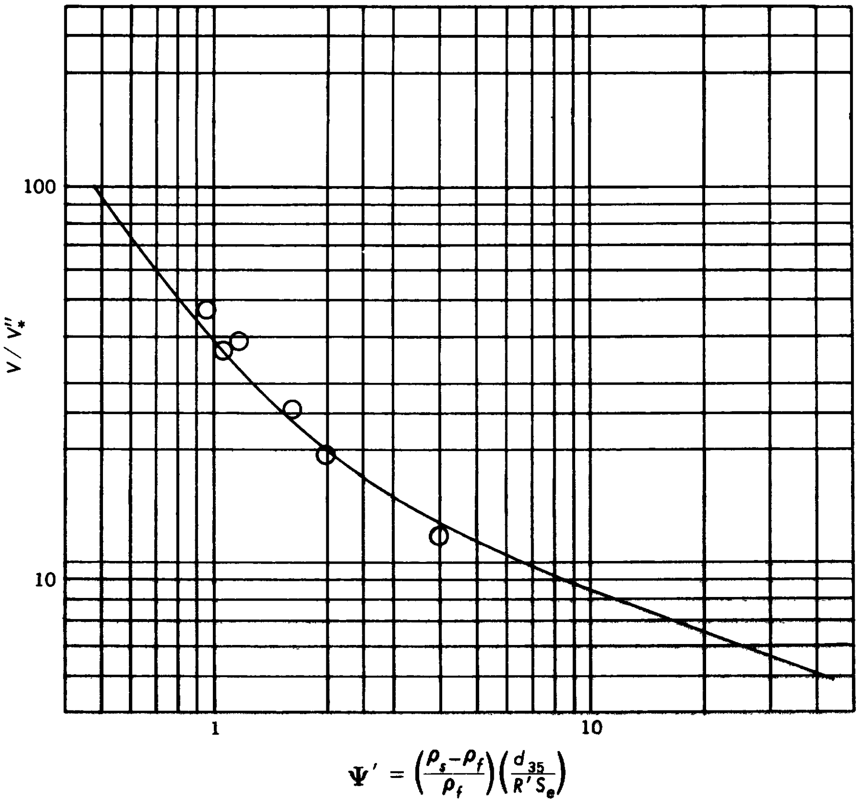

FIGURE 9.—Bar resistance for the average of 13 cross sections.

of least squares through the plotted water-surface profiles. Bed-material samples were collected at each cross section and were sieved to determine particle-size distributions. Values of d_{35} and d_{65} in table 9 were from the average size distributions given in table 10.

Figures 8 and 9 show that (1) the flow resistance for the reach is reasonably well described by the bar-resistance curve; (2) for a given flow intensity, there is an appreciable difference in bar resistance from one cross section to another; and (3) the bar resistance and hydraulic characteristics of an individual cross section, and especially a confined or partially confined section, are not indicative of the bar resistance and hydraulic characteristics of the reach.

In summary, the data for the Rio Grande, near Bernalillo, N. Mex., indicate that the general characteristics of the flow regime and forms of bed roughness and the values of the resistance coefficients compare reasonably well with the characteristics and values reported for several flume studies. Flow resistance for the average cross section

TABLE 9.—*Observed data and computed parameters for the average of 13 cross sections, 1952*

Date	Q (cfs)	A (ft²)	P_w (ft)	R (ft)	B (ft)	$\overline{V}$ (ft per sec)	$\overline{D}$ (ft)	T (°F)	S (ft per ft)	Bed material		ψ'	$\overline{V}/V''_*$	Flow regime
										d_{35} (mm)	d_{65} (mm)			
4-25-52	2,820	736	454.0	1.63	452	3.83	1.63	61	0.00090	0.230	0.330	1.61	25.7	Transition.
5-12-52	6,440	1,140	485.2	2.35	477	5.65	2.39	64	.00086	.278	.406	.96	47.1	Upper.
6-17-52	6,120	1,151	477.3	2.41	475	5.32	2.42	72	.00086	.270	.385	1.04	36.4	Do.
6-20-52	4,775	938	429.5	2.20	427	5.09	2.20	72	.00086	.290	.420	1.16	38.9	Do.
6-26-52	2,800	784	384.3	2.04	382	3.57	2.05	70	.00085	.260	.375	1.99	19.5	Transition.
7-24-52	2,030	826	424.4	1.95	422	2.46	1.96	78	.00088	.283	.405	3.94	11.9	Lower.

TABLE 10.—*Particle-size analysis of bed-material samples for the reach, 1952*

Date	Number of cross sections	Total number of samples	Percent finer than indicated size (mm)										d (mm)	σ
			0.062	0.125	0.250	0.500	1.0	2.0	4.0	8.0	16	32		
4-25-52	13	42	1.5	7.8	41.1	91.1	97.9	98.9	99.2	99.4	99.7	100	0.28	1.64
5-12-52	12	41	.5	3.4	27.9	79.3	93.8	96.6	97.8	98.0	100	-----	.33	1.73
6-17-51	14	46	.3	2.3	29.8	83.0	95.1	97.2	98.1	98.7	99.3	100	.32	1.61
6-20-52	13	40	.3	2.1	24.9	76.9	92.5	96.1	97.6	98.7	99.8	100	.35	1.76
6-26-52	13	39	.3	3.2	31.8	83.8	94.2	95.7	96.5	97.5	100	-----	.31	1.62
7-24-52	13	39	1.1	4.3	25.8	79.9	95.1	97.4	98.4	99.2	100	-----	.34	1.68

of the reach is described reasonably well by the bar-resistance curve, but the flow resistance may vary widely, for a given discharge, from one section to the next. Most of this variation in flow resistance is associated with flow in the transition zone between lower and upper regime flow. In the following section, some aspects of flow resistance in this transition region will be considered in detail.

TRANSITION FLOW

Flow in the transition region between upper and lower regimes will be called simply "transition flow". It has been shown in laboratory investigations (Brooks, 1958) and confirmed in the field (Colby, 1960) that for transition flow neither the velocity nor the sediment transport rate can be expressed as a single-valued function of the bed shear stress or any combination of the depth and slope or bed hydraulic radius and slope.

For the Rio Grande near Bernalillo, transition flow occurs frequently and generally occurs between discharges of 1,000 and 4,000 cfs. In terms of frequency, these flows are equaled or exceeded about 28 and 6 percent of the time respectively. Thus, flow may be in the transition between lower and upper regime about one day out of five. On the basis of the period 1942–59, it is estimated that transition flow accounts for about 34 percent of the total volume of flow and upper regime flow accounts for about 39 percent of the volume.

Flow conditions in the transition region are complicated by rather extreme changes in bed elevation. Figure 10, previously presented

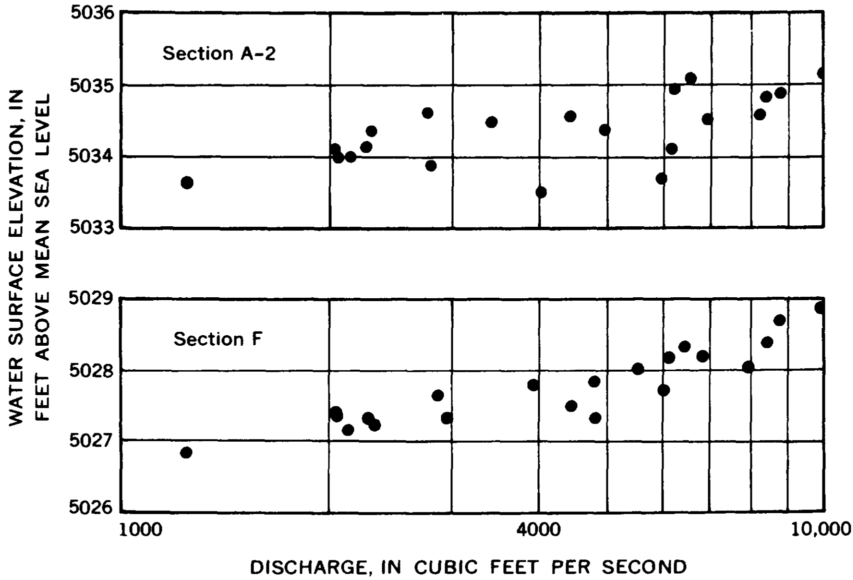

FIGURE 10.—Relation of water-surface elevation to discharge, sections *A*-2 and *F*.

by the writer and J. K. Culbertson (Nordin and Culbertson, 1961b) shows discharge plotted against water-surface elevation for sections *A*-2 and *F*. Above 4,000 cfs, flow resistance is approximately constant, and variations in the stage-discharge relation reflect changes in bed elevation due to scour and fill. Below 4,000 cfs, however, discontinuities in the stage-discharge relations reflect both changing bed elevations and changing bed configurations, and generally it is impossible to distinguish between the two effects except by frequent discharge measurements.

In terms of average flow conditions through the reach, the relation of flow resistance to discharge probably is best represented by some sort of gradual transition, such as the transition shown by the bar-resistance curve (fig. 9). Abrupt changes in the bed configurations and in the flow resistance through the entire reach are obvious only when the change in stage is very rapid.

A gradual transition through the reach is conditioned by two factors: (1) lateral variations in bed configuration and flow resistance at the individual cross sections, and (2) variations in flow resistance from section to section along the reach.

An abrupt change from a dune bed configuration to a plane bed configuration requires, among other things, that the cross section be relatively uniform (Colby, 1960). Where lateral nonuniformity of depth and velocity exists, as it does in most natural streams, multiple forms of bed roughness may exist (Simons and Richardson, 1962) and an appreciable change in discharge may be required to shift the entire cross section into a single form of bed configuration.

The multiple forms of bed roughness most commonly observed during transition flow in the Rio Grande consist of dunes and washed-out dunes across some part of the section, with a relatively plane bed across the remainder of the section.

The variations in flow resistance from section to section along the reach are shown in terms of the velocity-depth relations in figure 11. Basic data for the figure was provided by J. P. Beverage, U.S. Geological Survey (written communication, 1962). The letters beside the plotted points designate the cross sections shown in figure 1. Because the slope was about constant, the lines representing lower and upper flow regime are shown as line of constant $C/\sqrt{g}$, and are identical to the lines shown on figure 3.

For the observation of April 6, 1960 (fig. 11*A*), the velocity was remarkably constant through the reach. Five of the sections showed about the same velocity, and the other two varied by about 16 percent from the average. The Chezy coefficient varied by a factor of about 2, and bed configurations ranged from dunes across the entire bed at section *E* to a flat bed across most of the cross section *F*. For the May 24th observation (fig. 11*B*), the flow had receded and the general flow characteristics throughout the reach were those of lower regime, except at section *B*, where multiple bed forms persisted. Flow had channelized to about two-thirds of the bankful width at most of the sections.

On June 22, 1960 (fig. 11*C*), the water discharge was comparable to the discharge for the April 6th observation. Five of the eight sections had dune bed configurations, whereas multiple forms of bed roughness were observed at sections *A*, *D*, and *G*. Values of $C/\sqrt{g}$ ranged from 10 to 18, about the same range as for the April observations. Sections *B* and *F*, which had the lowest flow resistance for the April observation, showed a higher resistance typical of flow over a dune bed.

Although complicated in detail, the general pattern of channel adjustments through a spring runoff event is consistent from year to year. Leopold and Wolman (1956) have shown that the bed elevation of the reach (sections *A*–3 through *M*) is lowered by scour during a flood event, and that during the late summer and winter flows, the bed returns to about the same elevation as before. On the rising stage of a spring flood, the channel bed elevation is higher than later in the

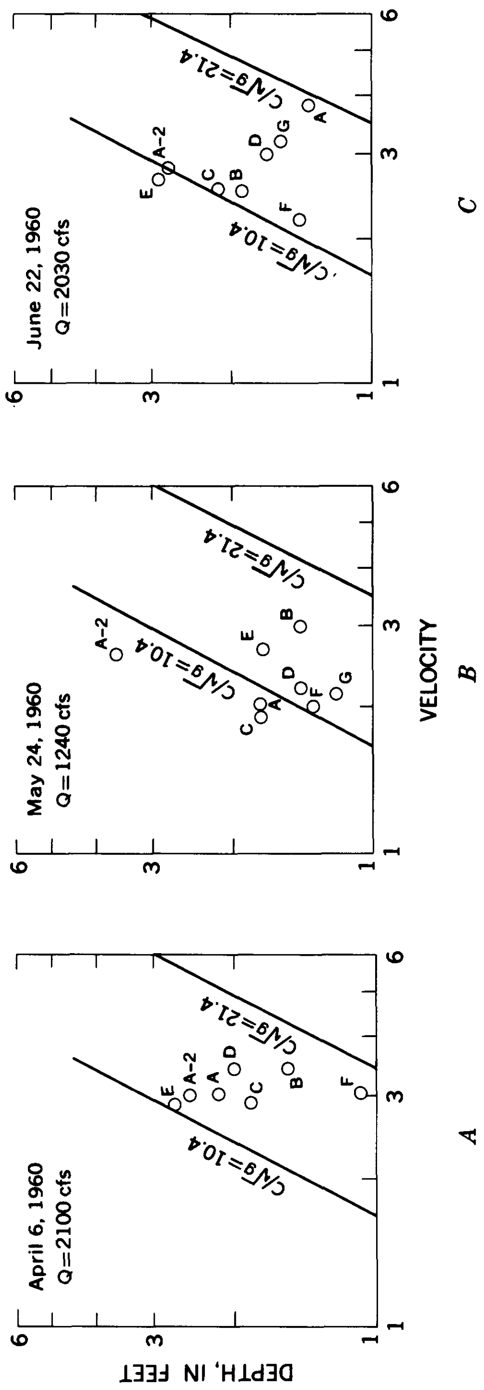

FIGURE 11.—Variations in the velocity-depth relations and in $C/\sqrt{g}$ for flow in the transition zone.

spring, the cross sections are reasonably uniform, and flow will occupy the entire width of the channel between the active banks. Bed configurations adjust quite rapidly to accommodate the imposed sediment and water discharge, and the velocity is nearly constant through the reach, regardless of the width of the cross section. If the discharge is great enough, upper regime flow will occur through the entire reach, together with a continued scour to lower the bed. During sustained transition flow or on receding stages, considerable channelization occurs with a concurrent decrease in the average width of the channel (Nordin and Culbertson, 1961b). This tendency toward a decrease in width is seen clearly in the data for the average flow conditions of the reach in 1952, table 9. The average width was 452 feet for a discharge of 2820 cfs on the rising stage (April 25, 1952) and 382 feet for a discharge of 2800 cfs on the falling stage (June 26, 1952).

Changes in width during transition flow occur quite rapidly and generally are somewhat variable and unstable. These changes should not be confused with the adjustments in bankfull width, which are features of the general regimen of the river, and which are related primarily to the bankfull discharge or to some dominant discharge (Blench, 1957) and to the characteristics of the bed and bank material (Schumm, 1960).

The most rapid channelization occurs in the transition region of velocities of about 3 fps. Qualitatively, this width development may be explained by considering the relation of velocity to the discharge rate of bed material, given by B. R. Colby (1961). Colby determined from empirical relations that, for a mean velocity of 3 feet per second and a median diameter of bed material of 0.3 mm, the discharge rate of bed material was independent of flow depth. For the flow conditions shown in figure 11 (mean velocity approximately 3 feet per second), the transport rate of bed material would vary directly with the width of the channel. For the channel to maintain continuity of sediment transport, channel adjustments must be in the direction required for equilibrium conditions to be established—a decrease in width or velocity at the wide sections, or an increase in velocity at the narrow sections, or both.

Table 11 presents a résumé of the velocities, channel widths, and bed-material transport rates at sections *A*–2 and *F* for the observations on April 6, 1960, and June 22, 1960. All sediment coarser than 0.062 mm was considered bed material, and total transport rates were computed both by the modified Einstein method (Colby and Hubbell, 1961) and by the method proposed by Laursen (1958). For April 6, the velocity was about the same at both sections, and the transport rate at section *F*, estimated by either method, was considerably greater than the transport rate at section *A*–2. For June 22, after section *F* had channelized to about two-thirds of bankfull width, the transport rates at the two sections were approximately the same. These figures support the idea that width development below bankfull stage is primarily in response to a tendency for the channel to maintain continuity of sediment transport.

The width adjustments of a channel, like the changes in bed configuration, flow resistance, velocity, and depth, are related in some manner to the sediment transport rates. The tendency for low flow resistance to accompany high concent ations of bed material is obvious from the data in tables 1 and 2. It is beyond the scope of this study to treat sediment transport in detail, but several general aspects will be considered.

TABLE 11.—*A comparison of total transport rates of bed material for sections* A–2 *and* F, *April 6 and June 22, 1960*

Date	Section	Mean velocity (ft per sec)	Width (ft)	Total transport rate of bed material (tons per day)	
				Modified Einstein method	Laursen method
April 6, 1960	*A*-2	3.04	269	8,400	3,400
	F	3.03	632	12.000	4,700
June 22, 1960	*A*-2	2.89	268	4,900	1,800
	F	2.23	357	5,400	1,500

SEDIMENT TRANSPORT

Figure 12 shows daily mean water discharge and sediment concentration for the Rio Grande near Bernalillo, April–July 1958. The maximum concentration preceded the maximum discharge by a period of about six weeks. Thereafter, the concentration decreased regularly, more or less independently of the water discharge.

The concentration curve in figure 12 was defined from suspended-sediment samples which contained both fine material (or wash load) and sand-size material (or bed-material load). Particle-size distributions of the samples (tables 3 and 4) show that much of the material transported on the rising spring flow was wash load. However, for the data presented herein, neither the size distributions of the samples nor the concentrations of bed material computed by various total-load formulas are sufficient to indicate whether the transport rate of bed material, for a given discharge, is greater on the rising stage or on the falling stage.

Usually, in a natural channel where the concentration of bed material is higher on rising stages, the increased concentration may be accounted for, at least in part, by the lower temperatures and increased viscosities, as clearly shown by L. G. Straub and his coworkers

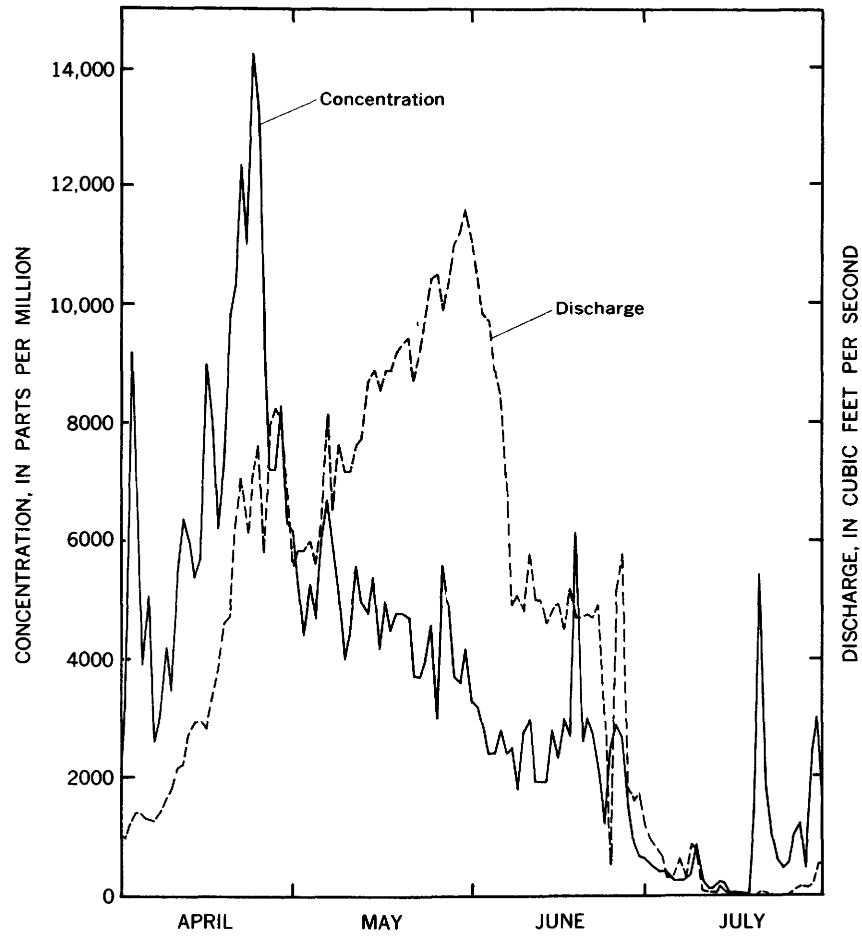

FIGURE 12.—Mean daily water discharge and sediment concentration, April-July, 1958,

(Straub and others, 1958). Straub found, in flume studies, that at a constant discharge, a decrease in temperature caused an increase in sediment transport and an increase in the energy slope, while the depth and the velocity remained about constant. In a natural channel with relatively slow changes in stage, the slope must conform to the natural topography and therefore will vary conservatively, while the velocity and depth change appreciably.

In the case of tributary inflow from storm runoff, where the temperature may be about constant but the change in stage is rapid, the increase in bed-material concentration on the rising stage is associated with an increased slope and with the higher viscosity induced by the high concentrations of fine material.

Leopold and Maddock (1953) have shown that for a given width and discharge, an increase in suspended sediment requires an increase in velocity and a reduction in depth. They concluded, from observations of channel adjustments during flood events, that the observed changes in the stream bed resulted from changes in the sediment load brought into the measuring reach from upstream. No evaluation was given of temperature effects or of the influence of fine sediments, and it must be assumed that some part of the observed channel adjustments may be attributed to these factors. However, the results of flume experiments, conducted at constant temperature, have supported the findings of Leopold and Maddock (Vanoni and Brooks, 1957; Kennedy, 1961b). Accordingly, several investigators have suggested that the bed-material load is an imposed variable, and that for a given discharge, a stream will adjust its bed form, friction factor, velocity, and depth to enable it to transport the load (Vanoni and Nomicos, 1960; Taylor and Brooks, 1961).

While the fine material certainly must be treated as an independent variable, there is little field data to support the idea that the bed-material concentration should be considered an imposed variable. This is especially true in respect to spring flood events, when there is a considerable change in temperature and fine material concentration between a given discharge on the rising stage and the same discharge on the falling stage.

In the case of tributary inflow, the bed-material concentration attributable to the inflow must be considered an imposed variable. However, the adjustments in the main channel which accompany tributary inflow are quite complex, and the observed behavior of a channel usually does not provide much insight into the relation between sediment load and flow resistance.

For example, consider the data in tables 1 and 2 for June 13 and June 18, 1958. The average of the measured discharges on both days was 4360 cfs. Slopes were the same for the two observations. On June 13 the stage was about constant, but on June 18 the discharge was increasing during the observations. The total concentration and the concentration of bed material was greater on June 18 than on June 13. Associated with the higher concentration were a lower velocity, greater depth, greater flow resistance, and higher temperature. Between June 13 and June 18, the median diameter of the bed material decreased, and the measure of sorting, σ, increased.

The difference in the observed behavior of the channel for the two dates was due to inflow on June 17, 1958, of a relatively heavy sediment load from Galisteo Creek, 23 miles upstream from the Bernalillo reach. The peak concentration from the inflow passed the Bernalillo reach about 12 hours before the June 18th observation. After the peak, the total concentration and the concentration of any particular size class decreased exponentially with time (fig. 13).

Relative to the Rio Grande, the Galisteo Creek transported higher concentrations and bed material of coarser grade. One might expect the bed material at Bernalillo to become coarser with inflow from the Galisteo, but such was not the case. In general, the channel adjustments which occur with tributary inflow, especially the minor changes in the characteristics of the bed material, are highly unpredictable.

From the data in tables 1 and 2, it is evident that minor changes in the characteristics of the bed material are not reflected in the measures of flow resistance.

The effects of changes in the bed-material size distribution on sediment transport rates are not obvious. However, there are some indirect indications that the minor variations of the bed material are important, as was suggested by Kennedy (1961b). Figure 14 shows the transport rates of bed material at section *A*–2 plotted against the transport rates at section *F*. The rates were computed using the modified Einstein method (Colby and Hubbell, 1961), the data in tables 1 through 4, and the average bed material size distribution of figure 2. There is a systematic deviation toward higher transport rates at section *F*. In figure 15, the transport rates were computed using the individual bed-material size distributions in tables 5 and 6. The plotted points show only random scatter about a line of perfect agreement, the relation which would be expected if there is continuity of sediment transport through the reach. In fact, it seems reasonable to assume that the minor variations in size distributions of bed material at different sections along a reach, like the width adjustments during transition flow, are manifestations of a tendency for the channel to maintain continuity of sediment transport—hence the random scatter in figure 15.

For the Rio Grande, as for most natural channels, total transport rates of bed material cannot be measured directly but must be computed by one of the various transport formulae. Figure 16 shows the transport rates of bed material for sections *A*–2 and *F*, computed by the modified Einstein method, and the transport rates for the average cross section of the reach in 1952 (tables 9 and 10), computed with the Einstein bed-load function. Figure 17 shows transport rates for sections *A*–2 and *F* computed by the Laursen method. It is obvious that for a given water discharge, there are considerable differences in the transport rates computed by the various methods.

The total discharge rates of bed material, Q_T, are compared with the discharge rate of measured suspended sand, Q_s, in figures 18 and 19. The discharge rates of measured suspended sand were determined

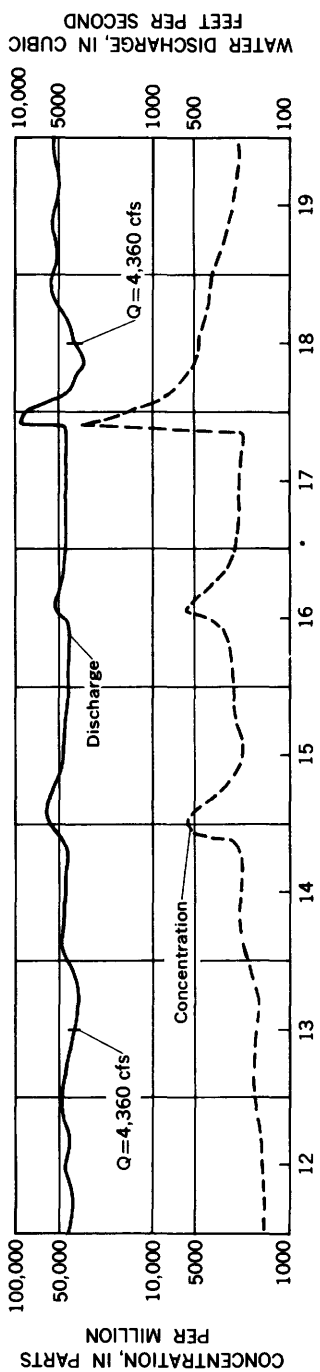

FIGURE 13.—Variation of discharge and concentration with time, June 12–19, 1958.

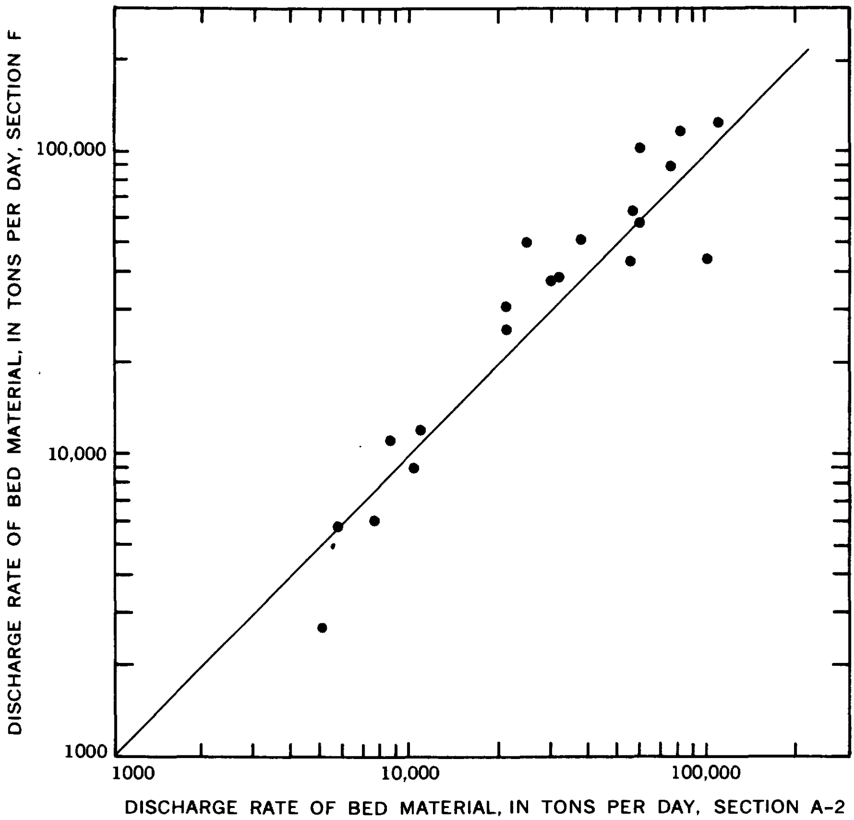

FIGURE 14.—A comparison of discharge rates of bed material at sections *A*-2 and *F*, computed using an average size distribution of bed material.

from water discharges and concentrations of sand in suspended-sediment samples (tables 3 and 4).

Figure 18 shows that, as an average condition, the total transport rate of bed material by the modified Einstein method, for a given cross section, is equal to the discharge rate of measured suspended sand multiplied by a constant. Culbertson and Dawdy (1964) determined the Bagnold transport function for the Rio Grande near Bernalillo to be a constant, 1.46, times the discharge rate of measured suspended sands. A line with the equation Q_T=1.46 Q_s would fall below most of the points on figure 18.

In figure 19, most of the plotted points fall below the line Q_T= Q_s; thus the total transport rates by the Laursen equation are less than the transport rates determined from suspended sediment samples.

A summary of the transport rates of bed material computed by the modified Einstein and Laursen methods for sections *A*–2 and *F* and by the Einstein bed-load function for the reach is given in table 12.

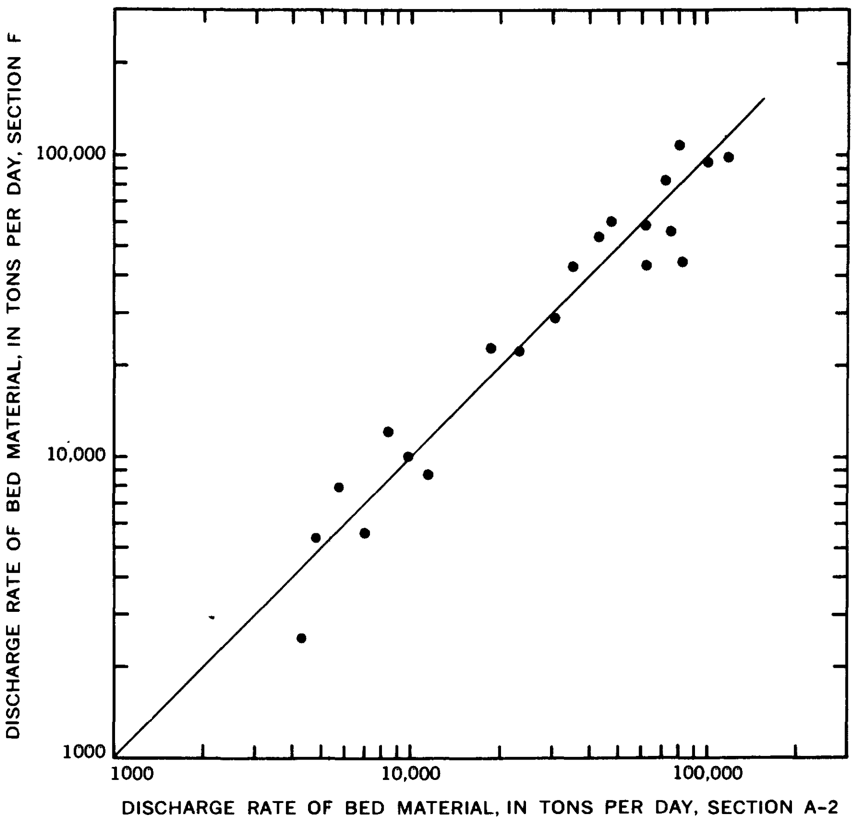

FIGURE 15.—A comparison of discharge rates of bed material at sections *A*-2 and *F*, computed using individual size distributions of bed material.

The modified Einstein method utilized the size distribution of suspended-sediment samples. Both the modified Einstein and the Laursen method require values of mean velocity and depth; so the methods have limited application in design where it is necessary to estimate depth and velocity for a specific range of discharge. The bar-resistance curve provides a method of estimating mean velocity but from figure 16 and table 9, it is seen that the relation of water discharge to bed-material discharge is poorly defined. Some of the scatter in the relation determined by the Einstein bed-load function is attributable to changes in slope, temperature, and bed-material size distributions, but as noted by Brooks (1958), the major cause of the scatter is that hydraulic radius and velocity are not unique functions of discharge.

Although the data for the Bernalillo reach fit the the bar-resistance curve better than most field data, velocities estimated from the curve

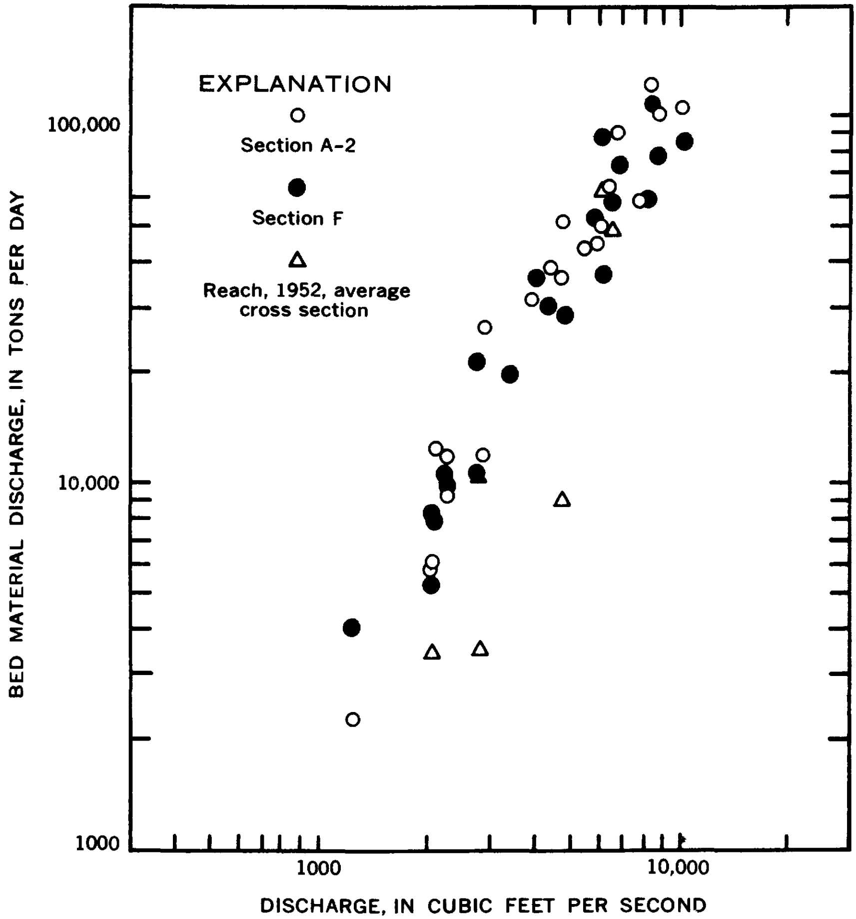

FIGURE 16.—Total transport rates of bed material, computed by the modified Einstein method for sections *A*-2 and *F*, and by the Einstein bed-load function for the reach.

vary by as much as 20 percent from the observed values given in table 9. The bar-resistance curve is not a sensitive measure of the flow resistance due to forms of bed roughness.

Colby (1961) has shown that mean velocity is the major factor determining the discharge of bed material. Although a discontinuity exists in the relation of bed shear stress to bed-material discharge for several stations of the Rio Grande in New Mexico, there is no discontinuity, for a given cross section, in the relation of velocity to transport rate. It is apparent that refinements in the methods of estimating the transport rates of bed material are contingent upon more reliable expressions for the interrelation of bed configuration, flow resistance, velocity, and depth. Of necessity, such expressions must be developed in carefully controlled laboratory experiments.

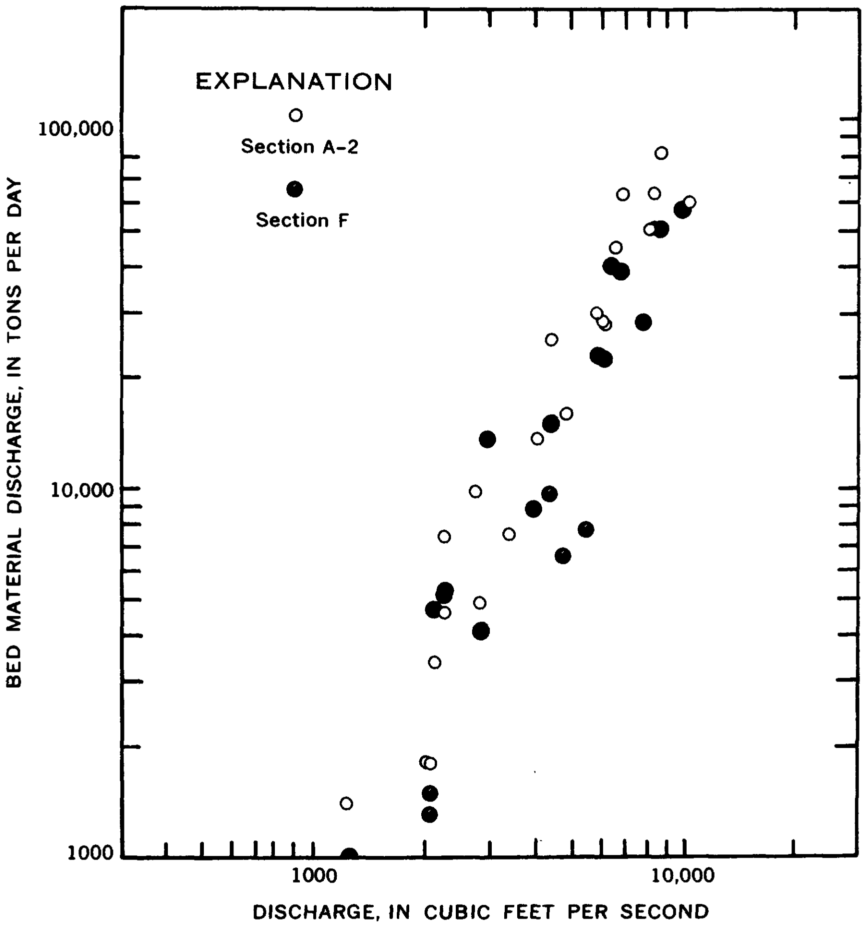

FIGURE 17.—Total transport rates of bed material, computed by the Laursen method.

The applicability and the limitations of experimental results, however, must be determined in the field.

Precise relations between bed configurations, flow resistance, hydraulic variables, and transport parameters probably can never be defined for many field conditions. Several of the more important reasons for this lack of precision in the Rio Grande data are as follows:

1. Both the streamflow and the sediment discharge rates are extremely variable, as illustrated in figure 12. Uniform flow and uniform transport rates are probably never realized. There should be a tendency for the stream to adjust toward equilibrium conditions, but over a short time base—such as the time required for a single observation—there is no reason to assume that equilibrium exists.

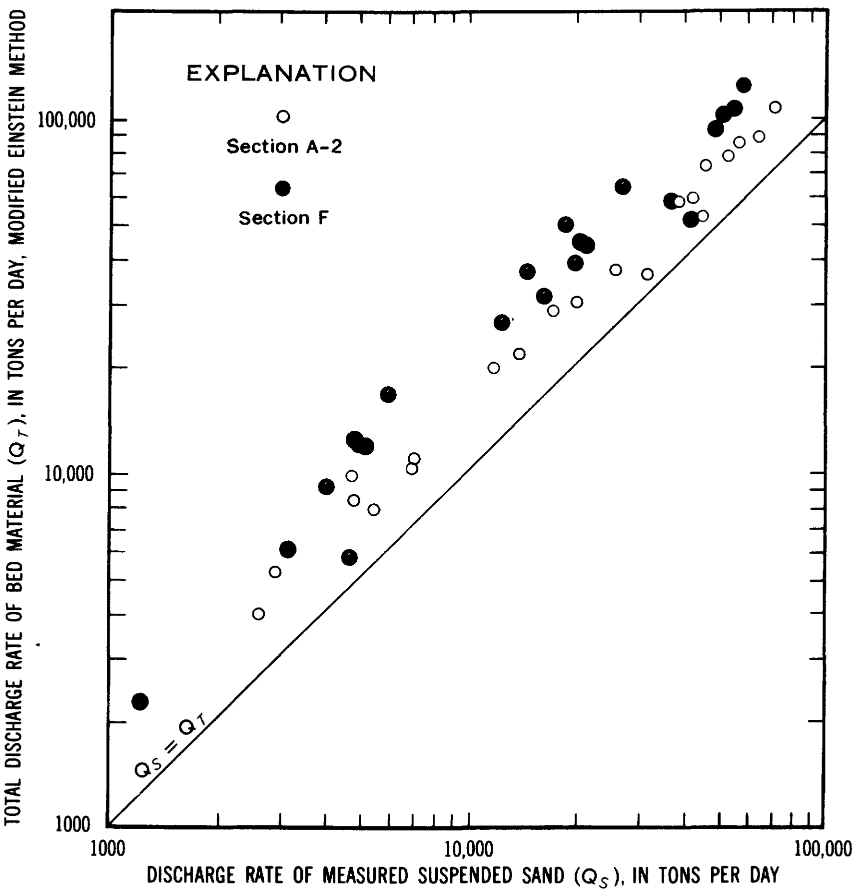

FIGURE 18.—A comparison of the discharge rate of measured suspended sand with the total discharge rate of bed material computed by the modified Einstein method.

2. It is difficult to estimate, measure, or sample some of the variables involved. In figure 20, the water discharge and the concentration of fine material for section *A*–2 are plotted against the discharge and concentration for section *F*. Because the observations were only approximately concurrent, the scatter in the relations reflects both errors inherent in the measuring and sampling techniques and minor short-term fluctuations in the actual discharges and concentrations. Fine material is uniformly distributed in a cross section, so sampling errors should be minimized. The variations in concentration in figure 20 probably are representative of the actual fluctuations of concentrations of fine material in the stream.

Generally, the fluctuations in the concentrations for sand sizes are more pronounced than the fluctuations for the fine material. The concentration of sand may be affected by local factors. For example,

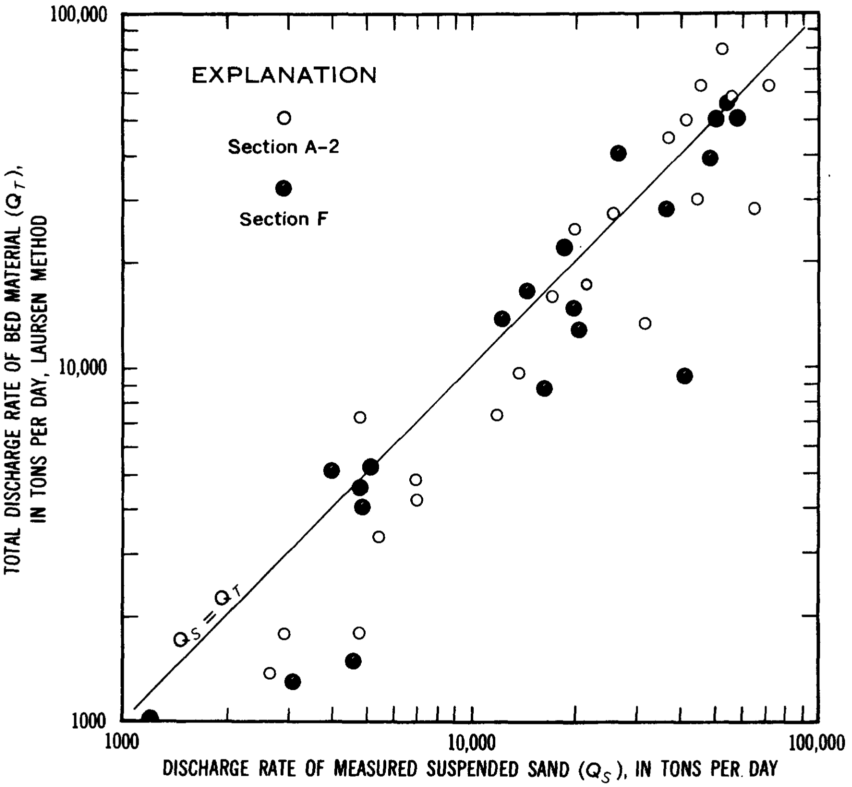

FIGURE 19.—A comparison of the discharge rate of measured suspended sand with the total discharge rate of bed material computed by the Laursen method.

the high concentration of sand on June 25, 1958, at section *A*–2 was caused by antidunes upstream from the section, a local influence which was not reflected in the concurrent sample at section *F*.

3. There exists a time-dependency of sediment concentration during flood events, both for spring floods extending over several months (fig. 12) and for minor flood events from tributary inflow (fig. 13). During such flood events, the concentration varies as a function of time, apparently independent of the hydraulics of the system. Thus, for any single observation, antecedent conditions may be of prime importance.

CONCLUSIONS

The principle conclusions of this study may be summarized as follows:

1. Flow resistance for the Rio Grande near Bernalillo, N. Mex., varies widely due to changing bed configurations.

TABLE 12.—*Total transport rates of bed material*

Date	Section A-2				Section F				Reach	
	Q (cfs)	Q_T (tons per day)[1]	Q_T (tons per day)[2]	Q_T (tons per day)[3]	Q (cfs)	Q_T (tons per day)[1]	Q_T (tons per day)[2]	Q_T (tons per day)[3]	Q (cfs)	Q_T (tons per day)[4]
4-25-52	2,730	21,700	23,100	9,800	2,910	26,700	22,800	13,700	2,820	3,570
5-12-52	6,490	58,000	75,900	45,400	6,390	64,600	56,200	40,500	6,440	47,800
6-17-52	6,140	37,000	35,700	27,700	6,100	50,000	43,300	22,100	6,120	62,000
6-20-52	4,830	28,900	30,500	16,000	4,720	36,700	29,200	16,600	4,780	8,980
6-26-52	2,760	10,700	11,300	4,900	2,850	12,000	8,700	4,100	2,800	10,100
7-24-52	2,060	8,330	7,000	1,800	2,030	6,100	5,600	1,300	2,030	3,480
5- 8-58	6,860	74,000	72,700	63,700	6,730	90,300	82,100	39,600		
5-13-58	8,320	108,000	101,000	63,600	8,310	123,100	96,000	51,200		
5-21-58	8,680	77,900	119,000	80,400	8,700	101,000	99,800	50,700		
5-27-58	10,100	85,000	80,100	59,200	9,970	106,000	107,000	57,100		
6- 4-58	8,160	59,900	61,600	50,200	7,790	58,500	59,800	28,400		
6-10-58	5,800	52,300	61,800	30,100	5,450	43,600	43,700	17,800		
6-13-58	4,340	30,100	42,300	25,100	4,380	38,800	54,500	15,000		
6-18-58	4,000	36,300	47,400	13,500	4,730	51,900	61,000	9,600		
6-25-58	6,040	88,200	93,900	28,400	5,960	44,600	44,500	23,000		
4- 6-60	2,100	7,900	8,400	3,400	2,100	12,300	12,000	4,700		
5-24-60	1,240	4,050	4,300	1,400	1,240	2,280	2,500	1,000		
6-22-60	2,030	5,230	4,900	1,800	2,030	5,790	5,400	1,500		
4-27-61	2,230	10,800	9,900	4,600	2,280	12,000	9,900	5,300		
5- 3-61	3,360	19,700	18,500	7,400	3,890	31,700	23,000	8,800		
5-19-61	2,260	9,820	5,700	7,400	2,260	9,200	7,900	5,200		

[1] Computed by the modified Einstein method, using average bed-material size distribution of figure 2.
[2] Computed by the modified Einstein method, using individual bed-material size distributions of tables 5 and 6.
[3] Computed by the Laursen equation, using average bed-material size distributions of figure 2.
[4] Computed by the Einstein bed-load function, using the bed-material size distribution in table 10.

2. Flow in the Rio Grande may be classified as lower regime flow over a dune bed and upper regime flow over a plane bed, with a transition zone between the two regimes.

3. Flow resistance is consistently greater at the partially confined section *A*–2 than at the wider section *F*.

4. The Einstein bar-resistance curve does not adequately describe the flow resistance for either section *A*–2 or *F*, but it does describe the flow resistance for the average cross section of the reach.

5. High concentrations of suspended sediment have more effect on the values of overall resistance coefficients for lower regime flow and flow in the transition zone than for upper regime flow.

6. Flow in the transition region is characterized by variable bed configuration, flow resistance velocity, and depth. These variations occur laterally at a cross section and from section to section along the reach.

7. Adjustments in the flow width and minor variations in characteristics of the bed material reflect the tendency for the channel to maintain continuity of sediment transport.

8. Transport rates of bed material, computed by the Laursen method, are less than the transport rates of measured suspended sands. For a given cross section, transport rates of bed material

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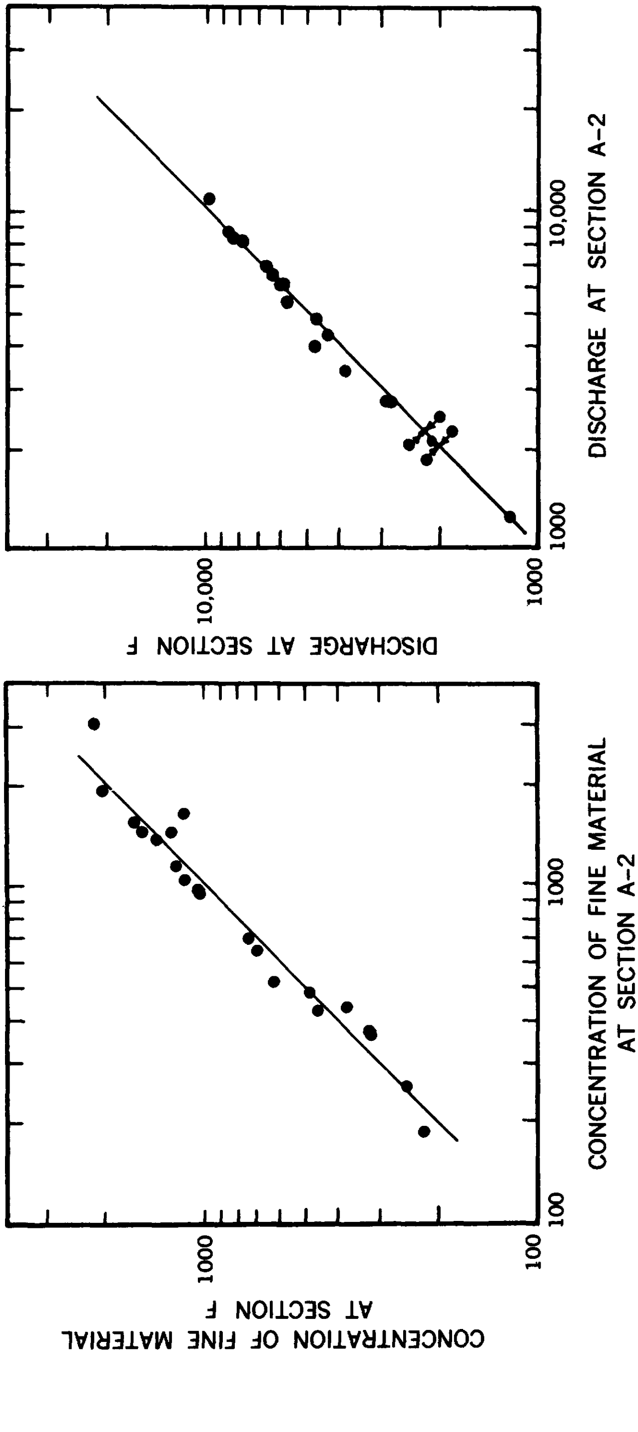

FIGURE 20.—Comparison of water discharge and concentration of fine material for sections *A*-2 and *F*.

computed by the modified Einstein method bear a constant ratio to the transport rates of measured suspended sands.

9. The interrelation of flow resistance and sediment transport is complicated by the extreme variability of water and sediment discharge, and by the time-dependency of sediment concentration during flood events.

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