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Flow Characteristics of Elkhorn River Near Waterloo, Nebraska

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By E. W. BECKMAN *and* L. W. FURNESS

STUDIES OF FLOW IN ALLUVIAL CHANNELS

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1498-B

Analysis of depth-discharge relationships with changing bed configuration

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LETTERS, SYMBOLS, AND UNITS

Symbol		Units
A	Area of cross section of stream	ft²
B	Top width of cross section of stream	ft
C	Chezy coefficient of roughness	ft½/sec
C_a	Empirical discharge coefficient proposed by Liu and Hwang	ft^{1-x}/sec
C_s	Concentration of sediment in suspension, in parts per million	
D	Mean depth of flow in cross section	ft
d or d_{50}	Median fall diameter of streambed material	ft
d_{65}	Grain size of bed material at which 65 percent are finer; used as K_s by Einstein and Barbarossa	ft
d_{35}	Grain size of bed material at which 35 percent are finer; used as D_{35} by Einstein and Barbarossa	ft
F	Observed fall in a reach	ft
$\mathbb{F}$	Froude number $= V/\sqrt{gD}$	
g	Gravity acceleration $=32.2$	ft/sec²
k	A constant	

Symbol		Units
n	Manning coefficient of roughness	$ft^{1/6}$
P	Wetted perimeter of stream cross section	ft
Q	Total discharge of water-sediment mixture	ft^3/sec
q	Unit discharge: the average discharge of water-sediment mixture in a unit width of the stream cross section= Q/B	ft^3/sec
σ	Standard deviation of bed material	
R and R_m	Hydraulic radius= A/P; also used as average hydraulic radius when combining several sections in a reach	ft
R'	Hydraulic radius pertaining to grain roughness	ft
R''	Hydraulic radius pertaining to channel irregularities where $R=R'+R''$	ft
S	Slope of energy gradient	
T	Temperature of water	°F
V	Average velocity in a cross section, also used as average mean velocity when combining sections	ft/sec
V_*	Shear velocity= $\sqrt{gRS}$ or as $\sqrt{gDS}$ by Simons, Richardson, and Albertson	ft/sec
V'_f	Velocity pertaining to grain roughness= $\sqrt{gR'S}$	ft/sec
V''_f	Velocity pertaining to channel irregularities= $\sqrt{gR''S}$	ft/sec
ω	Fall velocity of sediment particles usually of the median-grain size, d	ft/sec
X'	A parameter describing sediment transport= $1.68 \frac{d_{35}}{R'S}$	
X	An exponent for R which varies with the median-grain size (d) of the bed material in the equation $V=C_a R^x S^y$	
y	An exponent for S which varies with the median-grain size (d) of the bed material	
ν	Kinematic viscosity of water	ft^2/sec
ρ	Unit mass density of water	$\frac{lb\ sec^2}{ft^4}$
ρ_s	Unit mass density of sediment in air	$\frac{lb\ sec^2}{ft^4}$
γ	Specific weight of water	lb/ft^3
γ_s	Specific weight of sediment	lb/ft^3

STUDIES OF FLOW IN ALLUVIAL CHANNELS

FLOW CHARACTERISTICS OF ELKHORN RIVER NEAR WATERLOO, NEBRASKA

By E. W. BECKMAN and L. W. FURNESS

ABSTRACT

The characteristics of flow in a reach of alluvial channels on the Elkhorn River were observed. The variations in channel width, bed elevations, bed configurations, and roughness coefficients are described and related to certain hydraulic parameters previously defined in laboratory and field studies of flow in alluvial channels.

INTRODUCTION

A better understanding of the relationship of discharge to depth and slope in alluvial channels was sought through observations on a reach of channel of the Elkhorn River in Nebraska. Measurement of bed elevation, velocity, and slope were obtained for 45 different flow events during the period 1951–56. Several determinations of size of bed material and suspended-sediment concentration were also made.

The hydraulic relationships in alluvial channels are complex because the configuration and elevation of the channel bed are unstable. It is recognized that general principles cannot be established from the history of events in a single reach in which slope and size of bed material are virtually constant. Laboratory studies during recent years have defined the regimes of bed configuration and the primary variables which determine flow depth. However, the results of laboratory studies cannot yet be applied to natural streams because the relationships of model to prototype flow of water-sediment mixtures is imperfectly understood. Studies of the mechanics of flow in natural channels should contribute towards a better understanding of these relationships.

The hydraulic characteristics of the Elkhorn reach are described in this report. Certain analyses of the data are presented in order to make comparisons with the results of laboratory and field studies previously published in the literature.

DESCRIPTION OF REACH

A reach 1,670 feet long on the Elkhorn River at King Lake Camp about 2 miles northwest of Waterloo, Nebr., was selected for investi-

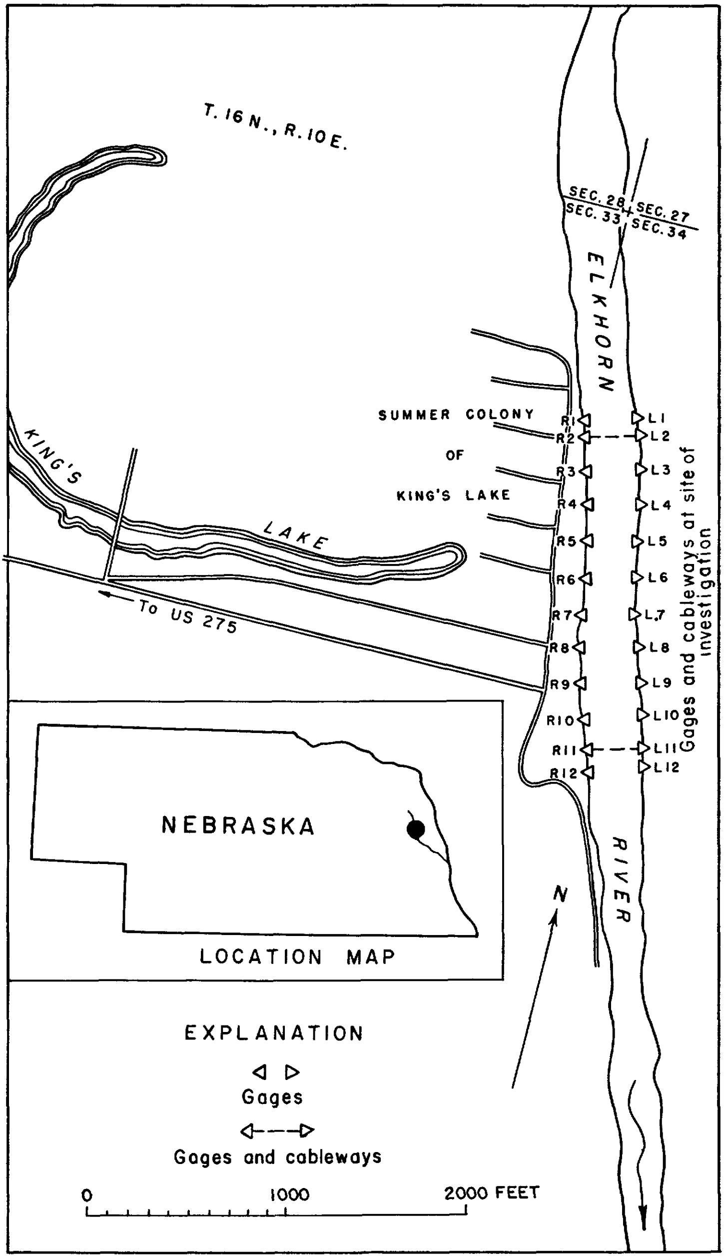

FIGURE 1.—Map showing site of investigation.

gation (fig. 1). The channel alinement is relatively straight, and, except for unusually high floods, the flow is confined to the channel. Vegetation tends to stabilize the relatively steep banks. The channel widens from about 250 feet at the upper end of the reach to about 285 feet at the lower end of the reach; the depth of flow decreases in a corresponding manner. The depth of flow ranges from 2 to 7 feet with a corresponding range in discharge from 1,000 to 13,000 cfs (cubic feet per second). The energy gradient through the reach is on the order of 4×10^{-4} foot per foot.

The stream channel is in alluvial sand. Samples of the bed material were taken in June 1956 and 1958 at points along the upper cableway section (site 2, fig. 1). The results of the analysis of these samples by the visual accumulation tube or sieve methods are shown in table 1 and figures 2 and 3. The size of the material ranges from 0.062 to

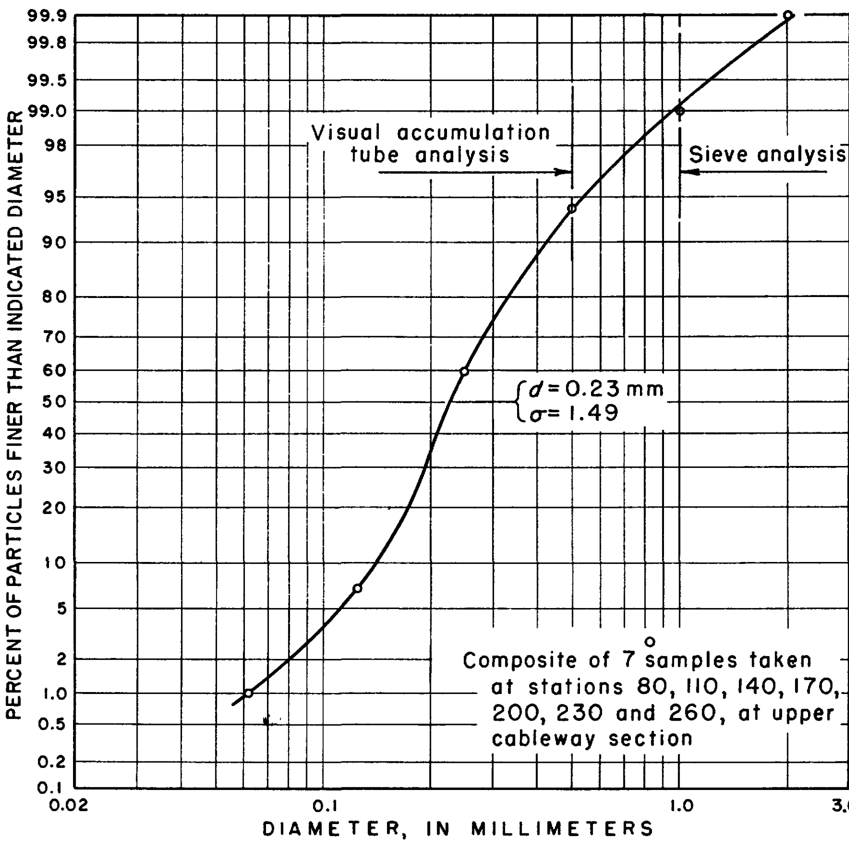

FIGURE 2.—Size distribution of bed material, June 1956.

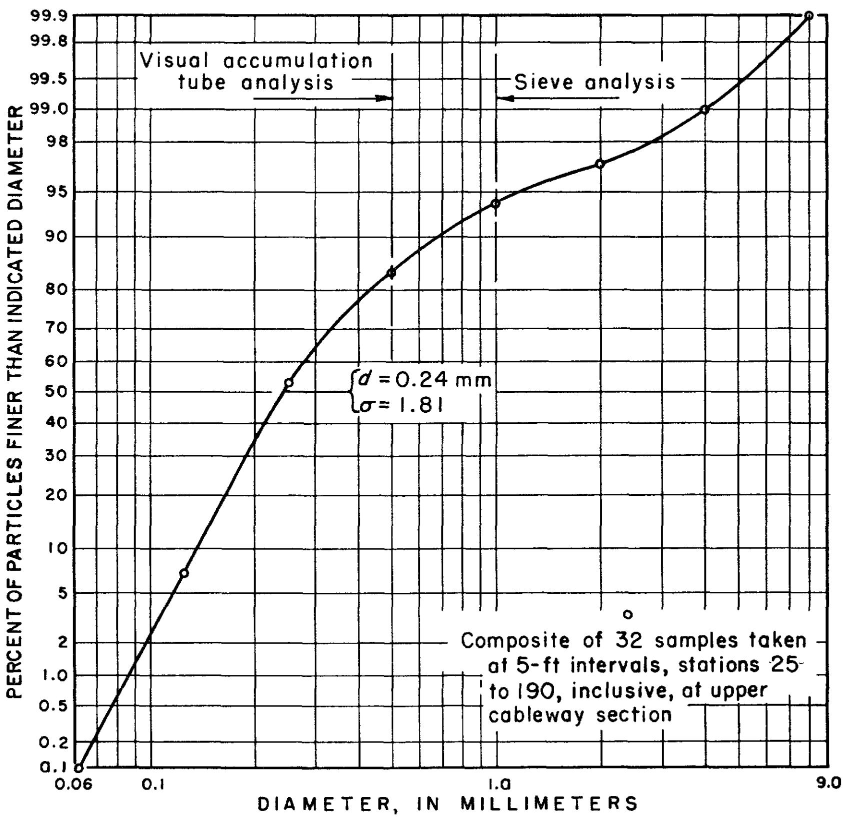

FIGURE 3.—Size distribution of bed material, June 1958.

8 mm; the median size is about 0.24 mm and the standard deviation is about 1.65. The median size of bed material was largest in the middle part of the channel.

Forty tons of bed material was taken from the reach in June 1959 for use in laboratory studies. The result of the analysis of 39 samples of this material is shown in figure 4. The median size is 0.28 mm and the standard deviation is 1.68.

Reference sizes d_{50}=0.24 mm, d_{35}=0.20 mm, d_{65}=0.28 mm have been used in the analysis in this report. The subscript for d shows the percentage of particles finer than the diameter indicated.

OBSERVATION PROGRAM

A summary of the data obtained during the period 1951–56 is given in table 2. Information on velocity, depth, width, and suspended sediment was obtained at the cableway site at the upper end of the reach; simultaneous measurements of depth and width were obtained at the cableway site at the lower end of the reach (site 11, fig. 1). Water-

TABLE 1.—*Particle-size analysis of two samples of bed material from upper cableway section*

[Methods of analysis: S, sieve; V, visual accumulation tube]

Date	Number of sampling points	Percent of bed material finer than indicated size, in millimeters								Methods of analysis	Sampling points
		0.062	0.125	0.250	0.500	1.000	2.000	4.000	8.000		
1956											
June 27	1	1	11	78	100	------	------	------	------	V	Station 80.
June 27	1	0	4	40	96	100	------	------	------	SV	Station 110.
June 27	1	0	1	34	84	95	98	100	------	SV	Station 140.
June 27	1	0	1	38	89	99	100	------	------	SV	Station 170.
June 27	1	1	25	82	98	100	------	------	------	SV	Station 200.
June 27	1	1	2	58	93	98	99	100	------	SV	Station 230.
June 27	1	1	7	89	100	------	------	------	------	V	Station 260.
June 27	7	1	7	60	94	99	100	------	------	SV	Composite from all points.
1958											
June 20	7	0	3	68	94	99	99	99	100	SV	Stations 25–55 at 5-ft intervals.
June 20	18	0	1	30	74	90	95	99	100	SV	Stations 65–150 at 5-ft intervals.
June 20	7	1	27	99	100	------	------	------	------	V	Stations 160–190 at 5-ft intervals.
June 20	32	0	7	53	84	94	97	99	100	SV	Composite from all points.

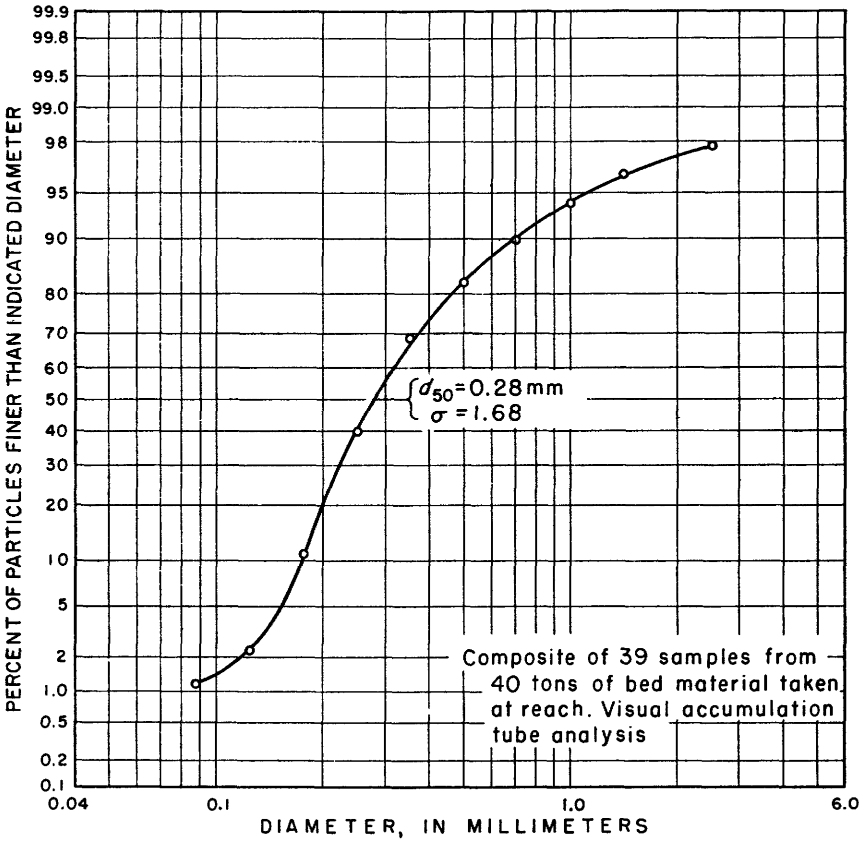

FIGURE 4.—Size distribution of bed material, June 1959.

surface elevations were read on a series of staff gages spaced along the stream channel at locations shown in figure 1. The fluctuations in the water surface due to surges did not exceed 0.10 foot. Each set of data was adjusted to a common time.

The results of the analysis of particle size for 10 samples of suspended sediment are given in table 3.

STABILITY OF CHANNEL

WIDTH

The width of the channel of the upper and lower cableway sections at time measurements were made is shown in figures 5 and 6. The banks of the channel are relatively stable, and variations in width for a given stage are not pronounced.

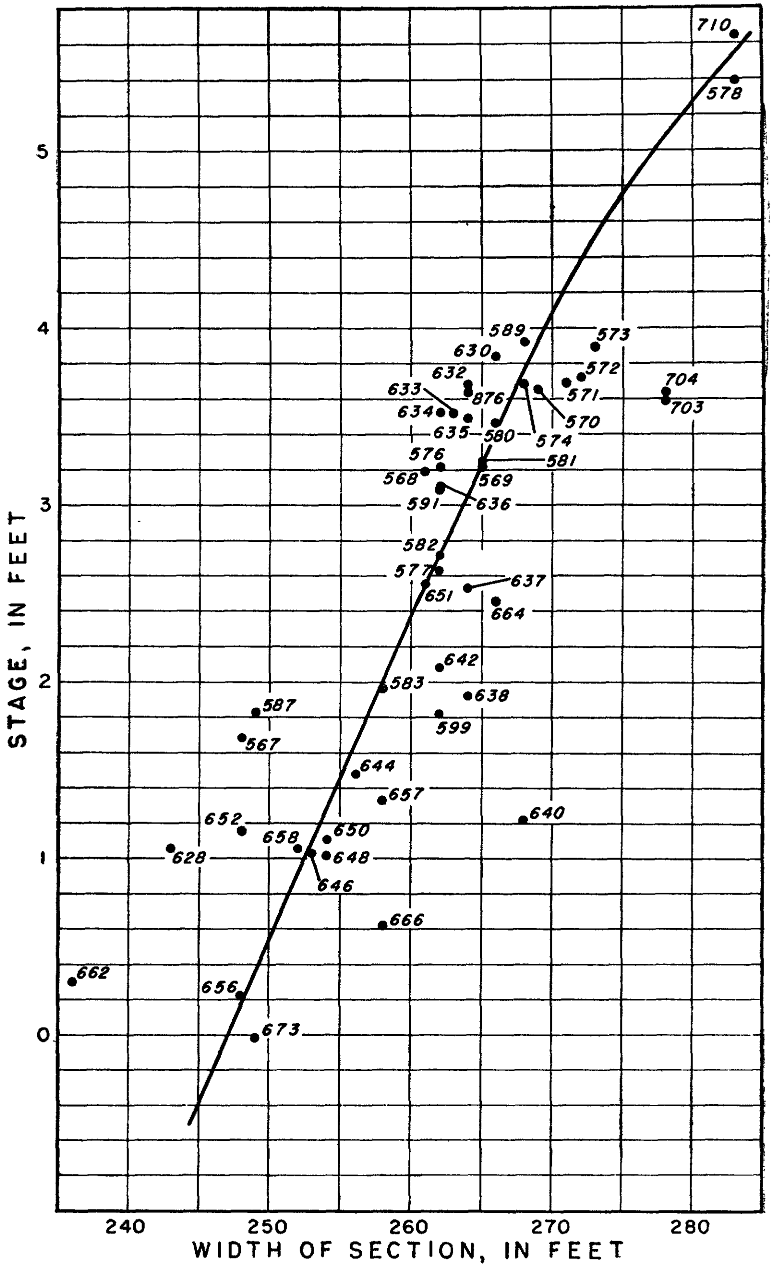

FIGURE 5.—Variation in width of stream at upper cableway. Figures correspond to measurement numbers in table 2.

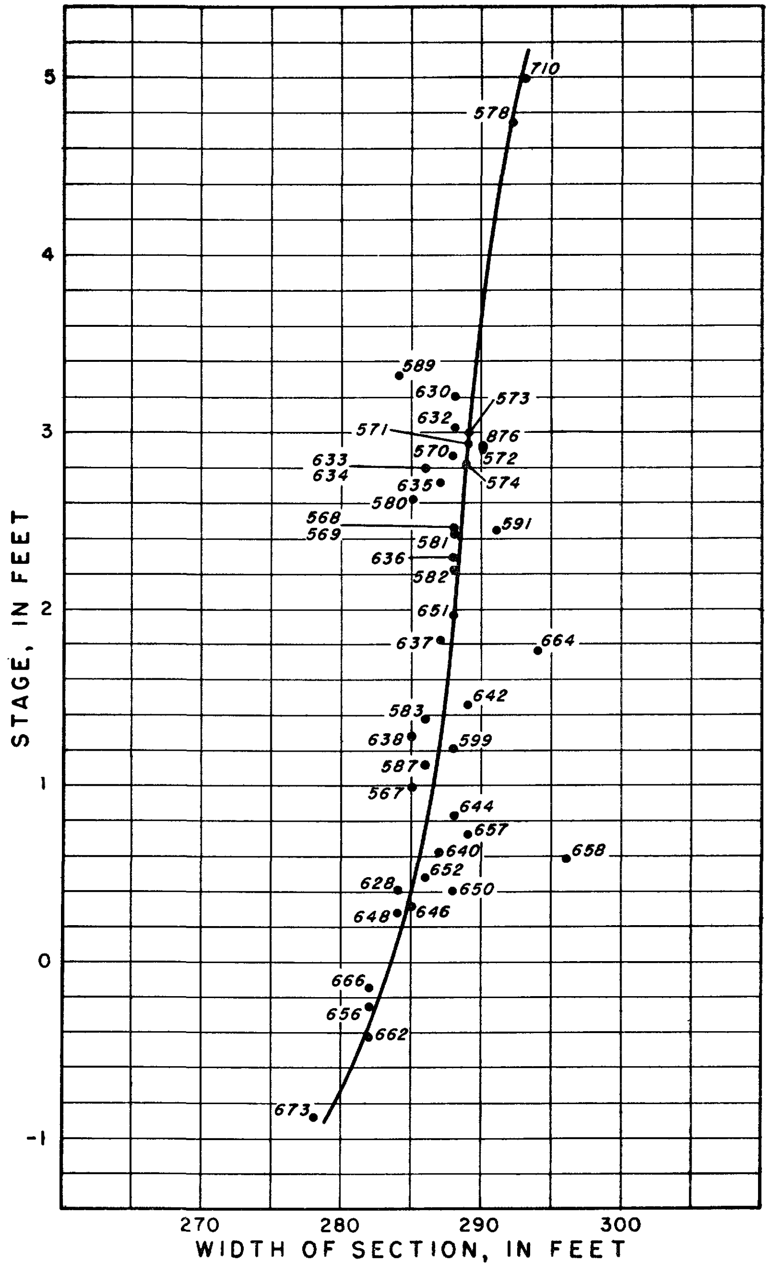

FIGURE 6.—Variation in width of stream at lower cableway. Figures correspond to measurement numbers in table 2.

TABLE 2.—*Summary of observed data*

[*Q*, Discharge, in cubic feet per second; *T*, water temperature (°F); *B*, surface width, in feet; *D*, mean depth of section, in feet; *V*, mean velocity in feet per second; *R*, hydraulic radius, in feet; *A*, area of cross section, in square feet; C_s, concentration of suspended sediment, in parts per million; *F*, water surface fall, in feet between sections; *S*, energy slope of water between sections; *n*, Manning coefficient of roughness; *C*, Chezy coefficient of roughness]

Measurement No.	Date	*Q*	Time	*T*	Upper cableway section							Lower cableway section						*F*	$S \times 10^{-4}$	$n \times 10^{-2}$	*C*
					Stage	*B*	*D*	*V*	*R*	*A*	C_s	Stage	*B*	*D*	*V*	*R*	*A*				
	1951																				
567	May 18	2,680	4:42 p.m.	[1] 68	1.685	248	3.76	2.87	3.74	934	------	0.985	285	3.32	2.84	3.25	945	0.70	4.19	2.45	74.8
568	May 21	6,630	2:54 p.m.	[1] 66	3.19	261	4.97	5.11	4.95	1,298	------	2.465	288	4.45	5.18	4.38	1,281	.725	4.26	1.66	115.8
569	May 21	6,800	6:19 p.m.	[1] 66	3.225	265	4.92	5.22	4.80	1,303	------	2.465	288	4.43	5.33	4.37	1,276	.76	4.43	1.64	116.7
570	May 22	7,660	10:22 a.m.	[1] 69	3.655	269	6.65	4.28	6.57	1,788	------	2.87	288	5.03	5.29	4.95	1,449	.785	3.79	1.94	102.5
571	May 22	7,560	1:30 p.m.	69	3.69	271	5.75	4.86	5.71	1,557	------	2.905	289	5.16	5.07	5.07	1,490	.785	4.50	1.95	100.8
572	May 22	7,700	4:51 p.m.	[1] 69	3.72	272	5.92	4.78	5.87	1,610	------	2.90	290	4.91	5.40	4.85	1,425	.82	4.31	1.85	106.3
573	May 23	7,750	9:47 a.m.	66	3.89	273	6.58	4.32	6.51	1,796	------	2.99	289	5.03	5.33	4.95	1,454	.90	4.47	2.08	95.5
574	May 24	6,780	9:53 a.m.	68	3.68	268	6.55	3.86	6.46	1,756	------	2.815	289	5.30	4.43	5.23	1,532	.865	4.73	2.52	79.2
576	May 25	5,790	12:48 p.m.	------	3.21	262	5.97	3.70	------	1,565	------	2.56	------	------	------	------	------	.65	------	------	------
577	May 26	4,860	12:17 p.m.	------	2.63	262	5.03	3.69	------	1,317	------	2.25	------	------	------	------	------	.38	------	------	------
578	May 31	12,600	5:34 p.m.	[1] 70	5.39	283	7.16	6.22	7.10	2,025	------	4.75	292	6.70	6.44	6.56	1,957	.64	3.56	1.59	128.7
580	June 1	6,830	1:22 p.m.	[1] 70	3.465	266	6.20	4.14	6.15	1,648	------	2.615	285	4.85	4.95	4.76	1,381	.85	4.39	2.12	93.0
581	June 1	6,160	4:01 p.m.	[1] 70	3.25	265	5.97	3.89	5.92	1,583	------	2,415	288	4.76	4.49	4.69	1,372	.835	4.52	2.29	85.7
582	June 3	6,440	5:47 p.m.	[1] 63	2.725	262	5.13	4.79	5.09	1,345	------	2.22	288	5.20	4.30	5.09	1,497	.505	3.22	1.73	112.7
583	June 5	4,370	11:23 a.m.	[1] 63	1.96	258	4.52	3.75	4.48	1,165	------	1.37	286	4.00	3.82	3.96	1,145	.59	3.48	1.91	98.9
587	June 28	2,760	2:59 p.m.	73	1.82	249	4.30	2.58	4.27	1,071	------	1.115	286	3.90	2.47	3.84	1,116	.705	4.23	3.08	61.0
589	July 5	8,560	1:58 p.m.	68	3.92	268	6.44	4.96	6.37	1,726	------	3.315	284	5.49	5.49	5.34	1,559	.605	3.10	1.58	126.3
591	July 19	4,380	2:07 p.m.	[1] 76	3.08	262	5.07	3.30	5.02	1,329	------	2.445	291	4.94	3.05	4.85	1,437	.635	3.87	2.68	72.4
599	Sept. 11	3,430	2:53 p.m.	73	1.81	262	4.01	3.26	4.00	1,051	------	1.21	288	4.03	2.96	3.97	1,160	.600	3.67	2.31	81.0
	1952																				
628	Mar. 26	2,830	9:48 a.m.	[1] 35	1.06	243	3.07	3.79	3.06	747	[2] 3,430	.405	284	2.88	3.46	2.86	819	.655	4.03	1.70	104.7
630	Apr. 1	8,960	8:39 a.m.	44	3.84	266	6.19	5.44	6.11	1,647	6,260	3.205	288	5.44	5.72	5.35	1,567	.635	3.51	1.60	124.3
632	Apr. 1	8,850	3:34 p.m.	46	3.68	264	6.08	5.51	6.02	1,606	[2] 6,010	3.02	288	5.34	5.75	5.25	1,538	.660	3.70	1.60	123.8
633	Apr. 2	7,900	9:54 a.m.	44	3.52	263	5.65	5.32	5.58	1,485	5,700	2.79	286	5.15	5.36	5.06	1,472	.730	4.32	1.76	111.6
634	Apr. 2	7,860	11:20 a.m.	46	3.52	262	5.73	5.23	5.66	1,501	[2] 5,010	2.785	286	5.17	5.31	5.07	1,480	.735	4.33	1.80	109.2

See footnotes at end of table, p. 11.

TABLE 2.—*Summary of observed data*—Continued

Measurement No.	Date	Q	Time	T	Upper cableway section							Lower cableway section						F	$S\times10^{-4}$	$n\times10^{-2}$	C
					Stage	B	D	V	R	A	C_s	Stage	B	D	V	R	A				
	1953																				
635	Apr. 2	7,540	3:52 p.m.	47	3.49	264	5.70	5.01	5.63	1,504	5,300	2.71	287	5.08	5.17	4.99	1,457	0.78	4.51	1.88	104.3
636	Apr. 3	6,520	10:58 a.m.	46	3.11	262	5.46	4.55	5.36	1,431	[2] 4,140	2.29	288	4.77	4.74	4.69	1,375	.82	4.75	2.04	95.3
637	Apr. 4	5,610	10:26 a.m.	44	2.53	264	4.65	4.57	4.60	1,227	3,780	1.81	287	4.41	4.43	4.35	1,267	.72	4.37	1.87	102.0
638	Apr. 9	4,020	10:10 a.m.	44	1.92	264	3.99	3.82	3.96	1,053	4,460	1.27	285	3.91	3.61	3.87	1,114	.65	3.97	1.98	94.4
640	Apr. 18	2,860	11:09 a.m.	52	1.22	268	2.90	3.68	2.89	777	[2] 1,520	.62	287	3.02	3.30	3.00	866	.60	3.72	1.69	105.3
642	Apr. 23	4,100	11:14 a.m.	53	2.075	262	3.92	3.99	3.90	1,026	2,570	1.45	289	3.81	3.72	3.78	1,101	.625	3.84	1.85	100.6
644	May 1	2,150	9:58 a.m.	68	1.485	256	3.02	2.78	3.01	774	[2] 1,000	.82	288	3.07	2.43	3.05	884	.665	4.07	2.41	74.2
646	May 7	1,700	9:48 a.m.	68	1.03	253	2.71	2.48	2.70	686	513	.31	285	2.48	2.41	2.46	706	.72	4.33	2.37	73.4
648	May 15	1,500	12:36 p.m.	66	1.01	254	2.84	2.08	2.82	721	[2] 600	.27	284	2.40	2.20	2.38	681	.74	4.38	2.73	63.9
650	May 21	1,540	11:17 a.m.	64	1.11	254	2.84	2.14	2.82	721	[2] 698	.40	288	2.48	2.16	2.46	713	.71	4.24	2.72	64.2
651	May 28	5,740	11:49 a.m.	68	2.56	261	4.44	4.95	4.42	1,159	813	1.96	288	4.19	4.76	4.15	1,206	.60	3.68	1.55	122.1
652	June 4	2,080	3:30 p.m.	76	1.16	248	3.42	2.45	3.38	848	1,210	.475	286	2.80	2.58	2.80	805	.685	4.04	2.51	71.5
654	June 12	1,260	11:00 a.m.	86	.52	248	2.41	2.11		597	398										
655	June 18	978	12:20 p.m.	77	.13	246	2.17	1.83		533	349										
656	June 26	879	12:02 p.m.	78	.22	248	2.21	1.60	2.20	549	604	−.26	282	1.96	1.59	1.96	554	.48	2.88	2.57	65.3
657	June 30	1,820	3:29 p.m.	79	1.33	258	3.44	2.05	3.43	888	[2] 3,410	.715	289	2.92	2.15	2.92	845	.615	3.64	2.90	62.1
658	July 10	1,890	12:59 p.m.	79	1.06	252	3.10	2.42	3.09	781	3,400	.58	296	2.83	2.25	2.81	838	.48	2.91	2.22	80.5
659	July 18	1,190	10:42 a.m.	80	.54	237	2.42	2.07		574	1,440										
660	July 24	749	11:55 a.m.	81	−.13	224	1.88	1.78		420	319										
661	July 31	673	12:30 p.m.	78		224	1.72	1.74		386	213										
662	Aug. 7	967	12:25 p.m.	74	.29	236	2.05	2.00	2.05	483	978	−.43	282	1.75	1.96	1.74	493	.72	4.32	2.38	69.6
663	Aug. 12	799	11:52 a.m.	75	.01	235	1.73	1.96		407	311										
664	Aug. 21	2,840	3:37 p.m.	74	2.45	266	3.75	2.85	3.73	998	3,790	1.755	294	3.76	2.57	3.74	1,105	.695	4.23	2.72	68.2
665	Aug. 27	1,000	11:15 a.m.	80	.35	251	2.03	1.96		510	578										
666	Sept. 2	1,150	2:56 p.m.	67	.625	258	2.28	1.95	2.27	589		−.15	282	2.00	2.04	2.00	565	.775	4.61	2.65	63.7
667	Sept. 9	650	10:32 a.m.	74	−.17	250	1.67	1.56		418	830										
668	Sept. 15	622	12:40 p.m.	75	−.13	249	1.59	1.57		397											
669	Sept. 22	685	3:10 p.m.	66	.00	252	1.56	1.75		392											
	1952																				
670	Sept. 30	517	11:05 a.m.	72	−0.28	248	1.35	1.54		335											
671	Oct. 7	488	4:42 p.m.	52	−.31	252	1.17	1.65		295											
672	Oct. 13	630	2:22 p.m.	55	−.19	252	1.31	1.91		329											
673	Oct. 23	616	2:07 p.m.	54	−.02	249	1.41	1.76	1.40	350		−0.89	278	1.29	1.72	1.29	359	0.87	5.22	2.38	65.6

	1953																				
703	May 11	8,180	4:05 p.m.	[1] 64	3.59	278	4.90	6.00	4.88	1,363											
704	May 11	8,160	6:40 p.m.	[2] 64	3.64	278	4.82	6.10	4.79	1,339											
709	June 8	11,800	6:18 p.m.		4.93	278	6.38	6.65		1,774											
710	June 9	13,600	10:02 a.m.	[1] 76	5.64	283	7.28	6.61	7.20	2,059		4.99	293	6.58	7.06	6.47	1,927	.65	3.32	1.43	143.
	1956																				
876	June 26	6,960	11:22 p.m.	71	3.63	264	4.38	6.00	4.34	1,160	[2] 21,000	2.91	290	4.55	5.27	4.50	1,320	.72	4.67	1.58	120.5

[1] Estimated water temperature, based on air temperature observed at Omaha Airport. [2] Sediment-size data available for this observation.

TABLE 3.—*Particle-size analyses of 10 samples of suspended sediment*

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

Measurement No.	Date	Time of sample	Water temperature (°F)	Concentration (ppm)	Percent of suspended sediment finer than indicated size, in millimeters											Methods of analysis	Number of sampling verticals
					0.002	0.004	0.008	0.016	0.031	0.062		0.125	0.250	0.500	1.000		
										Pipet	Sieve						
	1952																
628	Mar. 26	11:30 a.m.	[1] 35	3,430	18	18	24	28	49	61	64	77	96	100		SPWCM	3
632	Apr. 1	5:30 p.m.	46	6,010	22	25	29	35	48	68	72	85	98	100		SPWCM	3
634	Apr. 2	12:45 p.m.	46	5,010	19	24	27	32	45	68	71	85	98	100		SPWCM	3
636	Apr. 3	12:50 p.m.	46	4,140	17	20	24	29	42	63	66	82	98	100		SPWCM	3
640	Apr. 18	11:20 a.m.	52	1,520	18	18	21	24	36	52	58	80	99	100		SPWCM	3
644	May 1	12:45 p.m.	68	1,000	19	19	22	27	42	60	62	78	97	100		SPWCM	6
648	May 15	1:15 p.m.	66	600	23	23	26	31	46	60	63	77	98	100		SPWCM	6
650	May 21	11:45 a.m.	64	698	18	25	27	33	42	61	66	80	98	100		SPWCM	6
657	June 30	5:10 p.m.	79	3,410	50	63	71	77	85	93	94	98	100			SPWCM	6
	1956																
876	June 27	1:20 a.m.	71	21,000	38	48	60	72	82	90		96	99		100	VPCWM	7

[1] Estimated from air temperature observations at Omaha Airport.

AVERAGE BED ELEVATIONS

The plot, figure 7, of the average bed elevation at time of each measurement at the upper and lower cableway sections shows short-term variations of 0.6 foot from the mean and a long-term variation of about 1 foot during the period 1951–56. The short-term variations appear to occur randomly because there is no consistent correlation with discharge of other variable. These differences may be associated with movement of dunes or sand bars through the reach.

POINT BED ELEVATIONS

Although the average bed elevation at a cross section is relatively stable, scouring and filling is continuously occurring at any point in the cross section. A change of 5.5 feet at one point in the upper cross section occurred during a period of 4 hours. Point bed elevations observed for the upper and lower sections during the period May 21–24, 1951, are shown in figures 8 and 9. The discharge during this period varied from 6,630 to 7,750 cfs. The scour and fill pattern is much more pronounced at the upper section than at the lower section.

The maximum discharge of major floods is frequently determined by the slope-area method. The computations are based on field surveys of channel characteristics and high-water marks and on the Manning flow equation. The average elevation of the bed at the time of the peak is estimated after the flood is over by prodding the bed of the stream with a steel rod until a firm bottom is reached. The method assumes that the maximum scour at all points in the cross section occurred at the time of the peak discharge. It is evident from figures 8 and 9 that the prodding method would give incorrect results on the Elkhorn reach. The average bed elevation remains virtually constant as the scour hole moves back and forth across the channel.

BED CONFIGURATION

On the basis of laboratory investigation, Simons (Simons and others, 1961) has described the regimes of bed configuration of sand channel streams as ripples, dunes, plane bed, standing waves, and antidunes. This sequence of bed configuration occurs with increasing discharge. As the dunes wash out and the sand is rearranged to form a plane bed, there is a marked decrease in resistance to flow. After this rearrangement of sand the resistance to flow remains in effect the same for higher regimes of flow.

Albertson (Albertson and others, 1957) defined the occurrence of different forms of bed roughness from laboratory data as a function of V_*/ω and $\omega d/\nu$; this relationship is shown in figure 10. Accordingly,

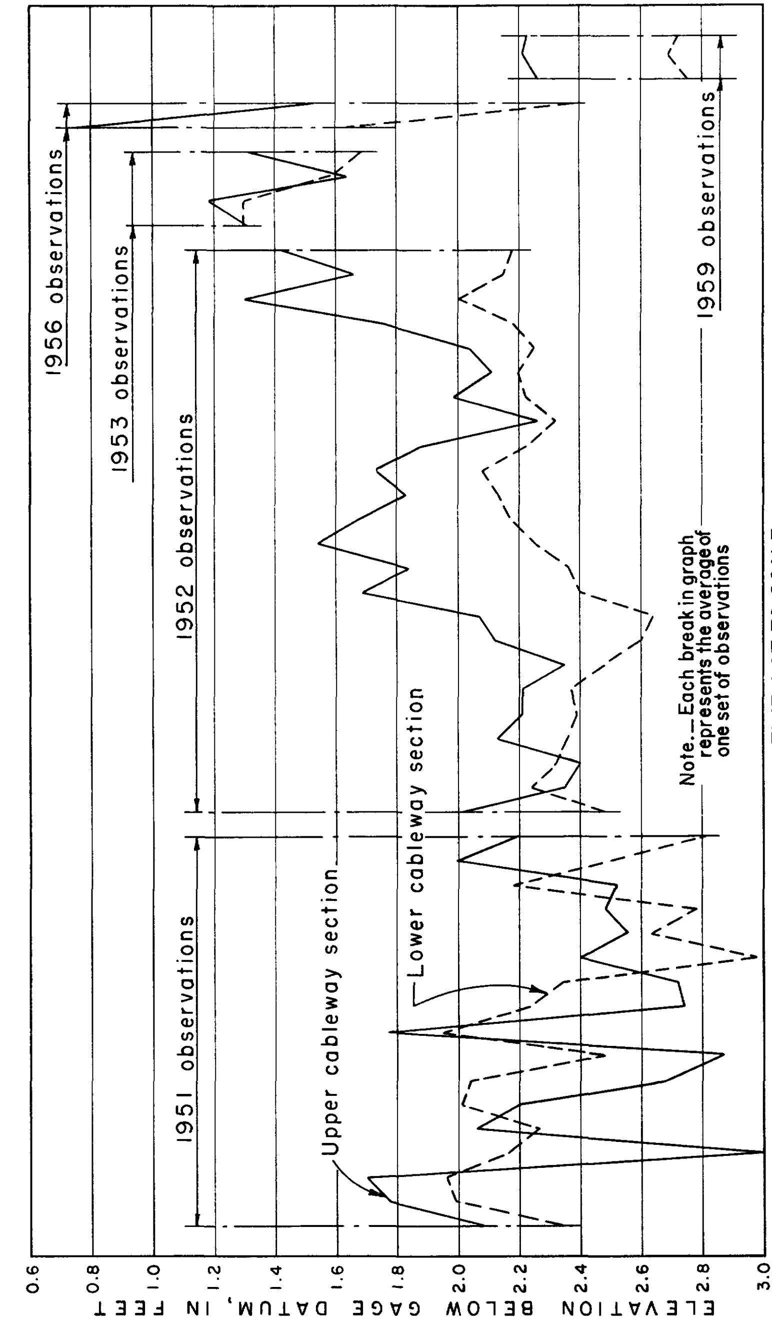

FIGURE 7.—Average channel bed elevations at upper and lower cableway sections.

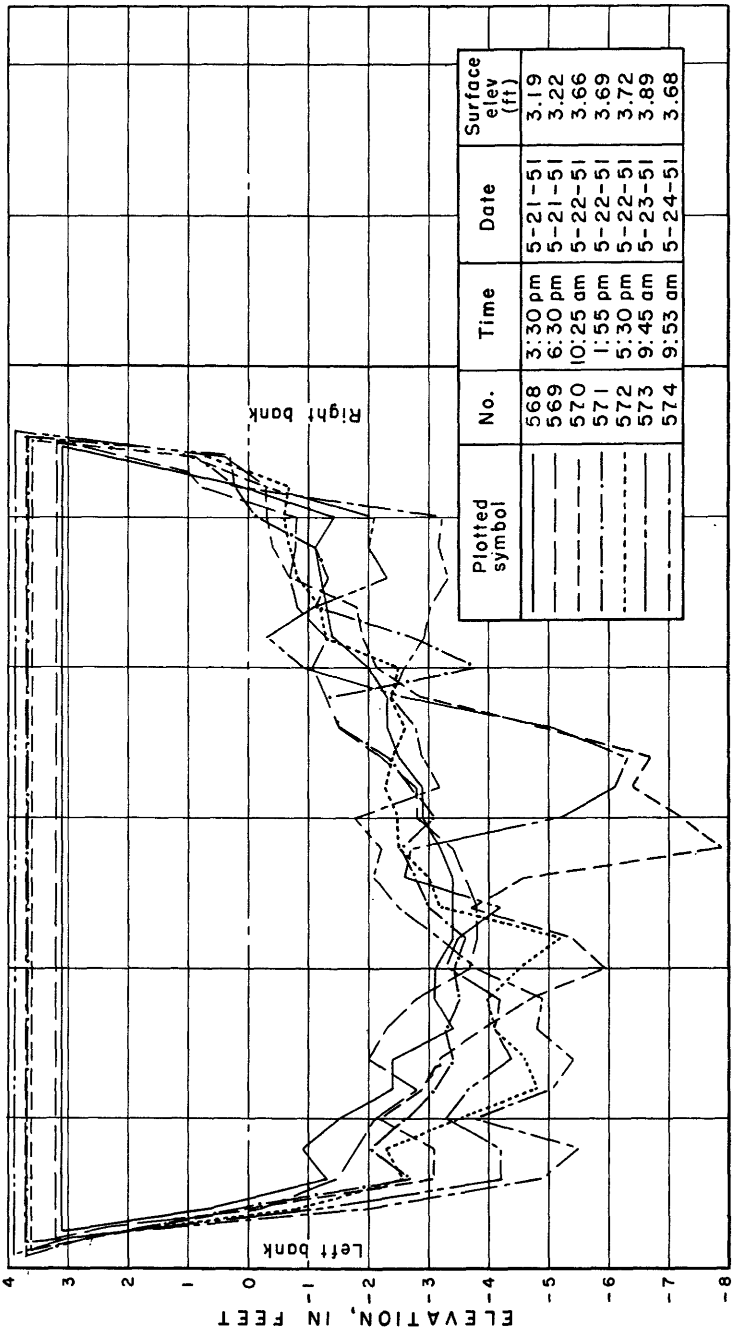

FIGURE 8.—Elevation of channel bed at upper cableway section at time of measurements.

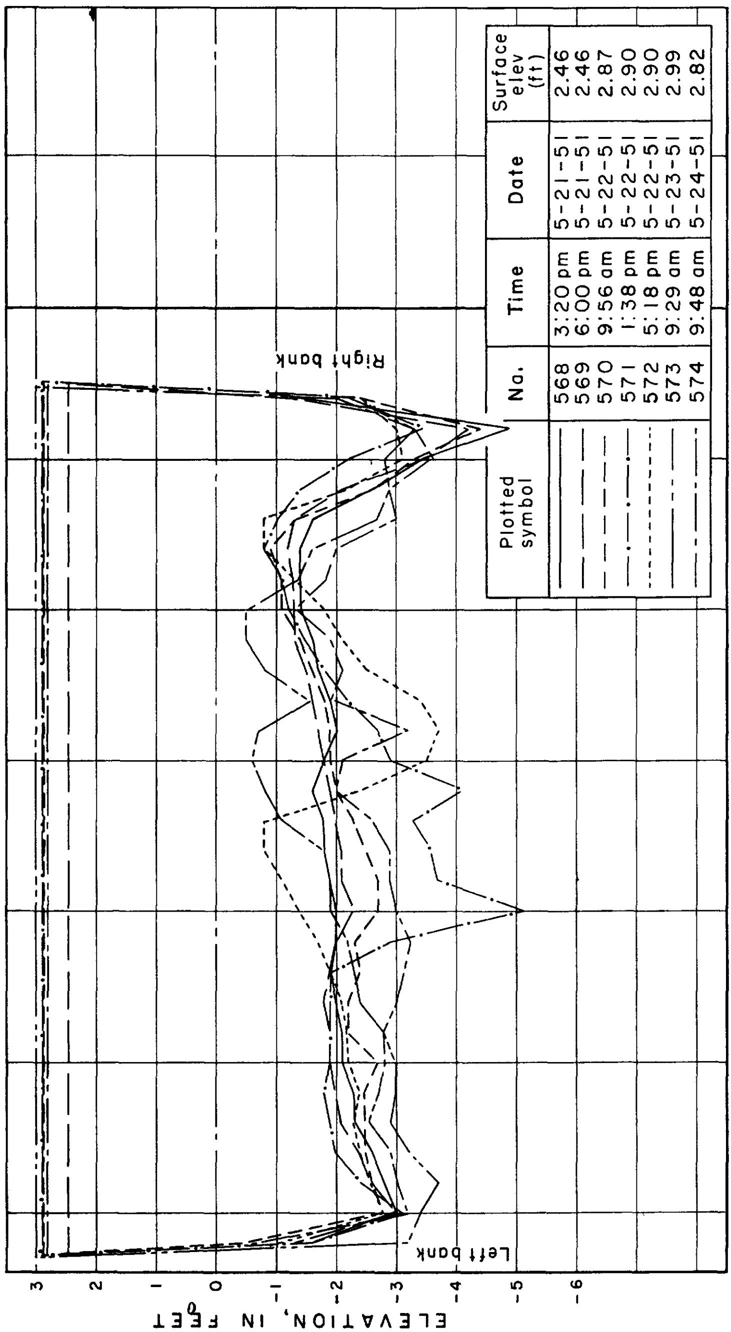

FIGURE 9.—Elevation of channel bed at lower cableway section at time of measurements.

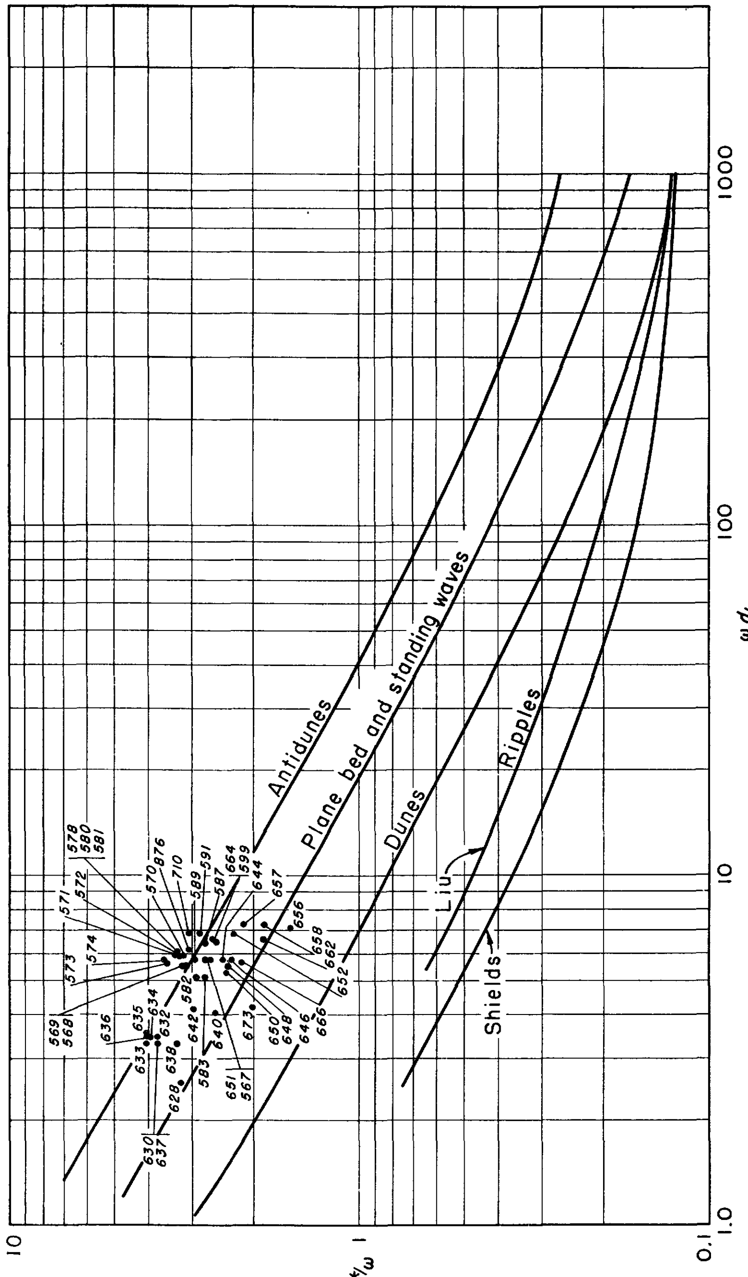

FIGURE 10.—Comparison of Elkhorn River bed configuration with Albertson's relationship. Figures correspond to measurement numbers in table 2.

these parameters were computed from the Elkhorn data and are plotted on figure 10. Their location indicates that most of the observed flows were in the plane-bed and antidune regimes. Although no direct observations of bed configuraton were obtained on the Elkhorn River, it is apparent from analysis of the depth-discharge relation and from the absence of waves on the water surface that most of the flows were in the dune regime and the remainder in the plane-bed regime. The laboratory relationship shown in figure 10 does not satisfactorily explain the regimes of bed configuration experienced on the Elkhorn.

Garde [1] defined the regimes of bed roughness in terms of $RS/1.65d$ and $V/\sqrt{gD}$. His relationship, which is shown in figure 11, predicts that all observed flows on the Elkhorn River would be in the ripple-dune regime; actually some of the flows were considered to be in the plane-bed regime.

There is no satisfactory method at present of predicting the occurrence of the various forms of bed roughness in alluvial channels.

DEPTH-DISCHARGE RELATIONSHIP

The effect of changes in bed configuration on the relation of mean depth to unit discharge at the lower cableway section is shown in figure 12. Two distinct relationships are apparent: the curve for ripples and dunes on the bed and the curve for a plane bed. The dunes begin to wash out at a unit discharge of about 10 cfs, and are completely washed out at a unit discharge of about 28 cfs. In this region of transition between dune and plane-bed regimes, part of the bed is plane and part is covered with dunes owing to the non-uniform distribution of depth and velocity in the reach. The depth-discharge relationship is very unstable in this region because changes in bed configuration can be triggered by changes in temperature, velocity, and depth of the water or by variation in the washload. Under certain conditions the discharge may double with no increase in mean depth.

Dawdy (1961) studied the relation of mean depth to unit discharge on 25 different streams. He found that equation 1 described the relationship for the plane bed through antidune regimes for wide channels.

$$q=kD_m^{3/2} \qquad (1)$$

This implies a constant value of Chezy's C in these regimes if the energy slope remains constant at a station. As shown in figure 12, equation 1 appears to fit the limited range of data for the plane-bed condition at the lower cableway section.

[1] Garde, R. J., 1959, Total sediment transport in alluvial channels: Doctor of philosophy dissertation, Colorado State University.

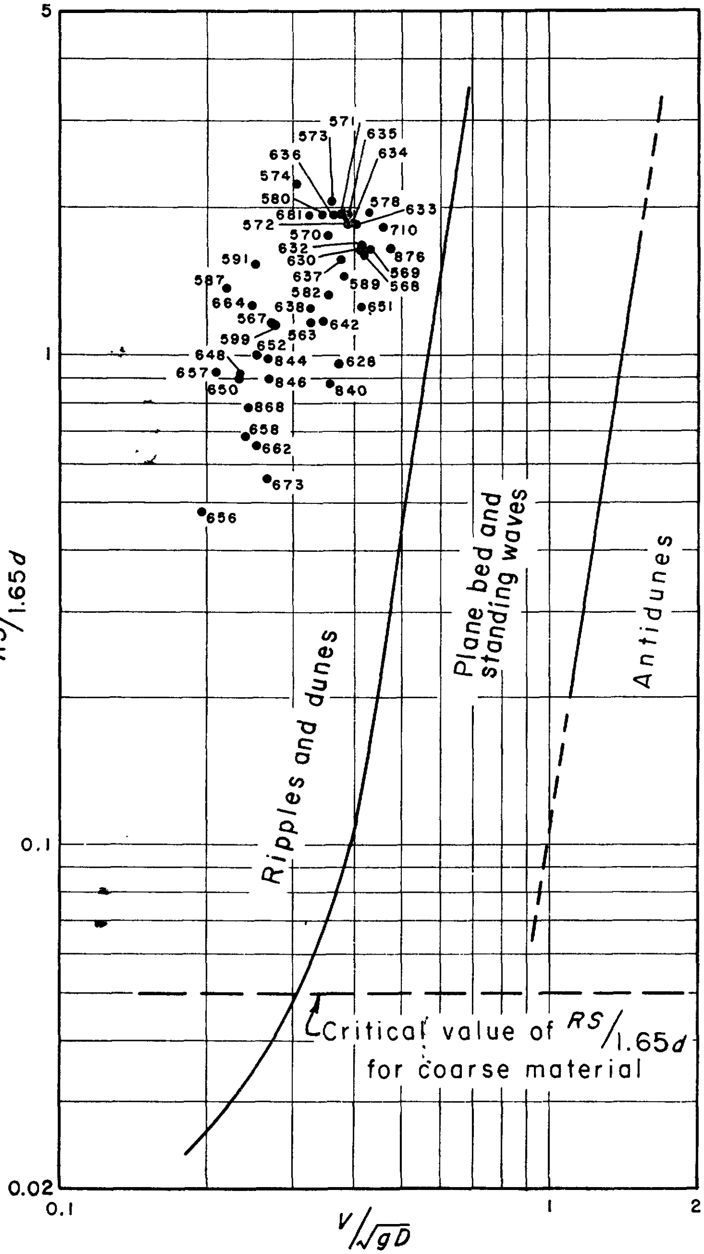

FIGURE 11.—Comparison of Elkhorn River bed configuration with Garde's relationship. Figures correspond to measurement number in table 2.

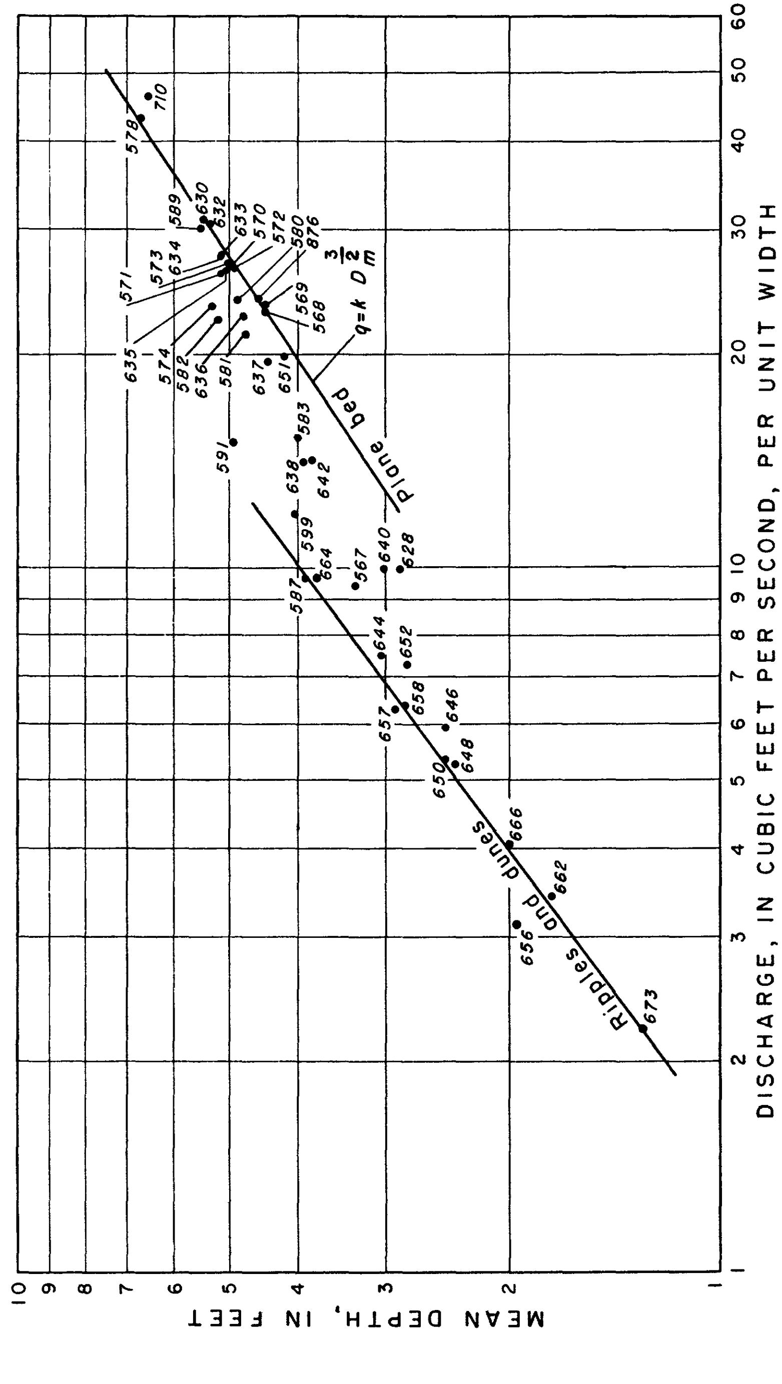

FIGURE 12.—Relation between depth and discharge at lower cableway section. Figures correspond to measurement numbers in table 2.

The mean depth-unit discharge relation for the upper cableway section (fig. 13) does not show a consistent pattern. Several measurements are obviously in the plane-bed regime, but the scatter of the data obscures any relationship that may exist.

GAGE HEIGHT-DISCHARGE RELATIONSHIP

Sixty discharge measurements made at the upper cable are shown plotted against the corresponding gage height in figure 14. A rating curve has been drawn as an average of the points. Thirty-seven of the measurements are within 10 percent of the curve, 45 are within 15 percent, and 52 are within 20 percent. The extreme measurements are 628, 640, and 664, which are +62, +45, and −36 percent, respectively, from the curve. This scatter is typical on stage-discharge plots of data secured at gaging stations on alluvial streams.

A series of 10 measurements were made during a flood period in May 1951. Discharge, mean depth, mean velocity, and slope are shown plotted against gage height in figures 15 to 18. The mean velocity is much lower, and depths are greater on the falling side of the hydrograph than on the rising side; slope, however, shows no consistent pattern. These compensating trends reduce the width of the stage-discharge loop. Data on suspended sediment were not collected during this flood.

ROUGHNESS COEFFICIENT

The roughness coefficients n and C used in the Manning and Chezy equations as computed for the Elkhorn reach are shown in table 2. The computations were based on the properties of the sections at the ends of the reach, and water-surface elevations observed on staff gages along the reach. Although the reach is fairly uniform, the area of the two sections was never exactly the same. If the area of the upper section was larger, the energy slope was computed by subtracting the change in velocity head from the fall of the water surface and dividing this quantity by the length of the reach; if the upper section was smaller, only 50 percent of the difference in velocity heads was added to the fall. The geometric mean value of $AR^{2/3}$ for the two sections was used in computing the Manning coefficient, and the average value of A and R for the two sections was used in computing the Chezy coefficient. The value of n varied from 0.0143 to 0.030 and the value of C from 61 to 143.

The variation in roughness coefficient is caused primarily by the variation in configuration of the channel bed. At low discharges the entire bed is covered by dunes; as the discharge increases, the dunes are washed out in the part of the channel where the velocities are highest; and finally all the dunes are washed out and a plane-bed

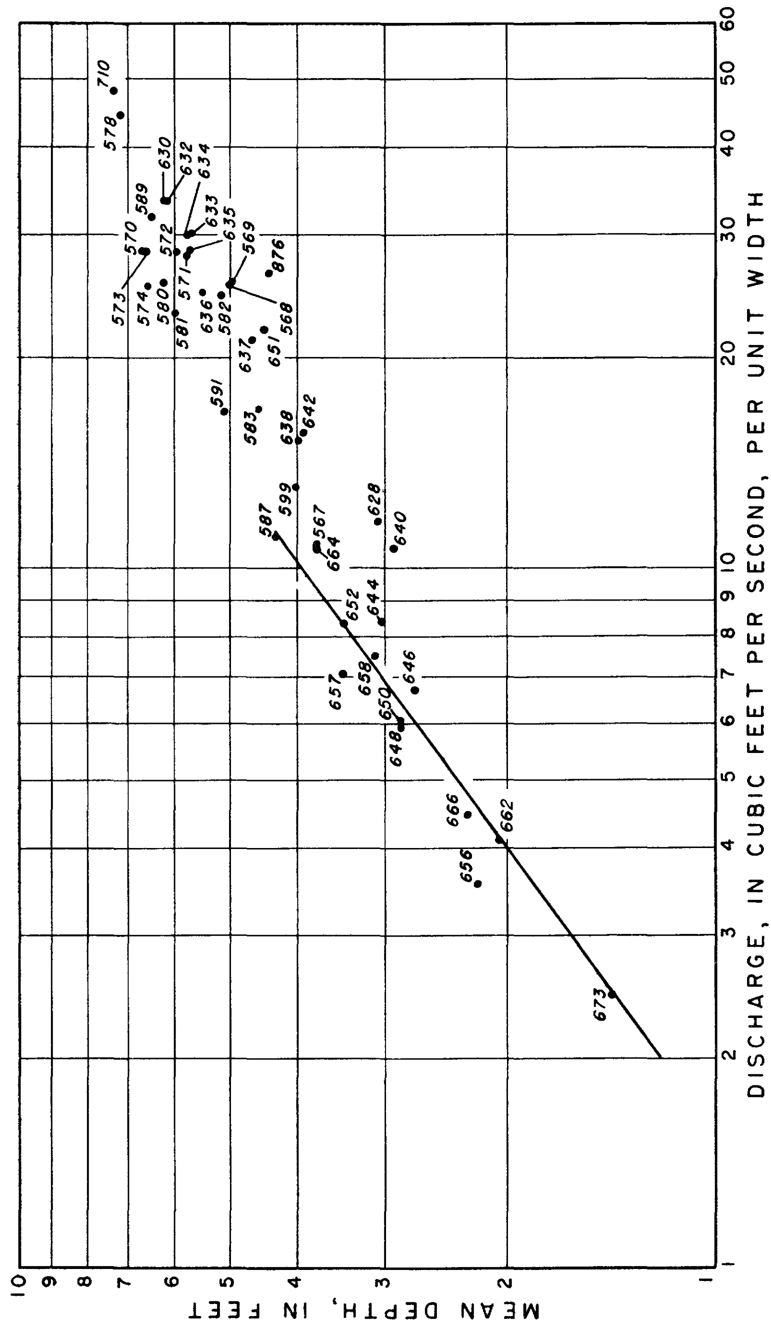

FIGURE 13.—Relation between depth and discharge at upper cableway section. Figures correspond to measurement numbers in table 2.

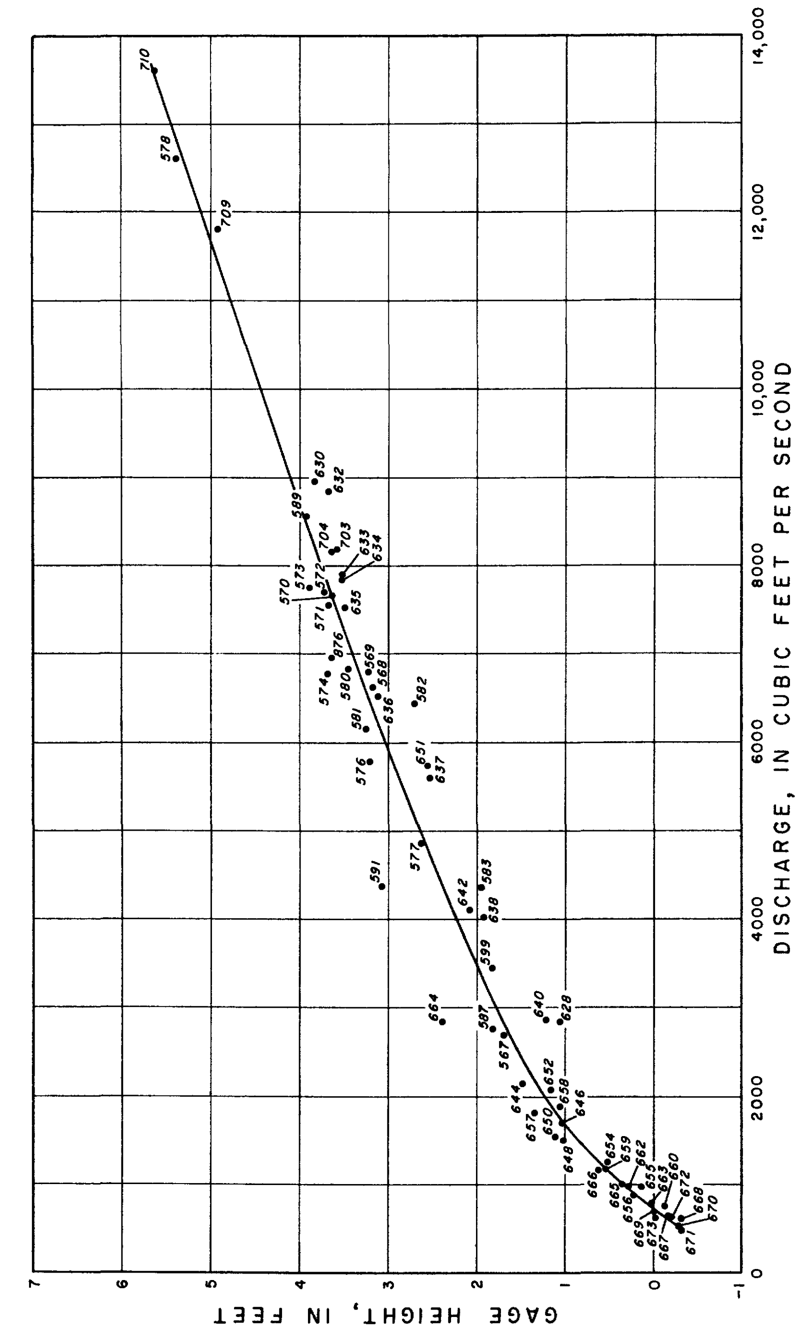

FIGURE 14.—Relation between gage height and discharge at upper cableway section. Figures correspond to measurement numbers in table 2.

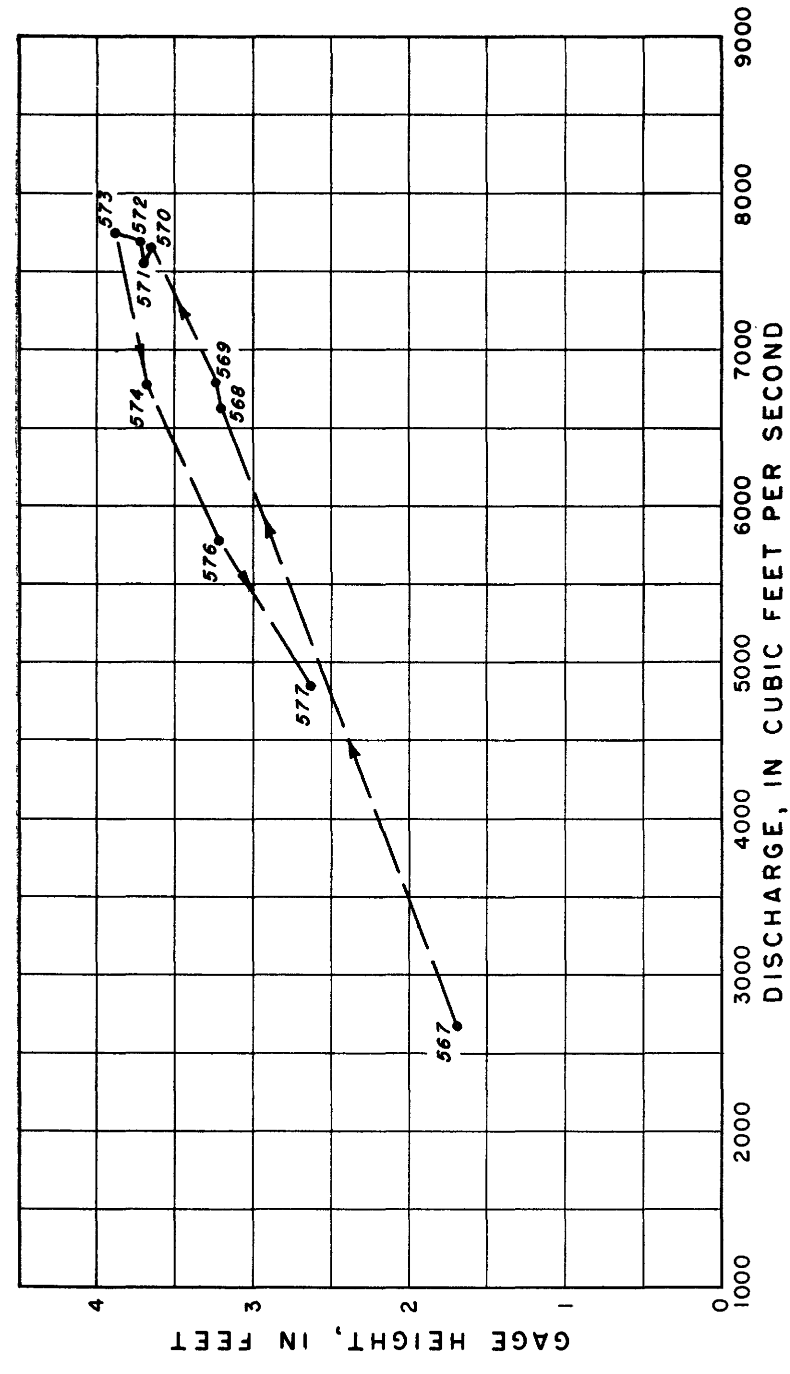

FIGURE 15.—Relation between gage height and discharge at upper cableway section during flood of May 1951. Figures correspond to measurement numbers in table 2.

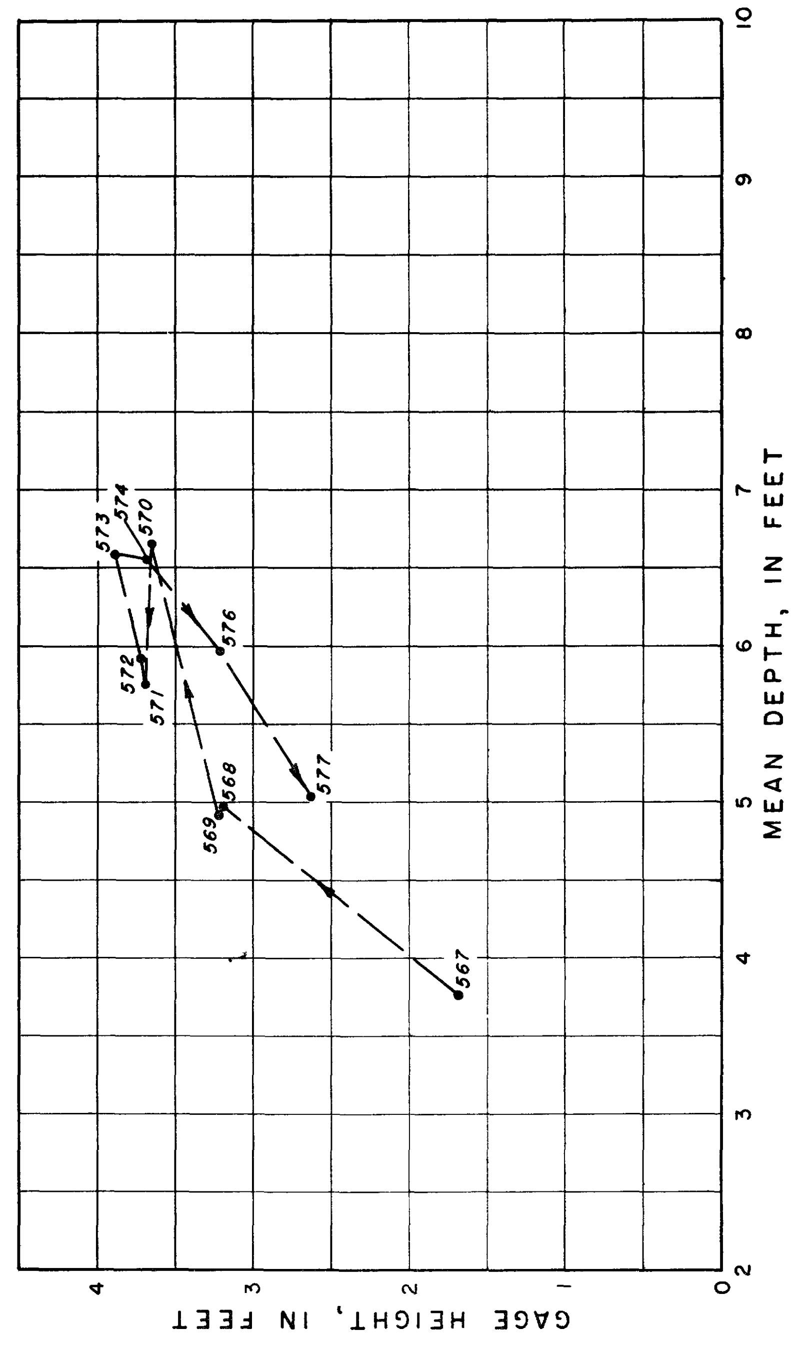

FIGURE 16.—Relation between gage height and depth of water at upper cableway section during flood of May 1951. Figures correspond to measurement numbers in table 2.

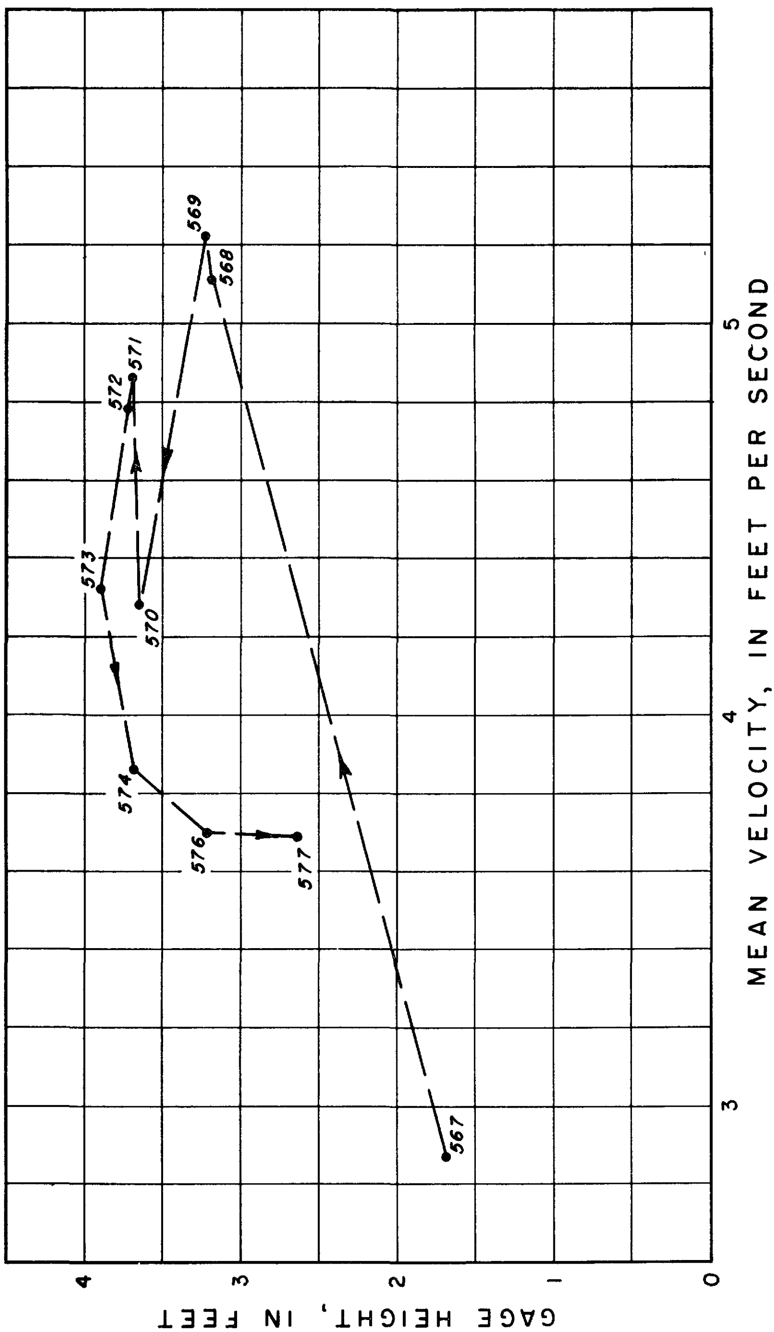

FIGURE 17.—Relation between gage height and mean velocity at upper cableway section during flood of May 1951. Figures correspond to measurement numbers in table 2.

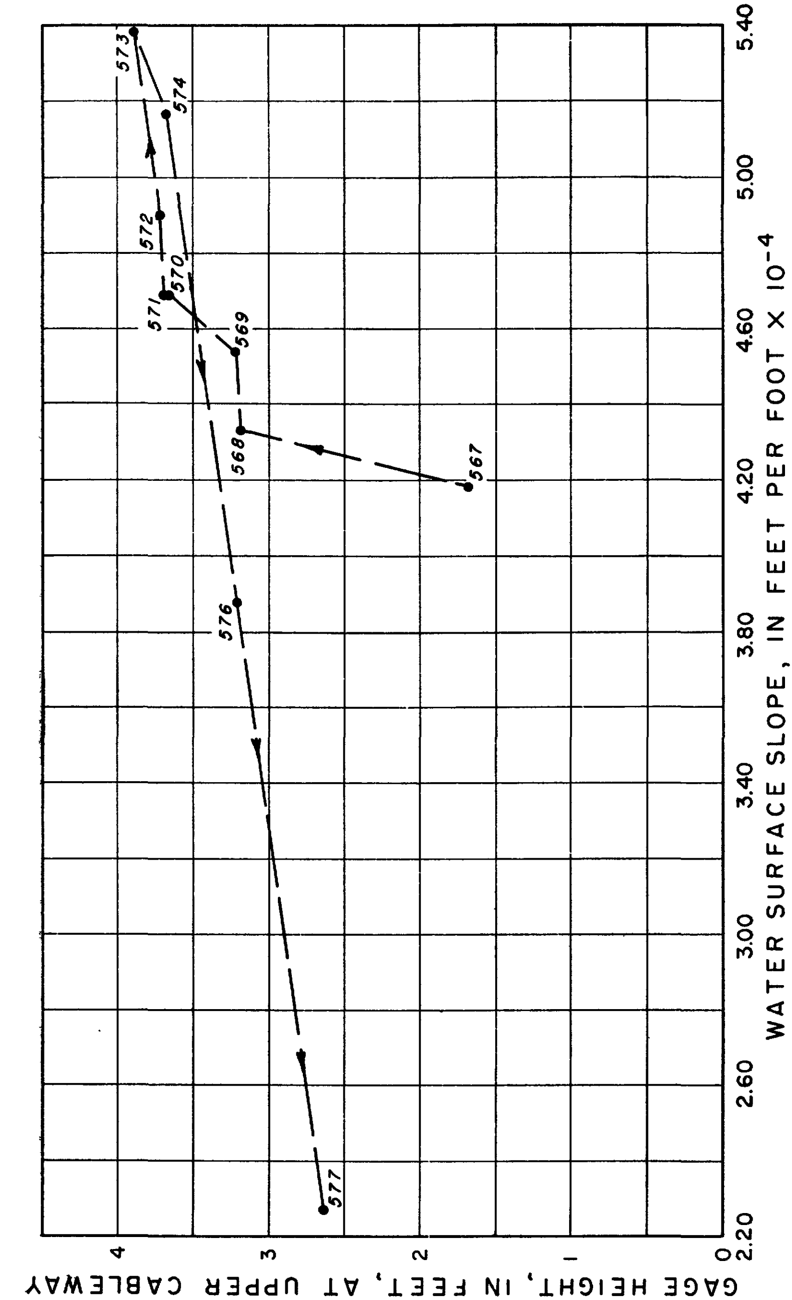

FIGURE 18.—Relation between gage height and slope of water surface during flood of May 1951. Figures correspond to measurement numbers in table 2.

condition exists throughout the reach. It is apparent that the roughness coefficient is a function of some parameter which in turn determines the bed configuration. The effect of mean velocity on the bed configuration and on the roughness coefficient is indicated by the S-shape of the curve in figure 19. The dunes begin to wash out at a velocity of 2.5 feet per second and are probably completely washed out at a velocity of 5 or 6 feet per second.

EINSTEIN'S PARAMETER

Einstein (Einstein and Barbarossa, 1952) suggested that the total shear force RS could be divided into two parts, $R'S$ and $R''S$, when $R=R'+R''$. The force $R'S$ is dissipated by sand-grain resistance according to Nikuradse's definition, and $R''S$ is dissipated by the dunes. He correlated resistance of the dunes V/V''_f with a parameter X' previously used to describe sediment transport.

$$X'=\frac{\rho_s-\rho}{\rho}\frac{d_{35}}{R'S} \tag{2}$$

The data for the Elkhorn reach are compared in figure 20 with the relation which Einstein developed on basis of data for eight streams. Although there is considerable scatter on the plot, the general trend is evident.

The values of Chezy's C for the Elkhorn reach are shown plotted against X' in figure 21. There is a tendency for C to remain constant in the dune and plane-bed regimes and thus the curve tends to flatten out at the extremities. The variation of C in the transition from dunes to plane bed appears to be definitely related to X', but additional parameters must be used to define completely the roughness coefficient. Other investigators have noted the effect of temperature on the rate of sediment transport and bed configuration. Dunes are less likely to persist or form as the temperature of the water decreases. The effect of temperature is apparent in figure 21; the temperature of the water for measurement 628, 638, 640, and 642 was about 20°F lower than for measurements 574 and 581.

The amount of material in suspension of bed origin is not considered to be an independent variable in determining the roughness coefficient, but washload must be considered. Washload is composed of grains which are smaller in size than those found in appreciable quantities in the bed material. For example, only about 1 percent of the grains of bed material in the Elkhorn reach are smaller than 0.06 mm, but 63 percent of the grains in one sample of suspended sediment was smaller than 0.004 mm (table 3).

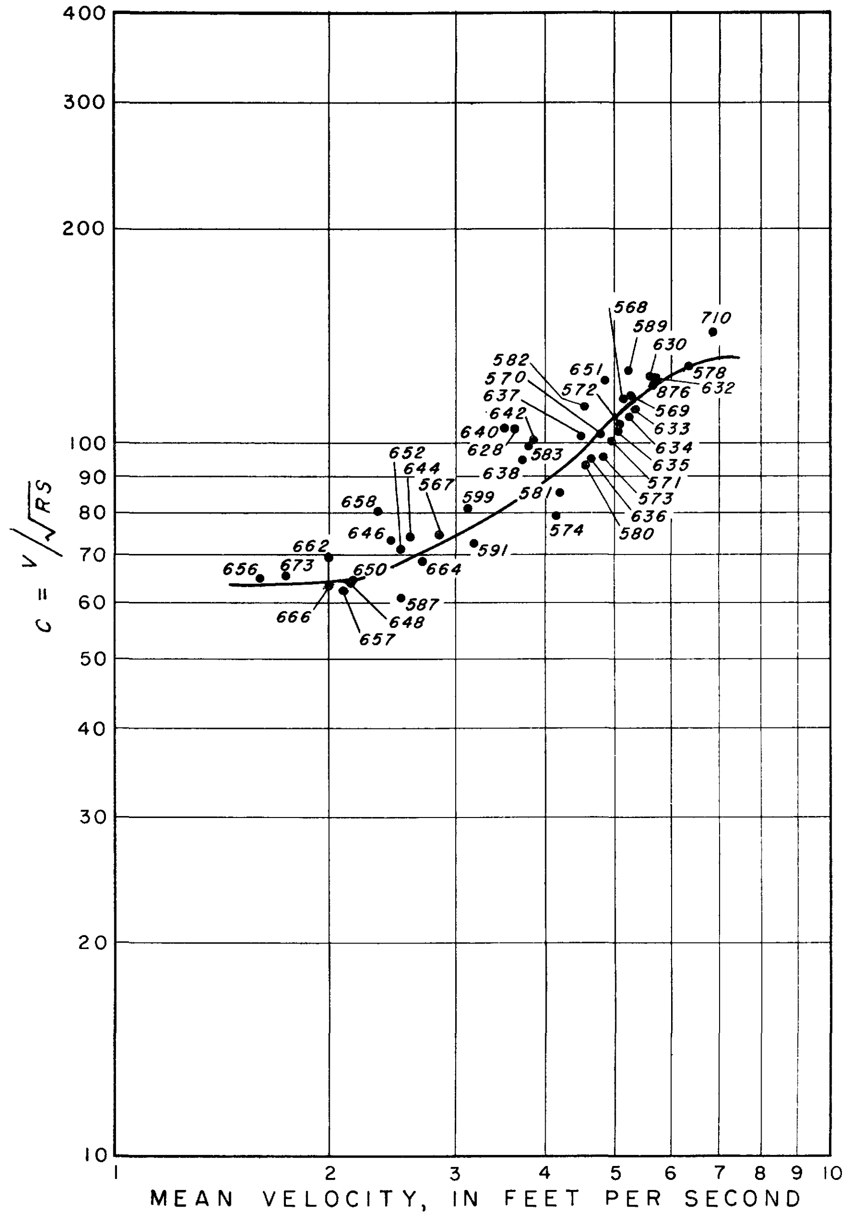

FIGURE 19.—Relation-between Chezy's C and mean velocity for measurements made at both cableways. Figures correspond to measurement numbers in table 2.

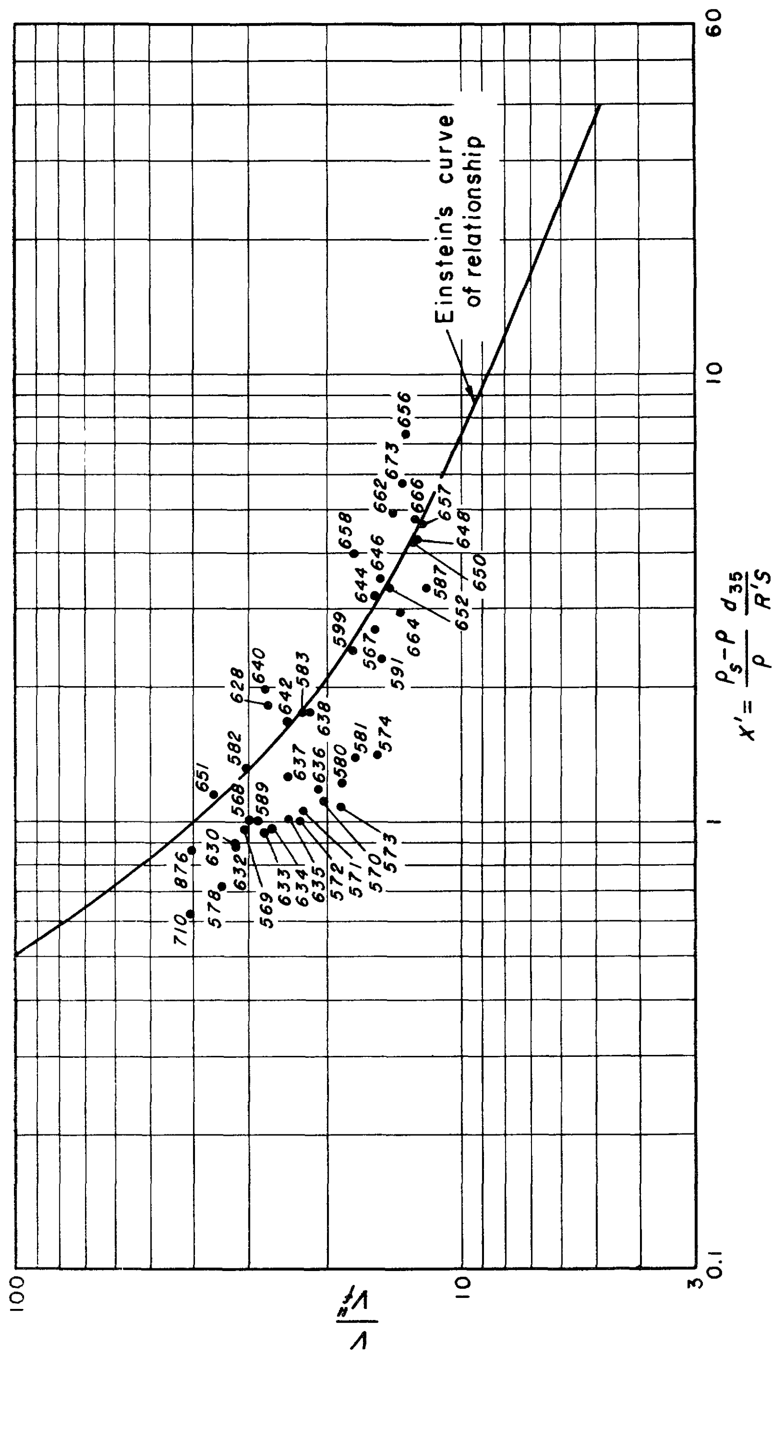

FIGURE 20.—Comparison of data from Elkhorn River with data from other rivers supporting Einstein's curve of relationship. Figures correspond to measurement numbers in table 2.

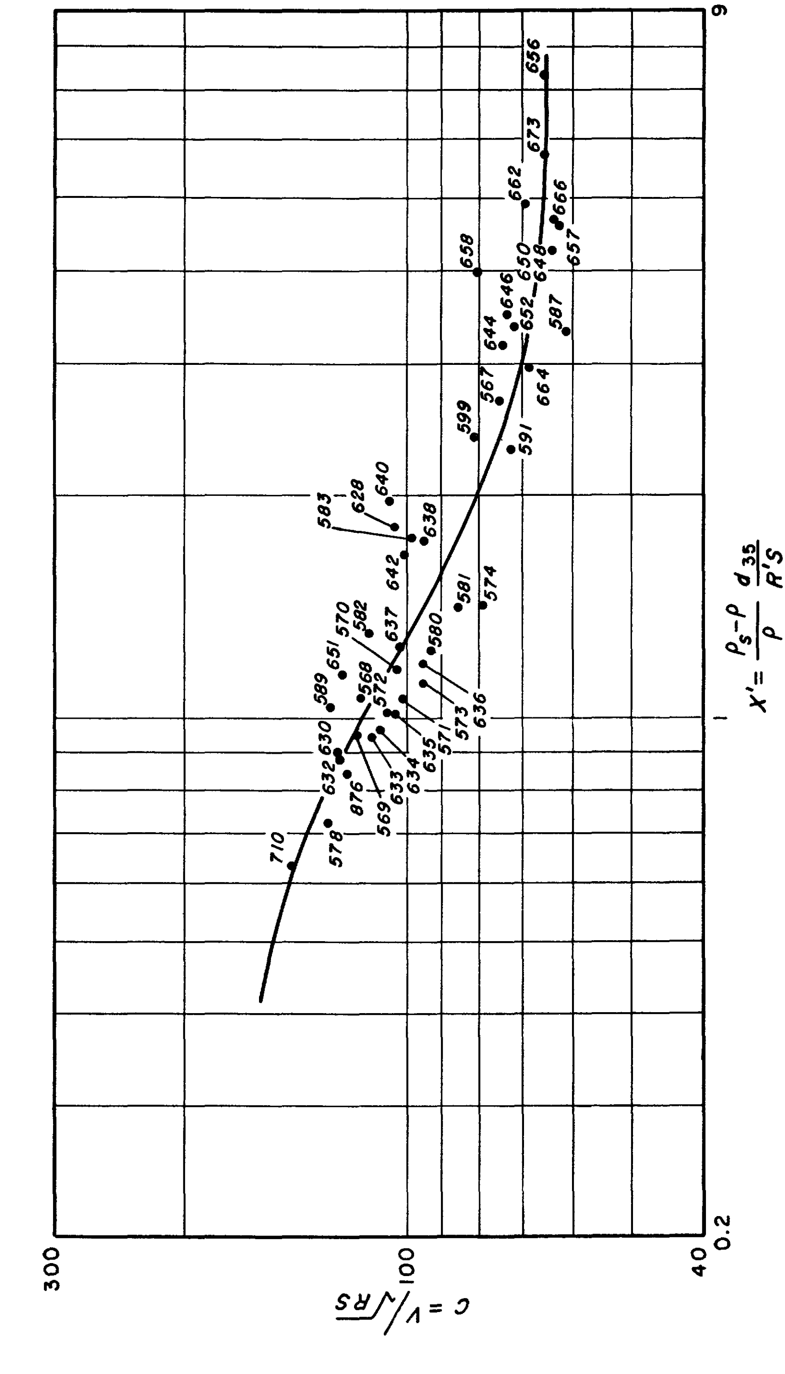

FIGURE 21.—Relation between Chezy's C and Einstein's X', Elkhorn River data. Figures correspond to measurement numbers in table 2.

Simons (Simons and others, 1961) found that washload has no appreciable effect on the roughness coefficient if the concentration was less than 20,000 ppm (parts per million). The maximum concentration of sizes less than 0.06 mm observed on the Elkhorn was only 3,000 ppm, and thus the scatter on figure 21 cannot be attributed to this variable.

SIMONS' EQUATION

The equation which Simons (Simons and others, 1961) developed for Chezy's C from laboratory tests of one sand size is—

$$C=\sqrt{g}\times 0.90\times 10^{-6}\frac{\gamma_s-\gamma}{\gamma S^2}\left[\frac{\omega dS}{\nu}\times 10^2+5\mathbf{F}^2\right]^{1.85}. \tag{3}$$

A comparison of C computed from this equation with $V\sqrt{RS}$ for the Elkhorn data is shown in figure 22. It is apparent that equation 3 cannot be used to predict the value of the roughness coefficient for the Elkhorn reach.

LIU'S EQUATION

Liu and Hwang (1959) determined a general equation for sandbed streams on the basis of all available laboratory data as

$$V=C_aR^xS^y. \tag{4}$$

The values of C_a, x, and y are related to the median size of bed material. A comparison of V computed from equation 4 with the observed velocity for measurements on the Elkhorn reach which were definitely in the dune or plane-bed regime is shown in figure 23. The velocities predicted from Liu's equation are about 40 percent too high in the dune regime and 40 percent too low in the plane-bed regime.

CONCLUSIONS

The configuration of the bed of the Elkhorn River changes from dunes to plane bed with increasing discharge. This causes a discontinuity in the depth-discharge relationship and a large variation in the roughness coefficient. The change from dunes to plane bed does not occur simultaneously at all points in the reach and thus a multiple roughness condition exists in the transition region.

Scour and fill occur simultaneously at different points in the cross section, but the average bed elevation remains relatively constant. The true cross section at the time of the peak discharge cannot be determined by prodding the channel bed after the flood event.

The roughness coefficient for the Elkhorn reach cannot be predicted from the relationships published by Simons, Liu, or Einstein. The

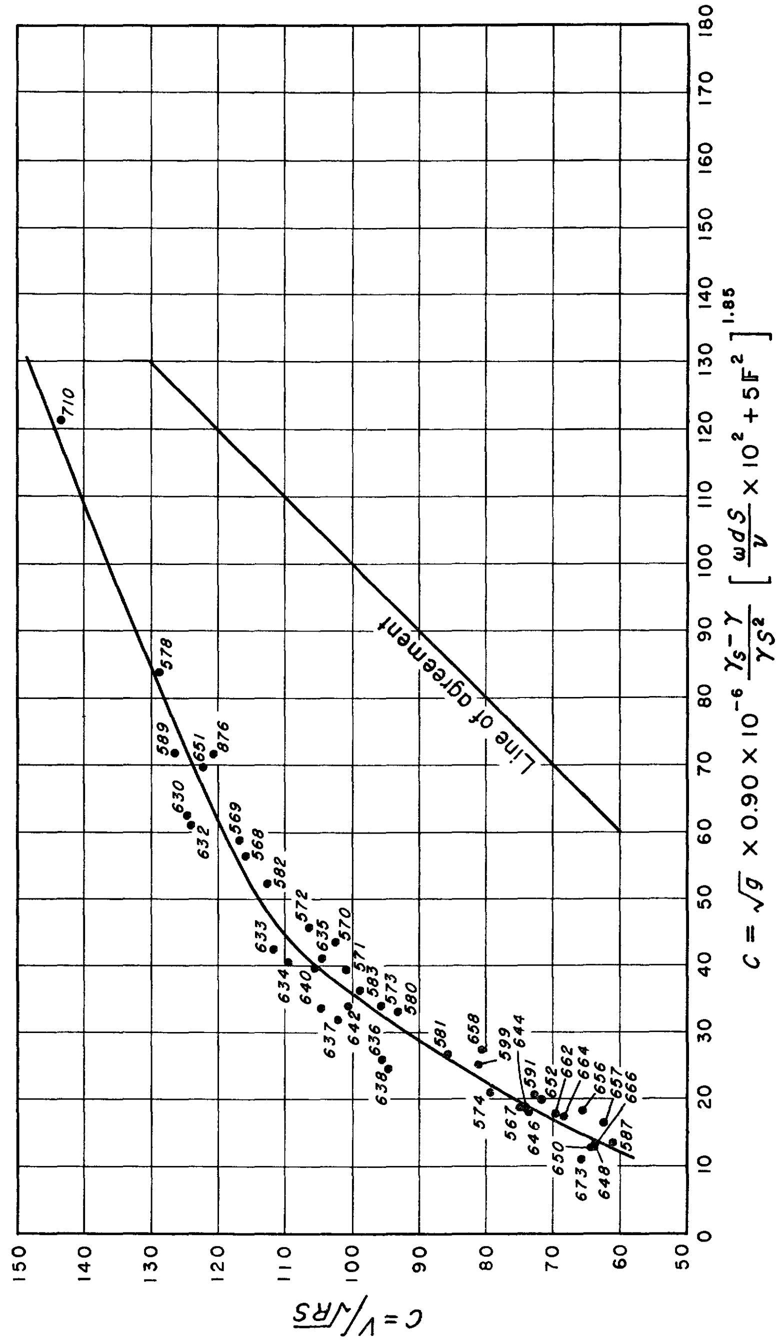

FIGURE 22.—Comparison of relationship between Chezy's *C* and Simons' *C*, Elkhorn River data. Figures correspond to measurement numbers on table 2.

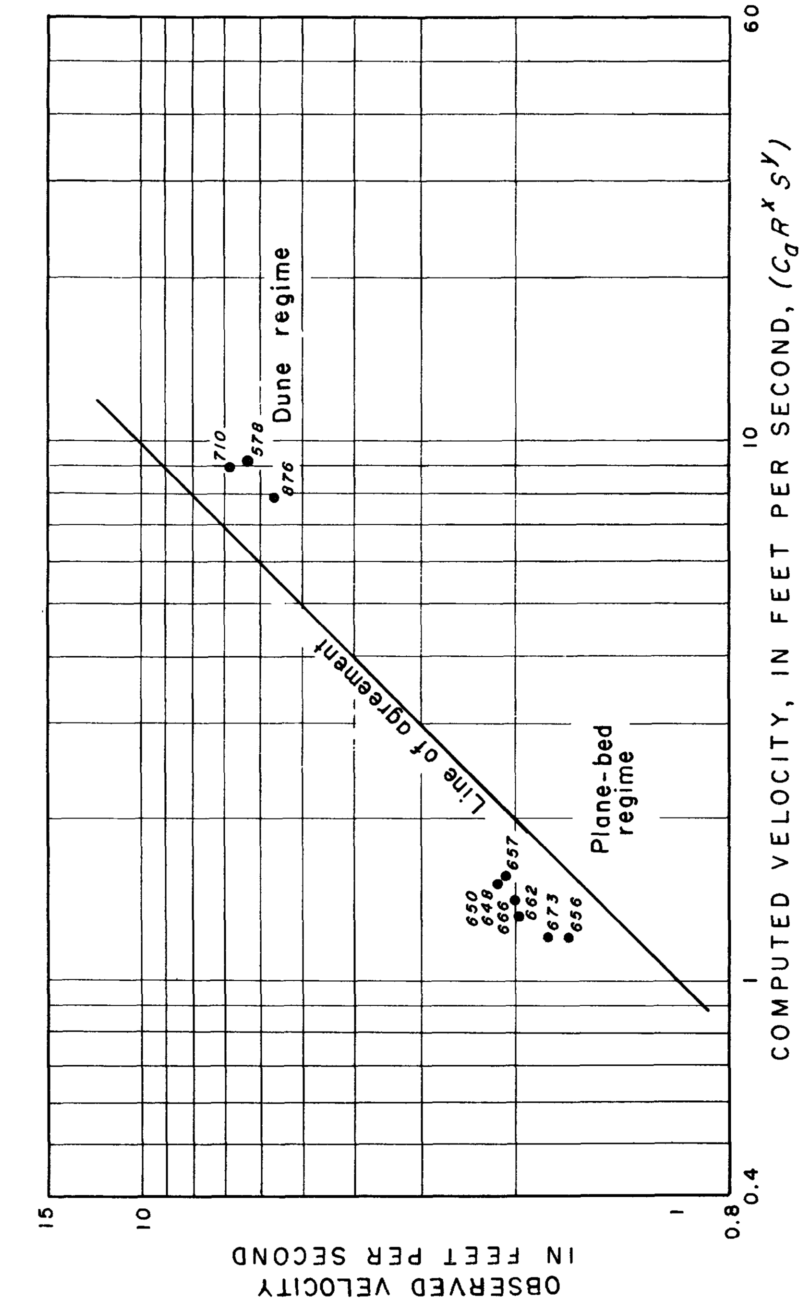

FIGURE 23.—Comparison between observed velocity and velocity computed by Liu's formula. Figures correspond to measurement numbers in table 2.

configuration of the channel bed does not agree with the classification proposed by Albertson or Garde.

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