Field Measurement of the Initiation of Large Bed Particle Motion in Blue Creek Near Klamath, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 562-G

Prepared in cooperation with the California Department of Water Resources

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By E. J. HELLEY

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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FIELD MEASUREMENT OF THE INITIATION OF LARGE BED PARTICLE MOTION IN BLUE CREEK NEAR KLAMATH, CALIFORNIA

By E. J. Helley

ABSTRACT

More than two-thirds of the field measurements of bed velocity necessary to initiate motion of coarse natural particles whose size, shape, specific gravity, and orientation angle were known agree within 20 percent of those velocities predicted from theory. The theory is based on balancing turning moments of the fluid forces of drag and lift with the resisting moment of the submerged particle weight.

Initial motion seems to depend more on size and shape than on specific gravity or orientation angle. In fact, shape differences almost completely compensate for differences in specific gravity ranging from 2.65–3.00 and orientation angles ranging from 0°–25°.

Bed velocities necessary to initiate motion of coarse bed material in Blue Creek are equaled or exceeded about 5 percent of the time. This fact and changes in channel topography and cross-sectional area emphasize the ability of perennial mountain streams to transport coarse bed material frequently.

INTRODUCTION

A particle on a rough streambed begins to move when the force of the column of moving fluid intercepting it generates a moment equal to the oppositely directed moment of the immersed particle weight. This phenomenon may be viewed as a balance between fluid forces of drag and hydrodynamic lift, which tend to turn a particle, and resisting forces of immersed-particle weight, which tend to keep the particle at rest. When these two opposing forces are just in balance, the fluid is competent to move its bed particles and critical or threshold conditions exist. In this report, mean values of drag and lift are used, but it should be recognized that forces much larger than the mean exist.

Determination of critical or threshold conditions of sediment movement has long been a problem for hydraulic engineers as well as for those geomorphologists interested in fluvial processes. An excellent historical review of measuring threshold conditions for sediment motion is given by Leliavsky (1966), who stated that measurements of this type began as early as 1753. Unfortunately, the problem of measuring and predicting these threshold conditions is still largely unsolved. This is especially true with respect to bed materials larger than pebble size.

If the problem of measuring threshold conditions of sediment motion is viewed as a balance between the forces of fluid flow and resting particle, then the initiation of motion becomes one of the simpler problems involving threshold conditions (Vanoni, 1966) and one which hold promise of solution. This should be particularly true when dealing with coarse bed material, whose physical properties can be measured more accurately than those of sand or finer size particles. Attempts at measuring threshold conditions necessary to initiate motion of very large bed particles in this study are based on the use of "bed velocity" rather than on the depth-slope product ("critical tractive force"). Rubey (1938) in a review of Gilbert's (1914) flume data showed that "bed velocity" is more significant than the depth-slope product, especially when measuring threshold conditions for particles larger than 2.5 mm (millimeters). In addition, the slope of the water surface of most natural streams needed to calculate tractive force is usually difficult to measure accurately—especially at high stages. This is particularly evident in mountain streams, whose alinement and channel geometry change frequently and irregularly, a change that generates secondary currents and superelevations and gives rise to local and changing slopes. In this report, bed velocity is defined as the velocity measured at some finite distance close to the bed.

PURPOSE

The primary purpose of this study was to determine bed velocities necessary to initiate motion of very coarse bed material by direct measurement and, thereby, to extend existing size-versus-velocity relations. A secondary objective was to determine channel changes due to aggradation or degradation in the vicinity of the test reach during the period of study. This was done in an attempt to evaluate the geomorphic significance of threshold conditions of particle motion.

The study was made by the U.S. Geological Survey in cooperation with the California Department of Water Resources. The work was done under the immediate supervision of Loren E. Young, chief of the Menlo Park office of the Water Resourses Division of the Geological Survey. The author wishes to express gratitude to personnel of the U.S. Geological Survey, especially Gerald LaRue, for assistance in the field and Carl Goodwin and Winchell Smith for assistance in the theoretical calculations and computer programming. The manuscript benefited from critical review by Carl Nordin, Everett Richardson, and John Ritter.

LOCATION

Blue Creek, a small tributary to the Klamath River in northern California (fig. 1), was chosen as the study site for the following reasons. Discharge measurements at the U.S. Geological Survey gaging station at Blue Creek indicated that runoff from this small, 120-square-mile drainage basin had velocities ranging from less than 2 fps (feet per second) to as much as 13 fps but that the discharge was not flashy or large enough to be difficult to measure. Observations of the streambed during summer low-flow periods indicated that the bed material consisted of particles averaging about 0.5 foot but as much as 3 feet in median diameter. Shifts in the rating curve during periods of moderate to high discharges showed that the streambed at the gaging-station cableway was changing and, hence, that Blue Creek was actively transporting its coarse particles as bedload.

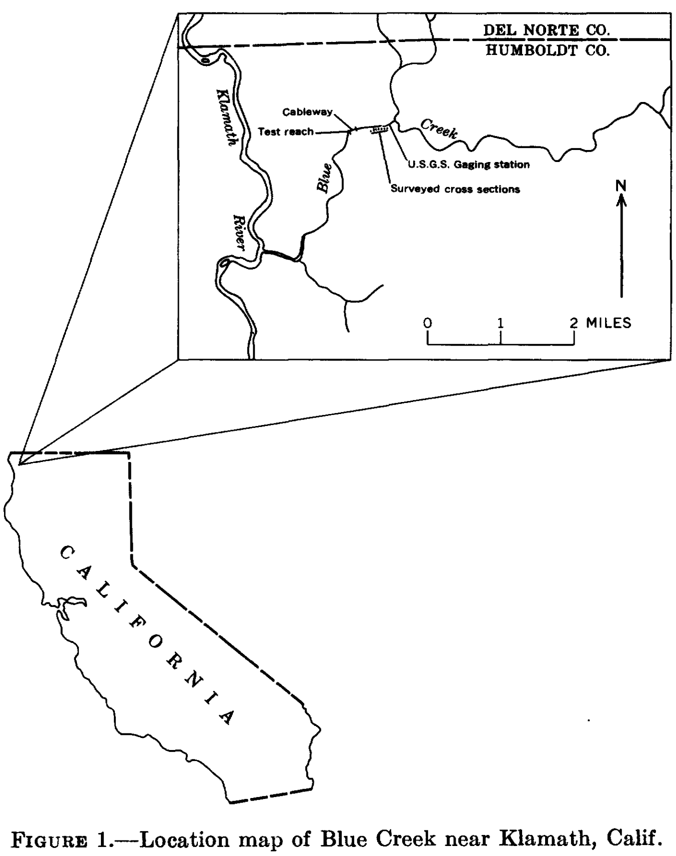


FIGURE 1.—Location map of Blue Creek near Klamath, Calif.

Blue Creek's drainage basin is underlain by a wide variety of rock types including shale, sandstone, and ultrabasic intrusive rock as well as minor amounts of granite (Irwin, 1960). Weathering characteristics of these rocks make available a wide variety of shapes and differences in mineralogy provide a large range in specific gravity from 2.60–3.10. Thus, the natural setting at Blue Creek was ideal for a study of the transport of coarse bed material. The gaging station and cableway also provided a means by which bed velocities could be measured.

PREVIOUS WORK

Previous attempts at measuring threshold conditions for sediment motion have been reviewed by Leliavsky (1966) and more recently by Raudkivi (1967). Most of their discussions concern smaller size particles and will not be discussed here. Mavis and Laushey (1949, p. 39) presented critical bed velocity-versus-size curves for particles up to 100 mm (0.3 ft). The coarsest material studied by direct measurement was that of Fahnestock (1963, p. 29), and his is probably the only data on particles greater than 1 foot in diameter. His measurements, however, were made under less than ideal conditions and on material in transport rather than at rest.

THEORY

The bed velocities necessary to initiate motion of coarse particles can be calculated by balancing turning moments of the fluid forces of drag and lift with the resisting moment of the submerged particle weight. The concept of balancing the turning and resisting moment is not new as shown by Leliavsky (1966, p. 36 and p. 149). Although past workers have considered various aspects of the initiation of motion of bed material, none have considered all the physical characteristics of the particles, their orientation, or a lift force. The general physics of initial grain motion is summarized by Shepard (1963) who reviewed the work of Shields (1936), White (1940), and Bagnold (1942).

Consider, for example, a particle at rest on the streambed as shown in figure 2. The orientation of the three mutually perpendicular axes as shown places the

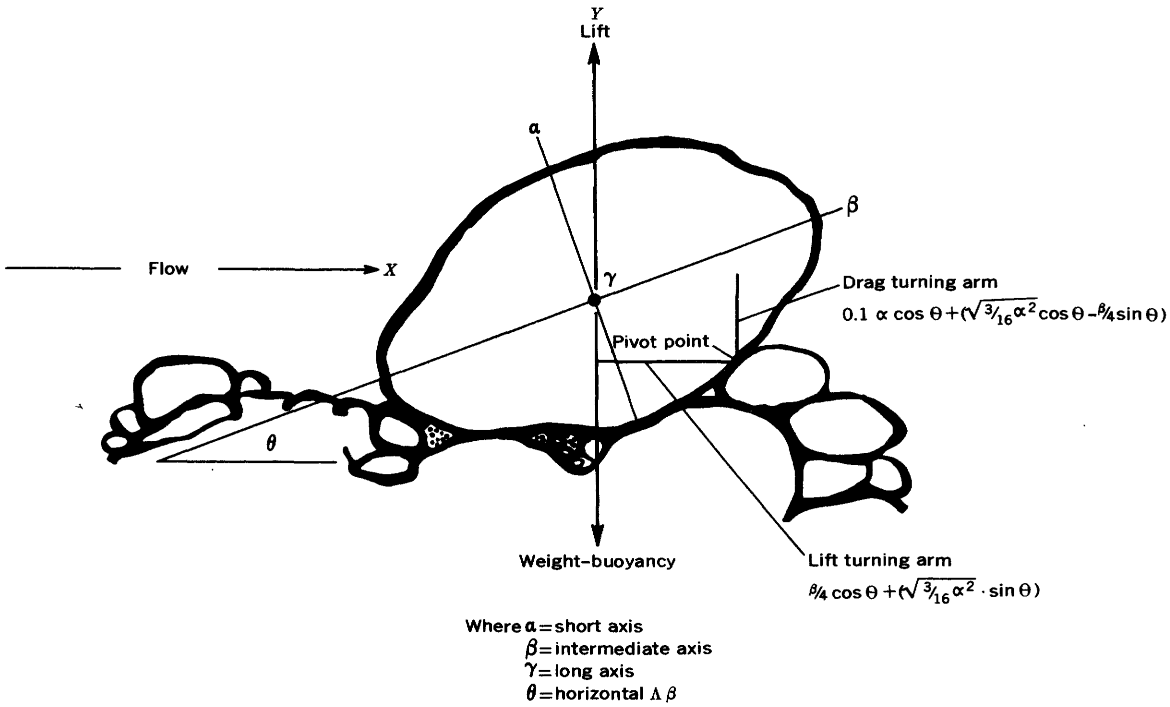


FIGURE 2.—Orientation of test particles placed on bed of Blue Creek.

long axis, γ, normal to the flow direction. The angle, θ, between the intermediate axis, β, and the horizontal is designated as the orientation angle. This neglects the bed slope, which is here considered insignificant. The orientation shown in figure 2 is considered typical of the bed material found in the test reach.

TURNING MOMENT

The moment tending to turn the particle in figure 2 must consist of two parts: first, the drag-force moment of the fluid parallel to the streambed, and second, a hydrodynamic-lift moment acting normal to the streambed (Einstein and El Samni, 1949, Vanoni, 1966, and Egiazaroff, 1967).

DRAG-FORCE MOMENT

The drag-force moment, neglecting fluid shear, may be expressed as the product of the average differential fluid pressure in the downsteam direction, the intercepted area of the particle, and the drag-force turning arm. Because the shapes of natural particles vary, the area intercepting the flow also varies, so that particles of the same size but of different shape exert a different form resistance to the flow. The Corey shape factor, $SF = \alpha/\sqrt{\gamma\beta}$, (Schultz and others, 1954), quantitatively expresses shape and can be related to the familiar drag coefficient, C_D. Because the Reynold's number in natural mountain streams like Blue Creek is extremely high, the drag coefficient (C_D) will be constant for a given shape factor; hence, the drag coefficient can be related to various shape factors. Figure 3 was constructed from the Reynold's number-versus-drag coefficient curve for various Corey shape factors, SF (U.S. Inter-Agency Committee on Water Resources Project Report No. 12, 1957, p. 20). The drag coefficient thus determined is for naturally worn sediments and was determined for free-falling bodies. Where particles are initially at rest on the streambed, not all the area described by the shape factor and drag coefficient exerts a form resistance to the flow. It is apparent that the drag coefficient for free-falling bodies must be modified before application to bodies at rest. An average drag coefficient used in this study is assumed to be $0.75C_D$ and is designated as C'_D. Egiazaroff (1967) has shown that the centroid of the drag force is 0.63 particle diameter up from the bottom of the particle. For simplicity this is taken as 0.6α, where α is the short axis of the particle shown in figure 2. As shown in figure 2. the drag-force turning arm is dependent on the location of the pivot point. This point was determined from observations of the orientation of particles deposited on the bed of Blue Creek. The position of this point, as shown in figure 2, may be expressed in terms of the flow direction, X, and lift direction, Y. Assuming that the particle shape is an ellipse in cross section and that the centroid of the drag force is at 0.6α, the X location is on a normal $\frac{\beta}{4}$ from the intersection of the mutually perpendicular particle axes. In the Y or lift direction the pivot point

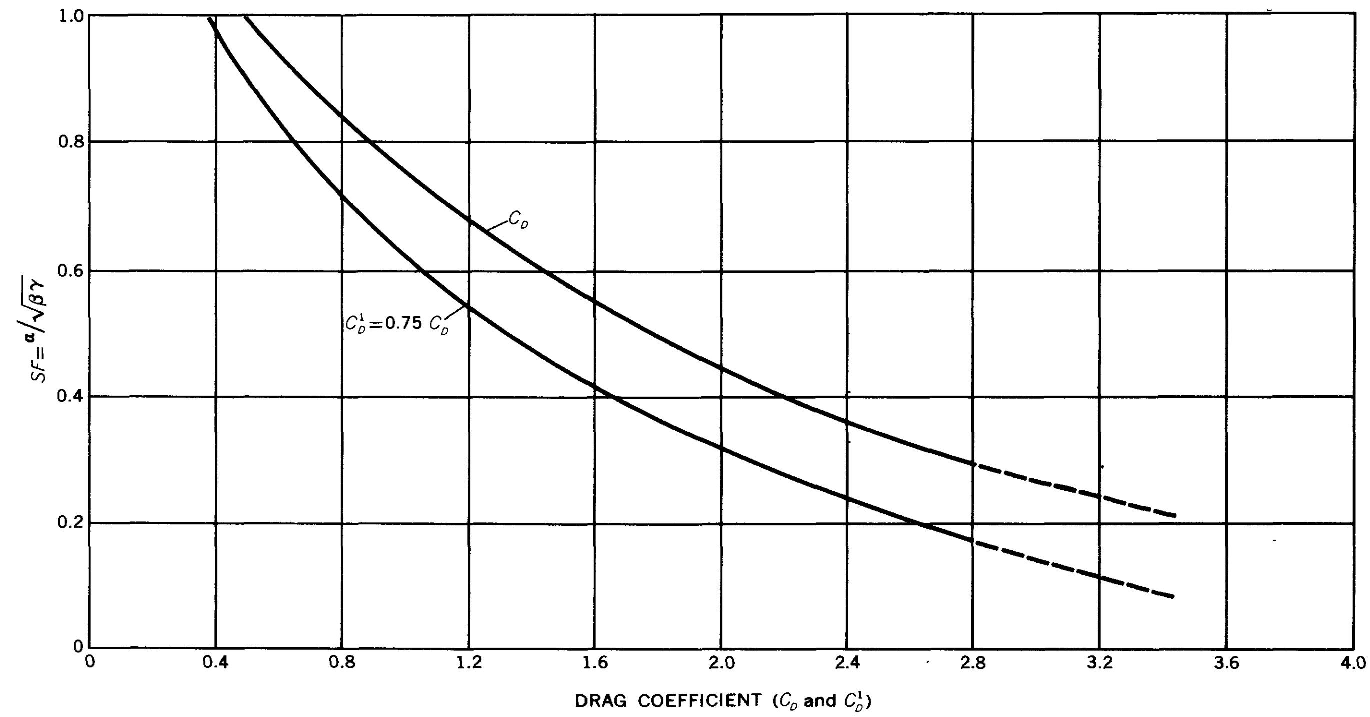


FIGURE 3.—Relation between shape factor, SF, and drag coefficient C_D and C'_D for high Reynold's numbers, >2000. C_D from U.S. Inter-Agency Committee on Water Resources Report No. 12 (1957, p. 20).

may be located by solving the equation of an ellipse which yields

$$Y^2=\left(\tfrac{1}{4}-\frac{(X)^2}{\beta^2}\right)\alpha^2$$

which reduces to

$$Y=\sqrt{\frac{3}{16}\alpha^2}.$$

The coordinates which describe the location of the pivot in the drag and lift directions are

$$\frac{\beta}{4} \text{ and } \sqrt{\frac{3}{16}\alpha^2},$$

respectively.

The drag-turning arm shown in figure 2 is then

$$0.1\alpha \cos\theta+\left(\sqrt{\frac{3}{16}\alpha^2}\cos\theta-\frac{\beta}{4}\sin\theta\right)$$

and is here designated as MR_D.

Using the symbols in figure 2 and expressing the particle shape in cross section as approximating an ellipse, the drag moment be written as

$$(C'_D)\ (\text{drag force})\ (\text{turning arm})$$
$$(C'_D)\left(\frac{v^2}{2g}\cdot 62.4\right)\left(\frac{\pi\alpha\gamma}{4}\right)(MR_D),$$

where

v= the bed velocity at 0.6α up from the bed

g= the acceleration due to gravity.

It should be noted that the expression is applicable for angles of theta less than about 25°.

LIFT-FORCE MOMENT

The lift-force moment may be expressed in a manner similar to that of the drag-force moment; however, the lift moment turns about a different turning arm. Actually, very little data are presently available to calculate lift coefficients reliably except for those developed by the experimental work of Einstein and El Samni in 1949 (in Vanoni, 1966). Because the size of the particles used in their experimental work is relatively large (0.225 ft), the Einstein and El Samni lift coefficient, 0.178, is applicable here. The lift force acting normal to the streambed turns about an arm of length

$$\frac{\beta}{4}\cos\theta+\left(\sqrt{\frac{3}{16}\alpha^2}\sin\theta\right),$$

where β is the intermediate axis,

α is the short axis, and

θ is the orientation angle shown in figure 2.

This turning arm is here designated as MR_L. Again approximating the particle shape as an ellipse in cross section, the lift-force moment may be written (lift coefficient) (lift force) (turning arm)

$$(0.178)\left(\frac{v^2}{2g}\cdot 62.4\right)\left(\frac{\pi\beta\gamma}{4}\right)(MR_L).$$

Combining the drag-force and lift-force moments into the turning moment (*MRT*), we have drag-force moment+lift-force moment

$$MRT=(C'_D)\left(\frac{v^2}{2g}\cdot 62.4\right)\left(\frac{\pi\alpha\gamma}{4}\right)(MR_D)$$
$$+\left(0.178\frac{v^2}{2g}\cdot 62.4\right)\left(\frac{\pi\beta\gamma}{4}\right)(MR_L);$$

and simplifying,

$$MRT=\frac{v^2}{2g}\cdot 62.4\,\frac{\pi}{4}\,[C'_D\,\alpha\gamma(MR_D)+0.178\,\beta\gamma(MR_L)]. \qquad (1)$$

RESISTING MOMENT

The force which resists the turning of the particle consists of the immersed weight. This force may be expressed as the product of the submerged specific gravity, the specific weight of water, and the volume of the particle. Because the force of the immersed weight acts downward normal to the streambed, the turning arm needed to compute the resisting moment is the same as that for the lift-force moment. Approximating the volume with an ellipse rotated about its minor axis to form a prolate spheroid and using the symbols in figure 2 we may write the resisting moment (*MRR*) as:

(submerged specific weight) (volume) (turning arm)

$$MRR=(\text{sp gr}-1)\ (62.4)\left(\frac{4}{3}\pi\frac{\gamma}{2}\right)\left(\frac{\alpha+\beta}{4}\right)^2(MR_L),$$

where sp gr is the specific gravity of the particle.
Rearranging and simplifying:

$$MRR=(\text{sp gr}-1)\ (41.6\,\pi\gamma)\left(\frac{\alpha+\beta}{4}\right)^2(MR_L), \qquad (2)$$

which holds for small angles of theta (less than 25°).

CONDITIONS FOR MOTION

At the instant when motion takes place, the sum of the turning and resisting moments is zero.

Moment (turning)=Moment (resisting) @ incipient motion combining equations (1) and (2); *MRT=MRR*.

$$\frac{v^2}{2g}\cdot 62.4\,\frac{\pi}{4}\,[C'_D\,\alpha\gamma\ (MR_D)+0.178\beta\gamma\ (MR_L)]$$
$$=(\text{sp gr}-1)\ (41.6\pi\gamma)\left(\frac{\alpha+\beta}{4}\right)^2(MR_L).$$

Simplifying and solving for v at 0.6α

$$v^2=\frac{\frac{41.6\pi}{16}\ (\text{sp gr}-1)\ \gamma\ (\alpha+\beta)^2\ (MR_L)}{\frac{62.4\pi}{2g}\ [C'_D\ \alpha\gamma\ (MR_D)+0.178\beta\gamma\ (MR_L)]}$$

$$v_{(0.6\alpha)=3.276}\sqrt{\frac{(\text{sp gr}-1)\ \gamma(\alpha+\beta)^2\ (MR_L)}{C'_D\ \alpha\gamma\ (MR_D)+0.178\ \beta\gamma\ (MR_L)}} \qquad (3)$$

or the bed velocity, $v_{(0.6)}$, at a distance 0.6α up from the streambed will be a constant at incipient motion if sp gr, θ, α, β, γ, and C'_D are known. Equation 3 has the form of the familiar "Sixth-power law" (Rubey, 1938) except it attempts to consider particle shape, density, and orientation.

FIELD MEASUREMENTS

Field techniques for direct measurement of bed velocities were developed during topographic mapping of a test reach at Blue Creek in the summer low-flow period in 1967. At that time a 450-foot-long reach bisected by the Blue Creek gaging station cableway was selected as the test reach (fig. 4). During this initial survey, the streambed consisted of particles finer than those sizes desired for study; therefore, it was necessary to place particles of the desired size on the natural bed. Because natural gravel deposits often display a definite fabric or preferred particle orientation (Krumbein, 1940, 1942, Potter and Pettijohn, 1963), the particles placed for study on the streambed were oriented as others which had been naturally deposited by Blue Creek in the test reach. Measurement of 100 large particles at the downstream end of the test reach showed a bimodal orientation which seemed to be mainly a function of shape (fig. 5). For example, rodlike particles tended to orient themselves such that the mean angle between their long axes and the flow direction was 39°±24°. Platelike particles, on the other hand, tended to display an almost perpendicular orientation of their long axis to the flow direction; their mean angle between long axis and flow direction was 77°±12°. In general, almost all particles were inclined upstream; those that were not, were horizontal. Platelike particles, generally, had lower inclinations than those less flat. The long axes of larger particles seemed to be oriented either normal or parallel to the flow direction more often than the long axes of the smaller particles. This was also true with those particles touching or making contact with others than isolated particles. The orientation angle Θ, ranged from 0°–30°, but most of the angles were less than 15°.

TEST PARTICLES

During the summer low-flow period of 1967, four plots of nine particles each were designed and placed just upstream from and parallel to the cableway at

FIGURE 4.—View downstream of test reach at Blue Creek. (Note: man at left center is standing under cableway.)

the Blue Creek test reach. Each plot covered an area of 10 by 10 feet, and particles were spaced about 2 to 3 diameters apart so that no one rock directly influenced the flow over other rocks. Thirty-six rocks of various sizes, shapes, and lithologies from a nearby gravel bar were selected as test particles. As each particle was removed from the gravel bar, its three mutually perpendicular axes, α, β, and γ, were measured, and a small chip was removed for specific-gravity determination. Each particle was painted fluorescent red and numbered before placement on the streambed. The long axis was oriented normal to the flow direction. The angle θ, between the intermediate axis and the horizontal, was measured for each particle with the clinometer of a Brunton compass. As specific gravity and θ had been measured and C'_D calculated from measurement of α, β, and γ, it was possible to calculate the theoretical bed velocity necessary to initiate motion using equation 3. The physical properties of the 36 test particles used in this study and the calculated bed velocities necessary to initiate motion are summarized in table 1.

VELOCITY MEASUREMENTS

Attempts to test the theory of turning and resisting moments expressed in equation 3 were begun in the winter of 1966–67. At the outset it became readily apparent that turbid water made direct observation of bed-particle motion impossible. Large particles painted a bright fluorescent red could not be seen through depths exceeding 3 feet. Unfortunately, velocities at the test site did not initiate motion of the test particles until depths exceeded 4 feet. During the fieldwork in the winter of 1967–68, this problem was resolved by placing spherical styrofoam floats, numbered to correspond to the test particles, under each particle. These floats were also painted fluorescent colors—a different color for each of the four test plots. In addition, each float was fixed with a 30-foot coil

FIGURE 5.—View upstream of Blue Creek showing the site at the downstream end of the test reach where particle orientation was studied. (Note large size of bed material.)

of monofiliment which was tied to a ring in a steel reinforcing bar driven in the streambed. Testing this system during low-flow periods showed that turning of the test particles released the float. The monofilament uncoiled with the float coming to the surface under the cableway from which it could be seen and its corresponding number easily read. The 30-foot length of monofiliment would be necessary during higher stages and velocities.

Attempts to measure bed velocities with a standard Price current meter failed to reach the desired distances above the bed, 0.6α, which in two cases was less than 0.2 foot (table 1). In order to measure velocities closer to the bed, a Pygmy current meter was mounted on the nose of a 75-pound sounding weight upstream from the point of flow stagnation at 0.2 foot above the base of the weight. A foot plate was attached to the base of the weight extending under the Pygmy meter to protect the meter, and the area of the tail fin of the weight was doubled to increase stability. Because the revolutions of a Pygmy meter could not be counted manually at high velocities, a mechanical counter and an electrical relay mechanism were designed and added to the meter system. This allowed counting rates of 12.5 impulses per second or velocities of approximately 12.5 fps. The weight-mounted Pygmy meter and counting device are shown in figure 6. The Pygmy meter and standard Price meters used in this study are described and their limitations discussed by Corbett and others (1962). In normal practice the Pygmy meter is not designed for high-velocity measurements (Corbett and others, 1962, p. 180); therefore, it was necessary to compare velocities measured with the weight-mounted Pygmy system with those of a standard Price current meter. This was done by making simultaneous velocity measurements with both meters at the same height above the bed and

TABLE 1.—*Summary of physical properties of test particles and theoretical threshold velocities*

Rock No.	α (ft)	β (ft)	γ (ft)	0.6α (ft)	$SF\ \alpha/\sqrt{\beta\gamma}$	C_D'	$\theta°$	Sp gr [1]	Volume (ft^3) [2]	Weight (lbs) [2]	$v^{calc}_{0.6\alpha}$ (fps)
24	0.55	1.30	1.55	0.33	0.38	1.73	0	2.85	0.46	120.9	7.90
26	.90	1.10	1.70	.54	.66	.98	4	2.65	.70	147.2	6.78
14	.60	1.00	1.60	.36	.47	1.44	16	2.85	.40	94.3	7.78
8	.60	.85	1.70	.36	.50	1.35	0	2.72	.36	84.9	5.32
25	.70	1.45	1.70	.42	.45	1.51	2	2.65	.72	170.3	8.00
10	.55	1.25	1.65	.36	.37	1.80	15	2.70	.47	117.9	8.74
23	.65	.90	1.65	.39	.53	1.29	0	2.72	.40	88.3	5.53
9	.90	.90	1.95	.54	.68	.96	0	2.71	.56	140.4	5.45
15	.55	.65	1.25	.33	.61	1.12	0	2.85	.19	42.7	4.83
16	.55	1.10	1.50	.33	.39	1.70	0	2.70	.38	89.3	6.45
27	.95	1.35	1.70	.57	.62	1.10	0	2.85	.91	215.2	7.62
29	.65	1.00	1.20	.39	.59	1.16	8	2.65	.33	69.5	6.93
35	.45	.95	1.25	.27	.41	1.65	10	2.85	.23	56.9	7.40
36	1.20	1.50	2.00	.72	.69	.95	0	2.85	1.50	343.2	8.09
22	.80	1.10	1.15	.48	.72	.89	5	2.85	.42	99.6	7.95
7	.60	.90	1.60	.36	.50	1.35	0	2.85	.36	83.6	5.84
31	.80	1.70	1.90	.48	.44	1.56	0	2.65	1.08	94.3	8.44
21	.90	.95	1.40	.54	.78	.76	0	2.72	.50	108.6	6.38
34	.50	1.00	1.20	.30	.45	1.51	0	2.72	.25	59.4	6.50
19	.80	.95	1.45	.48	.68	.96	14	2.85	.46	103.1	7.65
20	.60	1.40	1.55	.36	.56	1.22	0	2.85	.54	144.1	9.30
2	.35	1.10	1.20	.21	.26	2.36	0	2.72	.19	56.0	7.16
28	.65	1.00	1.90	.39	.47	1.46	0	2.72	.51	113.7	5.80
11	.45	.80	1.45	.27	.42	1.62	11	2.72	.22	49.2	6.17
3	.30	1.05	1.40	.18	.25	2.40	0	2.85	.18	58.7	7.61
12	.75	.75	1.35	.45	.75	.82	0	3.10	.32	75.4	5.92
13	.75	.75	.95	.45	.89	.56	0	2.65	.22	48.0	6.22
4	.50	.70	1.30	.30	.53	1.29	14	2.74	.19	41.0	5.98
1	.70	.85	1.30	.42	.67	.99	12	2.64	.32	67.5	6.60
30	.40	.50	1.20	.24	.51	1.34	0	2.72	.10	22.1	3.86
17	.50	.55	.85	.30	.73	.86	0	2.70	.10	20.2	4.65
6	.60	.95	1.20	.36	.56	1.22	0	2.72	.29	64.5	6.20
18	.50	.60	1.00	.30	.64	1.05	0	2.70	.13	28.6	4.61
33	.60	.70	1.05	.36	.70	.92	0	2.72	.19	40.7	5.25
32	.50	.75	1.40	.30	.49	1.39	0	2.72	.22	47.5	5.07
37	.30	.70	.85	.18	.39	1.71	0	2.74	.07	30.8	5.61

[1] Measured.
[2] Computed.

comparing the measurements. A rectangular concrete-lined channel was used for comparison. Depths were about 2 feet, but velocities exceeded 12 fps. It was found that the Pygmy system differed from the standard Price meter by a maximum of only ±4.5 percent in velocities in excess of 8 fps. and only ±2 percent for lower velocities. Even though the thickness of the standard Price meter bucket wheel is at least twice that of a Pygmy meter and integrates velocities over a wider range in the vertical, the agreement is good. When the weight-mounted Pygmy meter was compared with other Pygmy meters which were rod mounted, velocity measurements differed by less than ±2 percent. Some difficulties were discovered when lowering the weight-mounted Pygmy meter into the flow. If lowered into the flow slowly, the entire system was twisted, thrown about, and almost impossible to handle. When, however the weight was immersed quickly, it remained fairly stable and was as easy to handle as a standard meter and weight. In actual practice at the Blue Creek cableway, either the redesigned Pygmy system or the standard Price meter was used, the choice depending on the surface roughness of the flow and the amount of floating debris.

Under field conditions during storm periods, it was practically impossible to maintain the suspended weight and attached meter, either Pygmy or standard Price, at the desired height above the bed, 0.6α. Most of the difficulties resulted from vertical motion of the cableway due to movement of the cablecar and water drag on the meter system. It was then necessary to determine the velocity distribution over each test-particle location. An average velocity distribution at each of the 36 test-particle locations was determined from measurements made by wading for flows from 125–700 cfs (cubic feet per second) and from the cableway for 24 particle

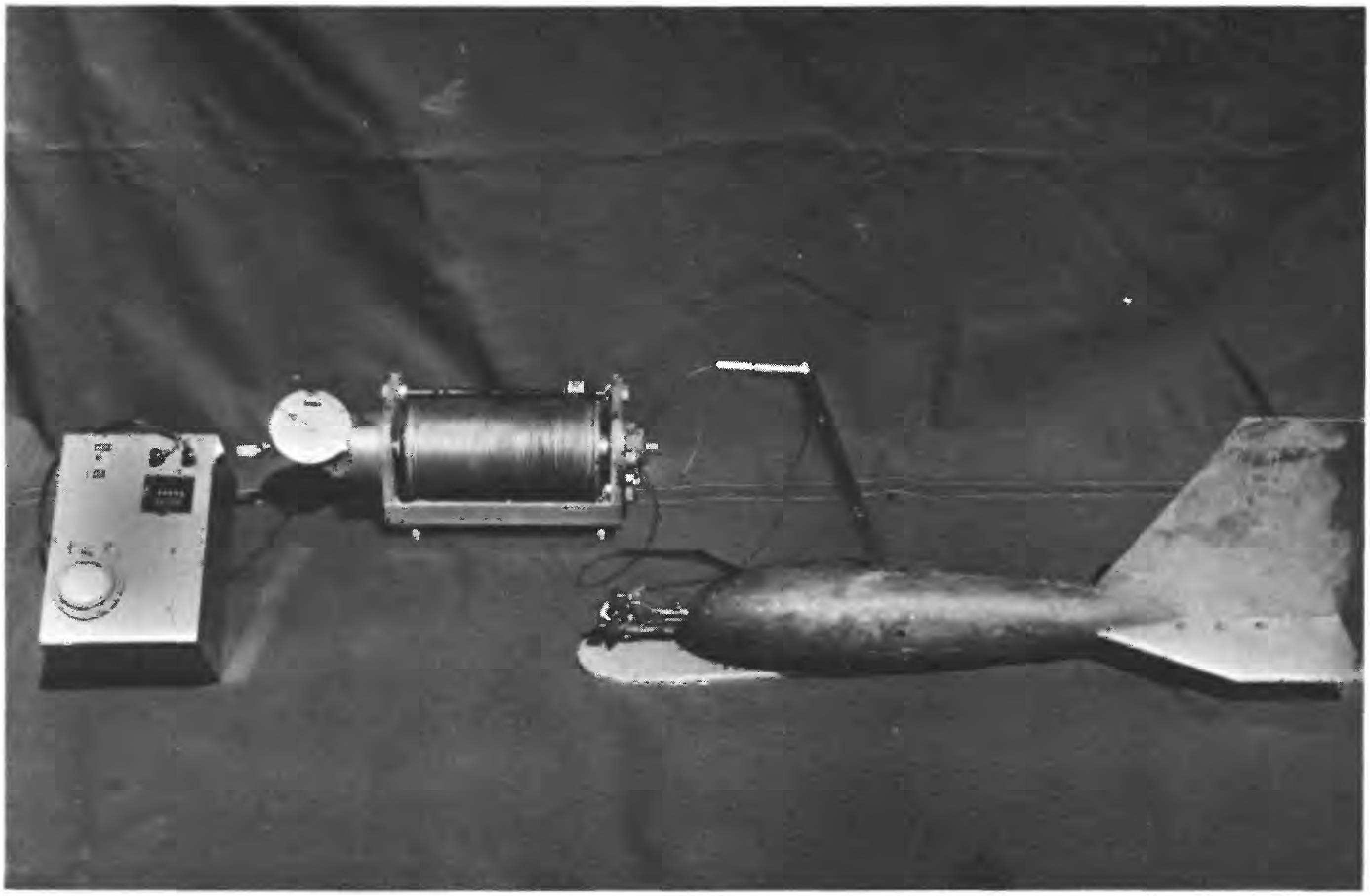


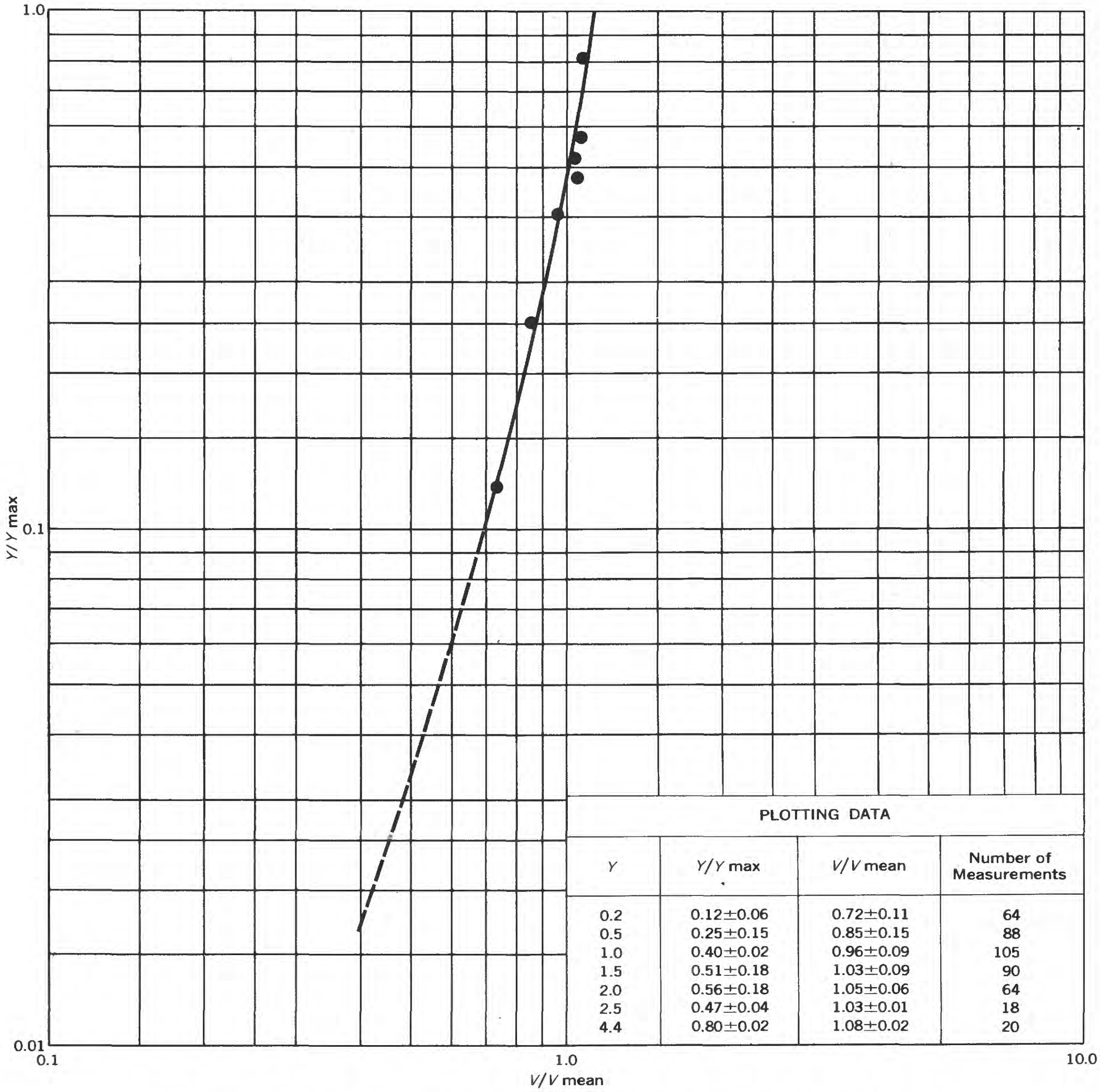
FIGURE 6.—Weight-mounted Pygmy current meter, standard A-reel, and counting device. (Note enlarged tail-fin assembly and foot-plate modifications on sounding weight.)

locations for flows ranging from 700–5,500 cfs. These data were combined into a dimensionless average velocity distribution for the entire cross section as shown in figure 7. The plotting data are also shown where Y is the height above the bed, V is the point velocity measured at Y, Vmean is the velocity at six-tenths the depth, and Ymax is the total depth.

The range of velocity measurements covered from 12–80 percent of the total depths (Y/Ymax) observed. By using the curve in figure 7, it is possible to determine the bed velocities at any 0.6α above the bed from the maximum depth and mean velocity in each vertical. For example, it is desired to find the threshold velocity at 0.6α for a rock with an α dimension of 1 foot. At the time of initial motion, the depth, Ymax, was 4.0 feet; and the mean velocity was 5.0 fps. By entering figure 7 on the ordinate with $Y/Y\text{max}=\frac{(0.6)\ (1.0)}{4.0}=0.15$, which intersects the curve at a V/Vmean of 0.77, then with a mean velocity of 5.0 fps, the velocity at 0.6α is 3.85 fps.

DISTANCE OF PARTICLE MOVEMENT

Although only 15 painted test particles were recovered, it was possible to measure the distance each had moved during a single runoff event. The particle numbers, distance moved, and measured velocities necessary to initiate motion are given in table 2. In general, no clear relation between the physical properties of the test particles and distance moved could be ascertained. Undoubtedly, the interaction between particles and bed roughness is an important factor but beyond the scope of this study. Interaction and abrasion must certainly influence the distance moved as most of the fluorescent red paint was removed from those test particles which had moved more than 50 feet. Because the distances moved are for only one runoff event, they emphasize the ability of a mountain stream to transport coarse material easily. The threshold bed velocities necessary to move the test particles were generated from discharge equal to or greater than 2,500 cfs, at least for the present channel geometry. Correlating this discharge with mean monthly discharges at the nearby gaging station and transposing flow duration from other



PLOTTING DATA

Y	Y/Y max	V/V mean	Number of Measurements
0.2	0.12±0.06	0.72±0.11	64
0.5	0.25±0.15	0.85±0.15	88
1.0	0.40±0.02	0.96±0.09	105
1.5	0.51±0.18	1.03±0.09	90
2.0	0.56±0.18	1.05±0.06	64
2.5	0.47±0.04	1.03±0.01	18
4.4	0.80±0.02	1.08±0.02	20

FIGURE 7.—Dimensionless average velocity distribution for cross section at cableway.

older gaging stations in the same area indicate that 2,500 cfs is equalled or exceeded about 5 percent of the time. This not only emphasizes the streams ability to transport coarse debris, but to do so for a significant amount of time.

Three runoff events in late December and January of 1967–68 moved all but two of the test particles. Sixteen particles moved during the first event, seven moved during the second, and 11 moved during the third. In general, the styrofoam floats behaved satisfactorily during the first runoff event, but behaved less satisfactorily for the second and third. Apparently, local scour around the test particle caused several floats to be released before the particles actually moved. It was necessary then, during the second and third events, to make velocity observations on the rising stage up to and including the peak discharge. The peak discharge lasted for only about 15 minutes during the second event. Assuming then that the particles moved at or near the peak discharge, the field measurements of

TABLE 2.—*Distance moved and measured threshold velocities of recovered test particles*

Particle No.	Distance moved (ft)	Velocity at 0.6α (fps)
8	5	4.79
10	35	5.83
9	235	5.47
16	9	5.06
22	30	5.76
34	6	5.49
2	40	5.04
28	1.5	5.67
11	65	7.62
3	6	4.67
13	4	6.77
4	45	5.41
1	100	6.65
17	7.5	5.28
18	65	5.18

velocities used to determine V at 0.6α are considered the best estimate of Vmean and Ymax for the time of actual movement.

COMPARISON OF FIELD MEASUREMENTS TO THEORETICAL PREDICTIONS

Using equation 3, and the range in physical characteristics found in the test reach at Blue Creek (table 1), a relation between the intermediate diameter, β, and bed velocity, $v_{0.6\alpha}$, may be drawn. Figure 8 shows a family of four curves for the range in specific gravity from 2.65–3.00, θ from 0°–25°, and for shapes of $SF=$

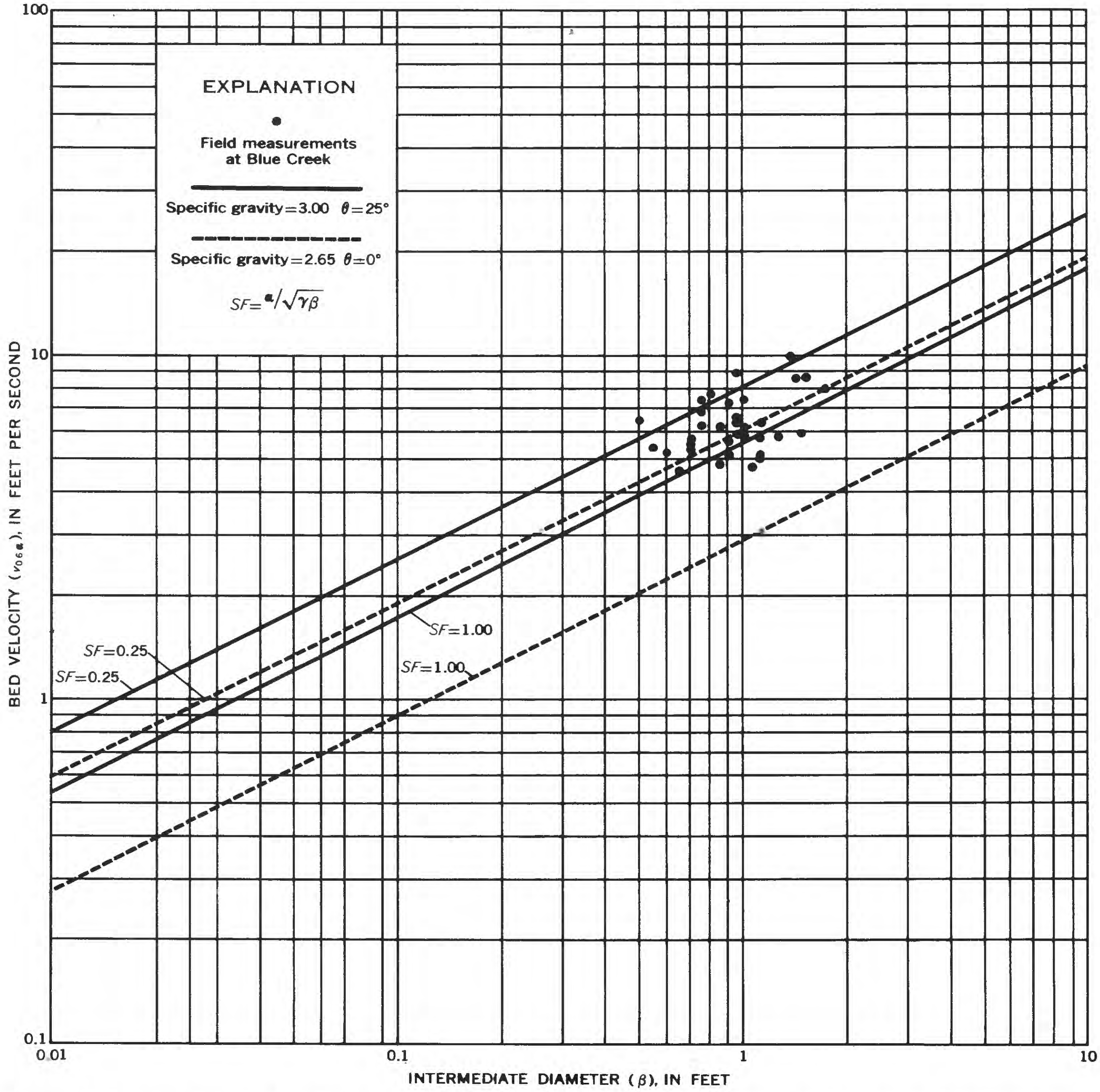
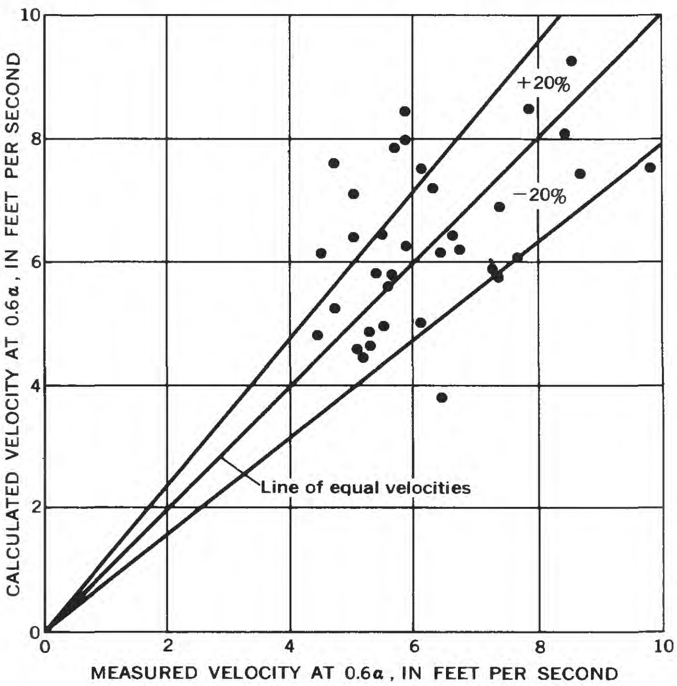


FIGURE 8.—Relation between bed velocity at incipient motion and intermediate particle diameter for the range in specific gravity, θ, and SF found in the test reach at Blue Creek as calculated from equation 3.

0.25–1.00. It should be readily noted that shape is a dominant factor in the determination of the bed velocity at incipient motion. In fact, changes in shape of particles of the same size (β axis) almost completely compensate specific gravity differences from 2.65–3.00. The angle of orientation θ, does not seem to be as important as shape or density and is one of the most difficult parameters to measure accurately.

Field measurements of bed velocities necessary to initiate motion of coarse particles made at Blue Creek, also plotted in figure 8, agree closely with the range in velocities predicted from theory. These theoretical bed velocities for the initition of motion calculated from equation 3 are plotted against the measured bed velocities in the test reach (fig. 9). This plot shows that approximately 70 percent of the data deviate by ±20 percent of that predicted from theory. At least the field data are compatible with the theory of turning and resisting moments. When the difficulties of making such measurements and the assumptions in the theory are considered, the agreement is good. The curves shown in figure 8 may be represented as an envelope by using extreme values for purposes of comparing previous work relating bed velocity and particle size (fig. 10). It should be noted that all curves are extrapolations over two log cycles when, in fact, most measurements are actually made over a range of about one log cycle. The direct measurements by Fahnestock (1963) agree fairly well, but the curve of Mavis and Laushey (1949) fits better—especially in the same size range as Fahnestock's. The major consideration in figure 10 is the fact that most differences in relations between velocity for the initition of motion and size result from differences in particle shape, density, and orientation. The envelope curves shown here are representative for the range in physical characteristics of particles in many natural streams with coarse beds and, therefore, should be applicable to other areas.



DISTRIBUTION OF ERROR

Percent Error	Number of measurements	Percent total
± 0–10	16	47.1
±11–20	8	23.5
±21–30	7	20.6
>31	3	8.8
	34	100.0

FIGURE 9.—Comparison of measured and calculated bed velocities at 0.6α for test particles.

CHANNEL CHANGES

Channel changes, as shown by aggradation or degradation, were studied at Blue Creek for two purposes. First, it was desired to describe the general channel behavior during the study period. This was necessary to relate the measured bed velocities needed to initiate motion to either an aggrading, degrading, or stable streambed. The second objective was to measure the response of a mountain stream, such as Blue Creek, to the effects of the devastating floods of December 1964. Blue Creek, as many other rivers and streams in northern California, underwent considerable streambed changes during these floods (Hickey, 1967). According to the studies done on Coffee Creek, also in northern California (Stewart and La Marche, 1967), the catastrophic 1964 flooding largely determined the channel morphology and the location and character of the alluvial deposits. The general hydrologic character of the December 1964 flood has been described by Rantz and Moore (1965); they showed that this event has been without precedent back to 1861 in northern California and in adjacent parts of Oregon, Idaho, and Nevada. In fact, geomorphic and botanical evidence indicate that a flood of the magnitude of the December 1964 flood had occurred only once in the last 400 years (Helley and La Marche, 1968). Fresh landslide scars, bank collapse, and uprooted trees give evidence to the fact that large volumes of colluvium and bank material were supplied to the channel of Blue Creek during the 1964 flood. Most of this material was deposited in the lower few miles of Blue Creek because of simultaneous high stages on the Klamath River. Narrow reaches in the lower course of Blue Creek commonly displayed boulder levees, and wide reaches contained large volumes of finer grained well-stratified deposits. Inspection of the Blue Creek channel from the gaging

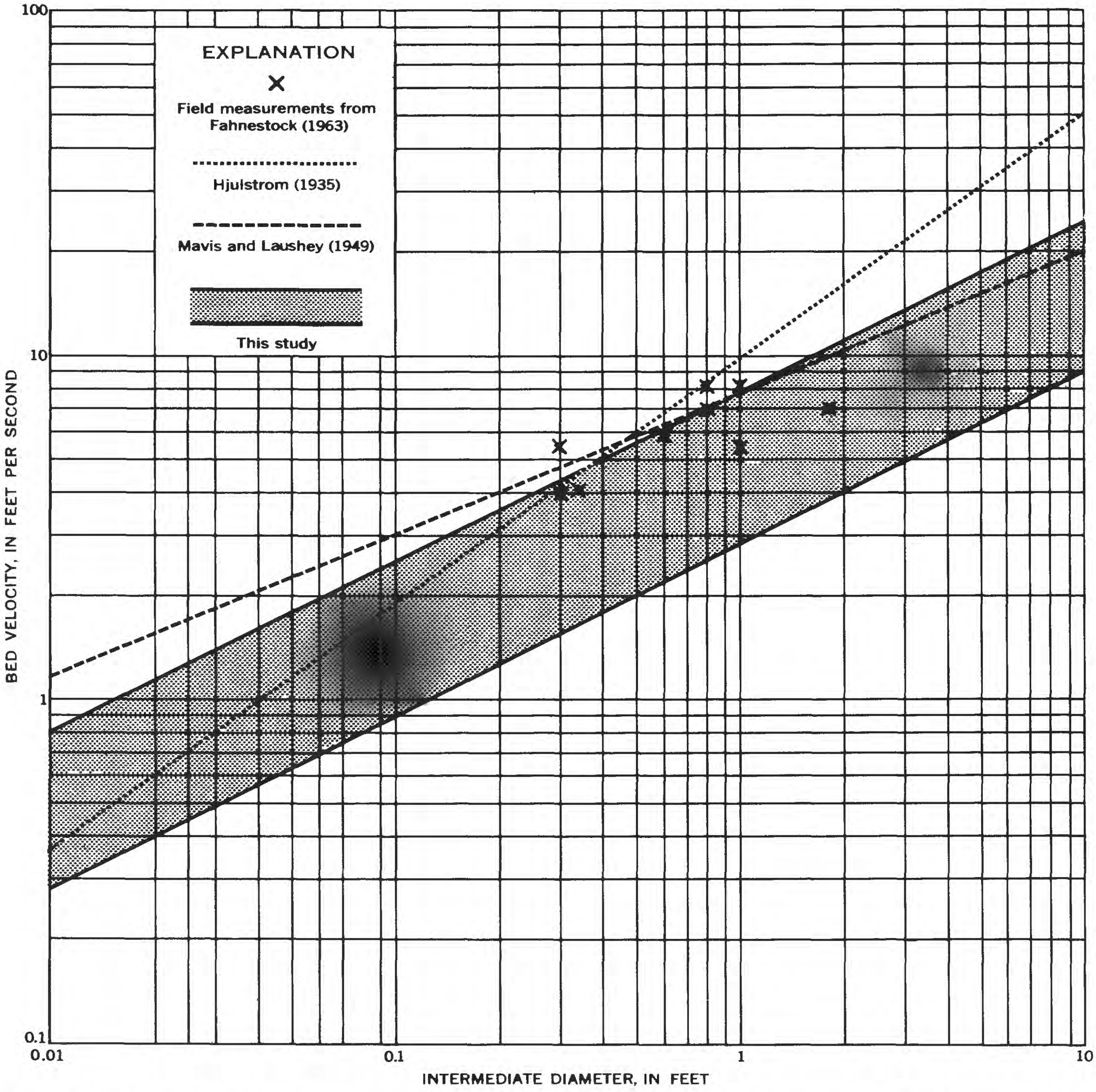


FIGURE 10.—Comparison of previous studies relating bed velocity to particle size with present study. In the present study, particles are initially at rest.

station downstream to its mouth (fig. 1) indicated that during the period of this study there was active erosion of the flood debris stored in the channel.

CROSS-SECTION SURVEYS

Seven cross sections were surveyed annually for 3 consecutive years (1965–67) at a reach extending about one-quarter of a mile downstream from the gaging station (fig. 1). Each cross section, spaced about 200 feet apart, was marked by steel reinforcing bars, which made relocation from year to year accurate. A tag line was stretched from each section end, and elevations were measured with a level. Elevations were determined at intervals of 10 feet along each section. Figure 11 shows these seven sections as viewed downstream. Most noticeable is an increase in cross-section area during the study period which was caused by an increase in depth. As expected, width changed only slightly because most of the side slopes are exposed bedrock of sandstone and shale. The thalweg profile of this reach

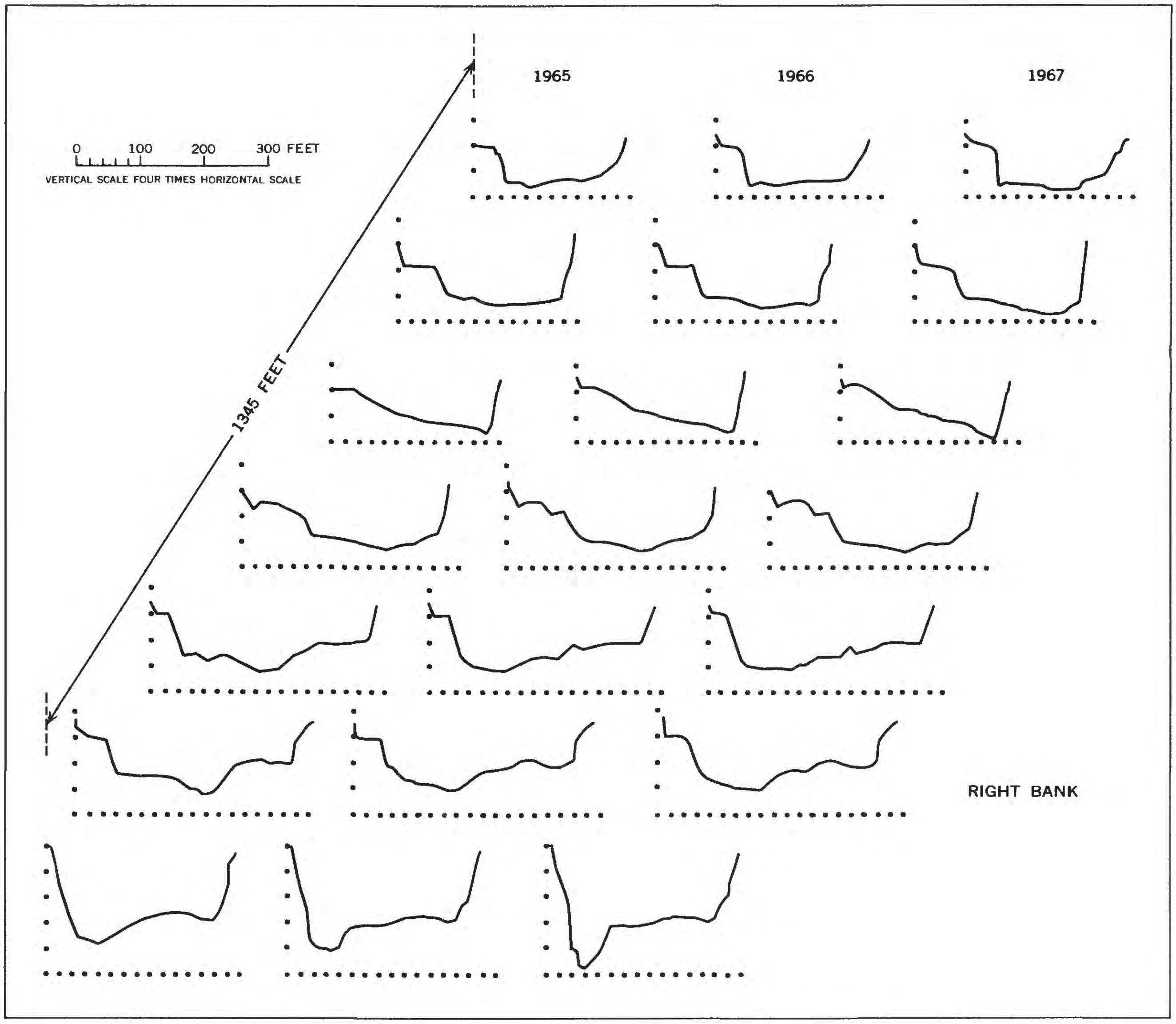


FIGURE 11.—Low-water cross sections, Blue Creek gaging-station reach.

shown in figure 12 clearly indicates that most of the increase in depth occurred during the rainy months of November through March of 1966–67, three seasons after the record flood of December 1964. Only one section shows a decrease in depth, a decrease that is very slight. Perennial streams with gravel beds commonly tend to scour over relatively long reaches (Leopold and others, 1964, p. 234). Although the net degradation over the gaging-station reach is not surprising, it is indicative of the ability of Blue Creek to move rapidly large volumes of coarse material supplied to the channel.

TOPOGRAPHIC SURVEYS

The cableway test reach half a mile downstream from the gaging station was surveyed in 1966 and again in 1967. Both surveys were done during summer low-flow periods and were used to describe the net change in the 450-foot-long test reach during the study period. The areal distribution of bedrock and bed material of various sizes according to the Wentworth scale are shown (with the topography) in figures 13 and 14. The distribution of bed material is generalized and indicates that the areas mapped are overlain mainly by the indicated size. The most noticeable change from 1966 to 1967 is in flow direction (shown by large arrows) which was caused by local scour of as much as 3 feet along the left bank. Lesser scour along the right bank has exposed additional bedrock underlying the channel. Particle size increased from pebbles to cobbles and boulders in the downstream portion of the test reach.

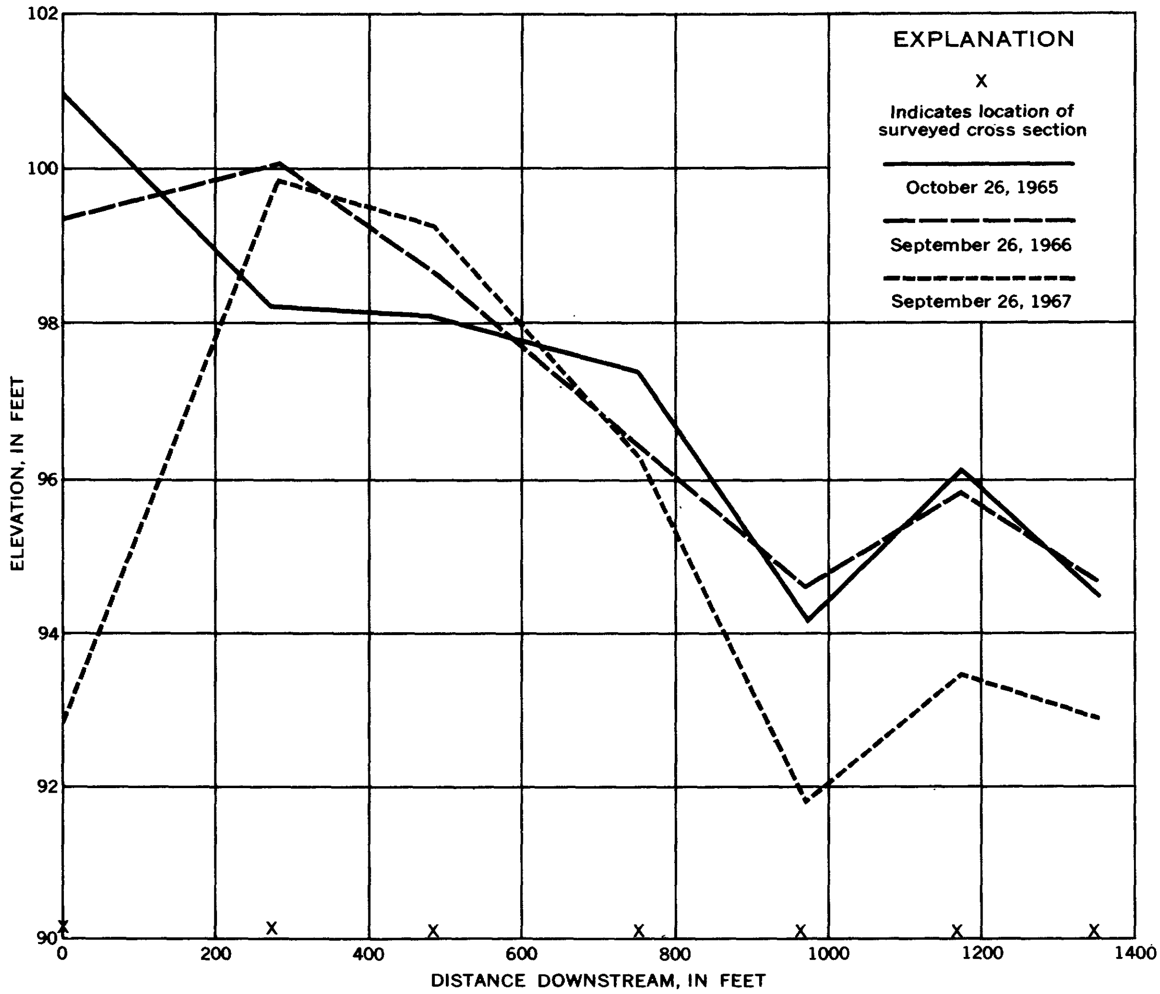


FIGURE 12.—Thalweg profiles of a reach of Blue Creek extending approximately one-fourth of a mile downstream from the gaging station.

Figure 15 shows the change in streambed topography and the net degradation that occurred during the study period. The volume removed from the test reach was determined by planimetry of an area bounded by the upper and lowermost cross sections. The removal of approximately 2,800 cubic yards resulted in an average bed-elevation decrease of 1.2 feet.

CONCLUSIONS

The bed velocities necessary to initiate motion of coarse bed material, as calculated from a theory which considers particle size, shape, specific gravity, and orientation angle agree well with those determined by field observation. The initial movement seems to depend more on particle size and shape than on specific gravity and orientation angle. In fact, difference in specific gravity from 2.65–3.10 is almost completely compensated by difference in shape.

Present data also suggest that threshold velocities necessary to move coarse material exists for at least 5 percent of the time in Blue Creek.

Field data were collected on channel changes and were completed during a degradational phase of channel adjustment. Long reaches of the channel of Blue Creek have degraded considerably since the December 1964 flood, and most of the degradation occurred during the rainy season of 1966–67—three seasons after the flood. Cross-sectional and topographic surveys indicated that approximately 2,800 cubic yards of material were scoured from a 450-foot-long reach of Blue Creek between September 29, 1966, and September 29, 1967. This demonstrates the ability of perennial mountain streams, such as Blue Creek, to transport very coarse debris.

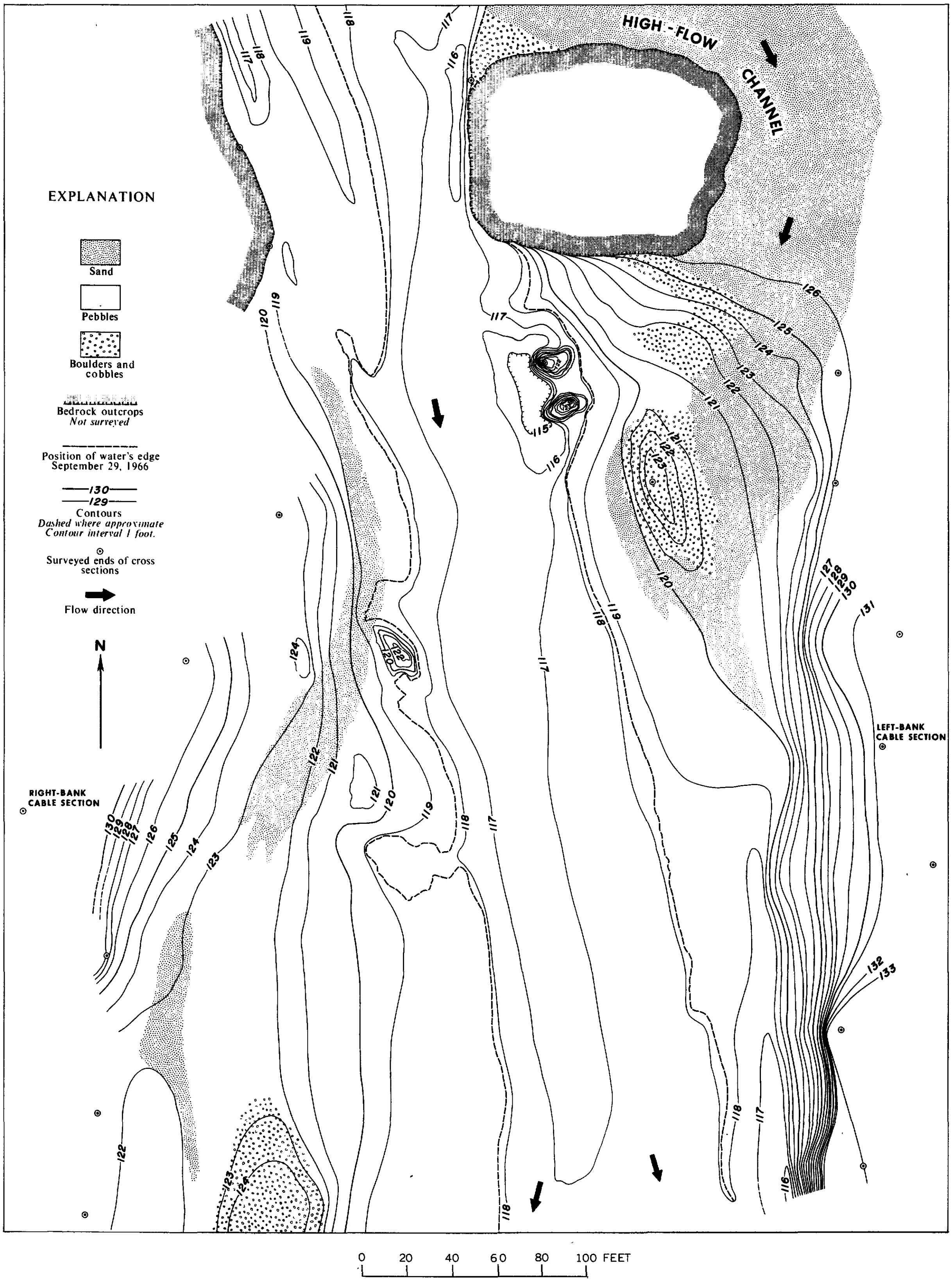


FIGURE 13.—Cable-section reach of Blue Creek, 1966.

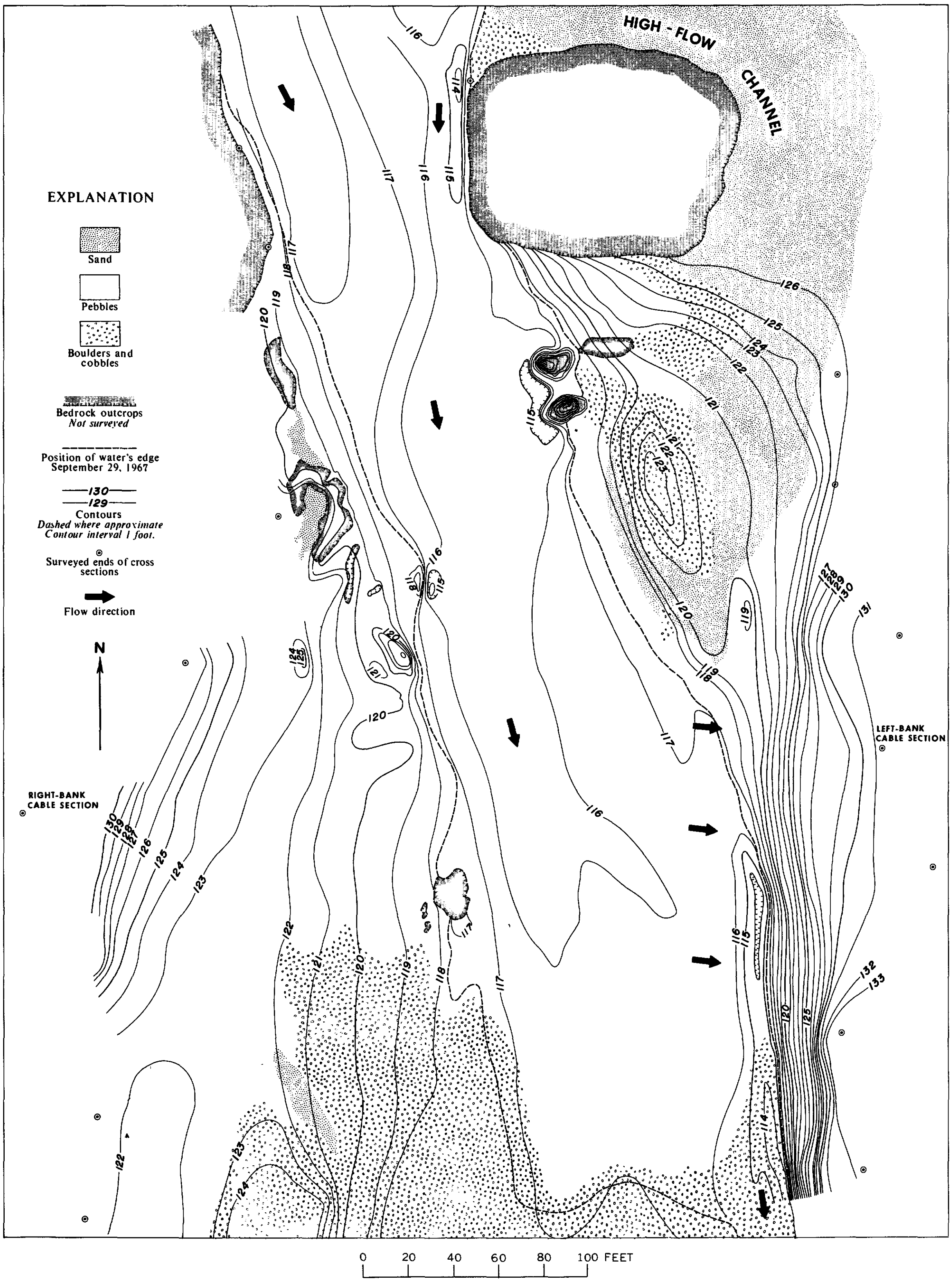


FIGURE 14.—Cable-section reach of Blue Creek, 1967.

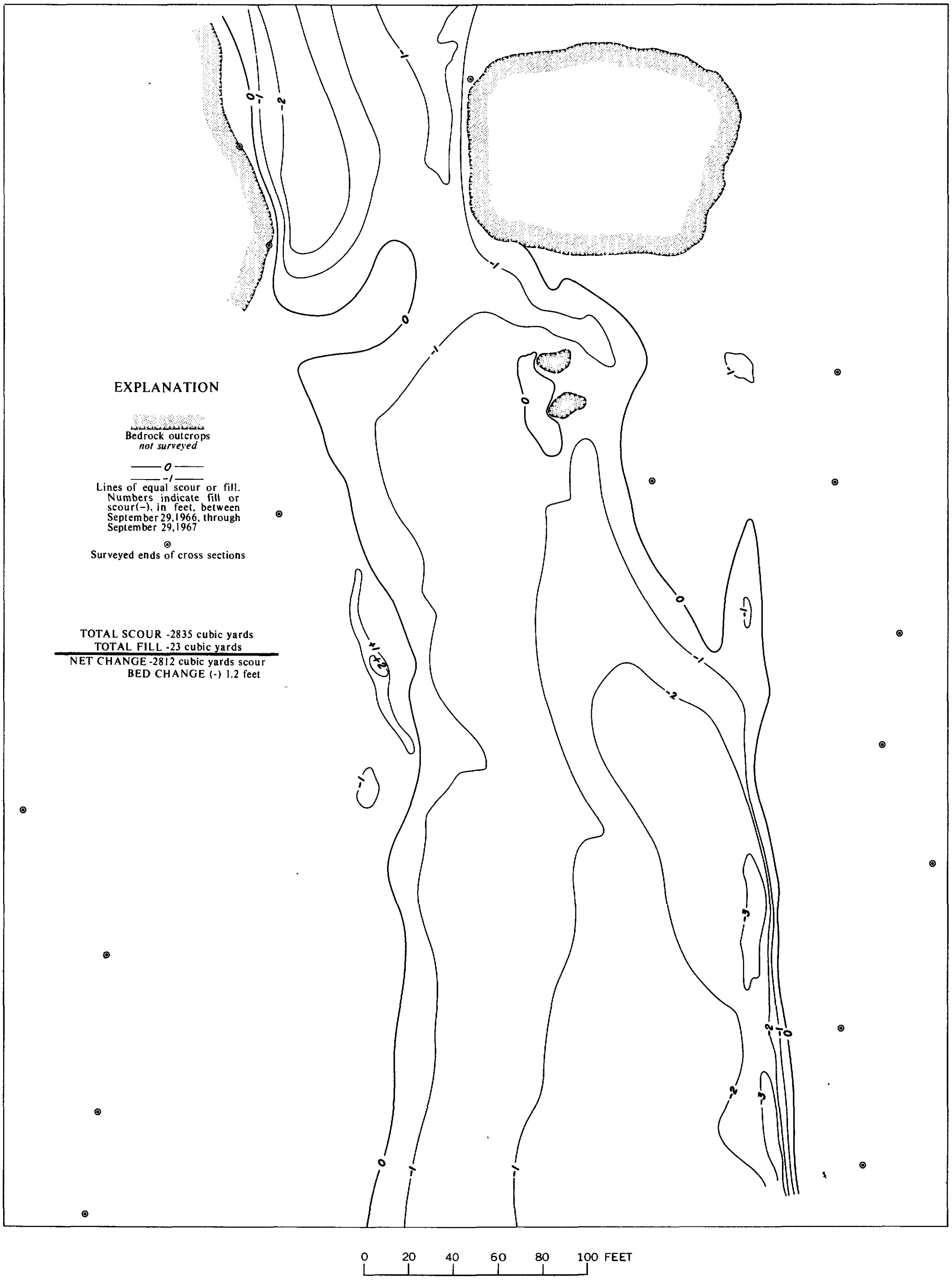


FIGURE 15.—Cable-section reach of Blue Creek, showing change of streambed topography, 1966–67.

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