FORM AND FLUVIAL PROCESSES OF DRY CREEK, NEAR WINTERS, CALIFORNIA

BY

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Form and Fluvial Processes of Dry Creek,
Near Winters, California

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B.S. (Fresno State College) 1965

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Geology

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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ABSTRACT

Lower Dry Creek near Winters, California, is an intermittent, entrenched, meandering stream with sinuosity greater than two. The channel material is primarily derived by bank caving as the meanders move laterally.

In Dry Creek two kinds of pools, primary and secondary, are differentiated by relative scour and channel morphology. Mean pool-riffle spacing of 5.9 times channel width in straight and curved reaches inclusive; 6.1 in curved reaches, and 5.7 in straight reaches is similar to that found by Leopold, _et al_. (1964). The number of secondary pools is directly proportional to the channel length between consecutive primary pools.

Direct observation confirms the conclusion drawn from "at-a-station hydraulic geometry" that bed-load material cannot be moved at all stages. Bed-load movement experiments indicate that as much as 68 percent of the variability of the distance a bed-load particle will move can be explained by the variability of the bottom velocity in the vicinity of the particle and by the particle's specific gravity, median diameter, weight in water and volume. The experiments also indicate that movement of particles through pools is more influenced by differences in particle parameters, whereas movement through riffles is more influenced by differences in bottom velocity.

The Hypothesis of Velocity Reversal, presented herein, seems adequate to explain the areal sorting of channel material, i.e., relatively large material in riffles and relatively finer material

in pools. The theory is based primarily on measured observations that with increasing discharge, the average bottom velocity of the pool increases faster than that of the riffle until at very high flow the average bottom velocity of the pool exceeds that of the riffle.

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INTRODUCTION

Purpose

Fluvial processes and channel form of Dry Creek were investigated to facilitate better understanding of how streams move and sort bed-load material, and to determine how pool-riffle spacing is associated with channel form. More detailed phenomenological studies of natural streams such as Dry Creek are necessary before we can understand how streams work.

Methods

Field and office work was carried out from February to July 1969. Bed-load movement and areal sorting was studied by analyzing stream gage data, by measuring bottom velocities, and by random sampling of the bed material. Channel form and pool-riffle spacing was determined by making a detailed topographic map of the stream bed and by measuring the pool-riffle spacing by stadia with a surveyor's level. The experimental data on bed-load movement was analyzed by an IBM-7044 digital computer, using simple linear and multiple linear regression models.

Previous Work

Bed-load movement in streams and flumes has been investigated by G.K. Gilbert (1914), W.W. Rubey (1937), R.A. Bagnold (1966), and many others. Channel form and pool-riffle spacing has been studied by L.B. Leopold and M.G. Wolman (1957), and Leopold *et al*. (1964). Hydrological data from a stream gage on Dry Creek was collected by the U.S. Bureau of Reclamation (1959-1969).

Acknowledgements

The writer is indebted to Dr. Charles G. Higgins for serving as chairman of the thesis committee and especially for his encouragement, suggestions, and criticism of this study. Appreciation is also extended to Dr. Donald O. Emerson and Dr. Roy J. Shlemon for serving on the thesis committee and for their helpful suggestions.

The writer acknowledges the help of Mr. John Sullivan in the field survey; Mr. Dave Chipping for his help and ideas in the area of sediment transport; Mr. John Uribarri for assistance in writing the necessary computer programs; Mrs. Ruth Darden and Mrs. Nancy Herman for help in drafting the illustrations; Mr. John Harris of the U.S. Bureau of Reclamation for the stream gage data; Mrs. Beverly Howard for the typing of this report; and Mrs. Marjorie Sholes for her greatly appreciated administrative help. Special thanks are extended to Mr. George Stotts for access to the area studied on Dry Creek.

Financial cost of this study was partially borne by a University of California Dean's Grant and UC Computer Center grants.

A final thanks goes to my wife, Jackie, for her never-ending encouragement throughout the investigation.

SOURCE AREA

General Description

The Dry Creek Drainage Basin is located in the eastern foothills of the California Coast Ranges approximately 30 miles west of Sacramento, California (Figure 1). The basin covers about 17 square miles, and is approximately 9 miles long and 1/2 - 3 miles wide (Figure 2). Altitudes in the basin range from about 125 feet to 2,200 feet. About 65 percent of the area lies below 1000 feet.

According to local ranchers, upper Dry Creek (Enos Creek) is largely fed from springs, and flows from the first rain until midsummer. Stream-gage data from the station one mile above the junction with Putah Creek shows that lower Dry Creek has measured flows 16 percent of the time between November and April, with an average of 29 flow days per year. This indicates that Dry Creek is an intermittent rather than ephemeral stream because it receives a significant amount of water from springs during the winter and early summer, when the stream channel in the upper reaches is below the water table.

From its headwaters to the gaging station one mile upstream from the junction with Putah Creek, Dry Creek is unaffected by dams or any other artificial controls. Below the gaging station farmers have tried to control the lateral movement of the stream by stacking junked cars or cement blocks on the outside of bends. This control has helped protect the almond and apricot orchards adjacent to the stream.

Vegetation

At the lower elevations, below 200 feet, the predominant vegetation consists of almond and apricot orchards, row crops, and grassland. The creek banks support a few widely spaced oaks and small groves of cottonwood trees. Intermediate elevations of 200 - 600 feet are characterized by grassland with abundant oak and digger pine along the creek. At

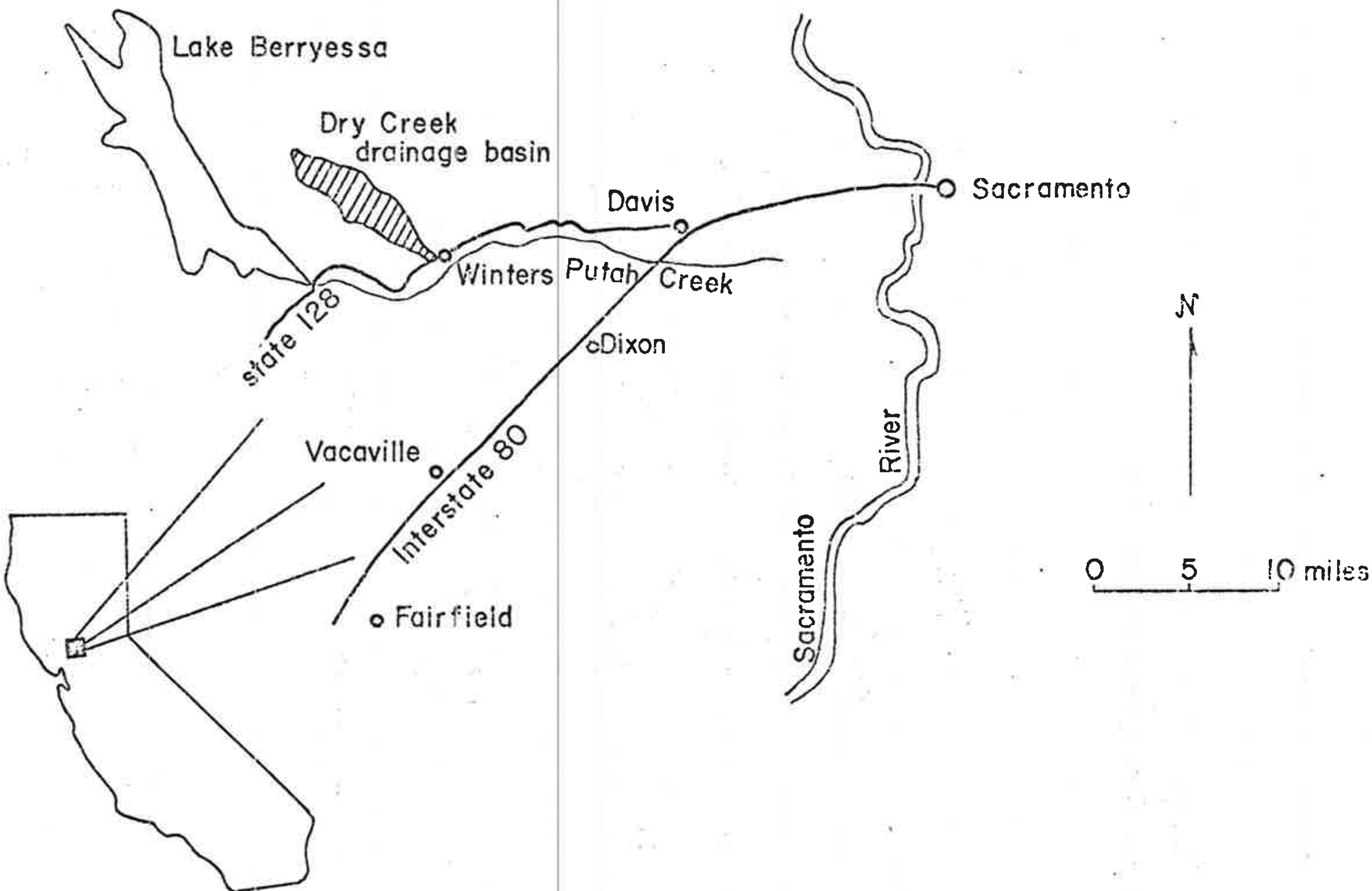


Fig. I. Index map to Dry Creek drainage basin

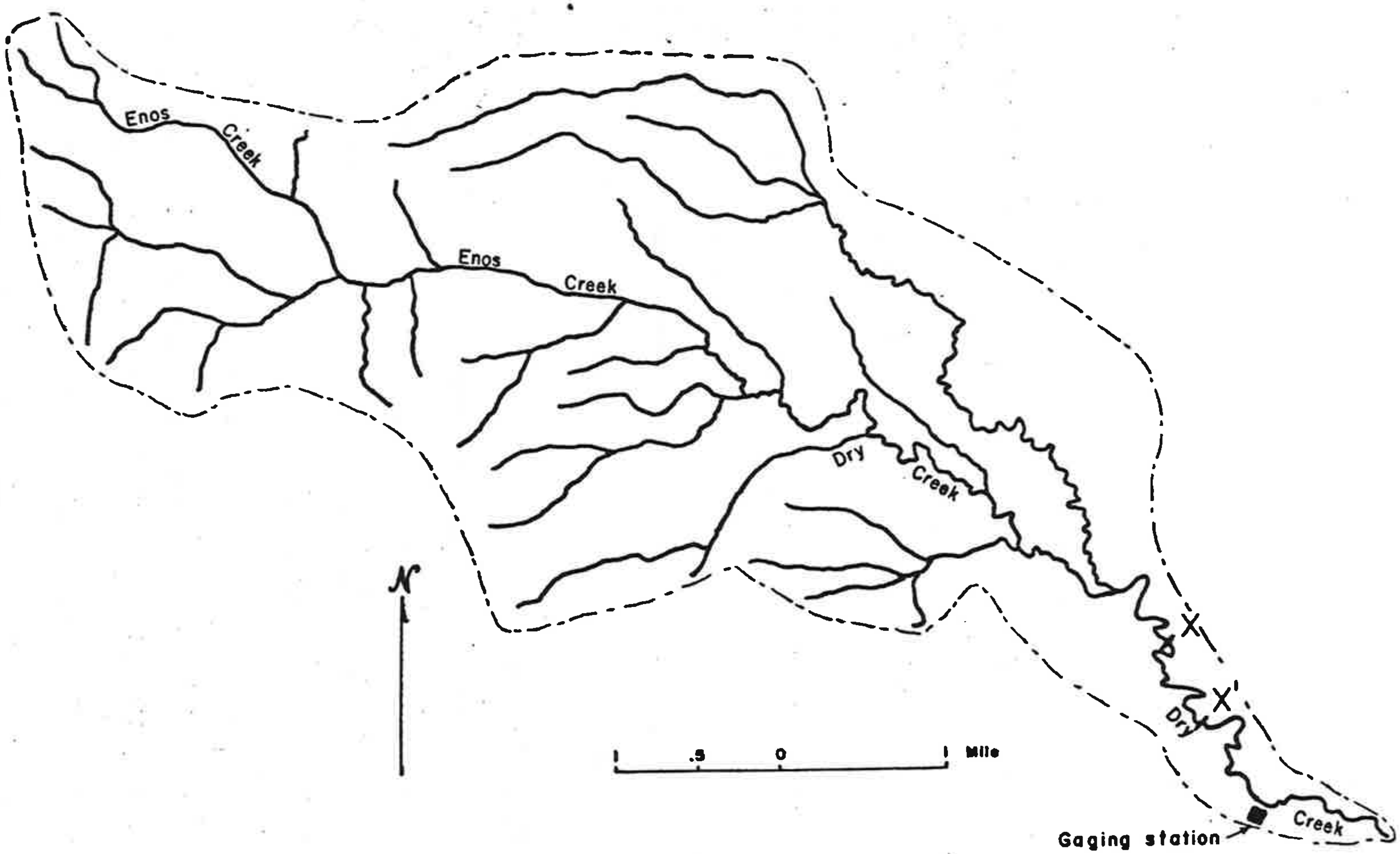


Fig. 2. Dry Creek Drainage Basin (16.8 square miles). X-X' is shown in greater detail in Fig. 5.

elevations greater than 600 feet the vegetation is a mixture of grassland and oak and digger pine woodland.

Climate

The Dry Creek Drainage Basin has a Mediterranean climate, with winter rains from November to April, followed by a long summer drought. U.S. Weather Bureau records for water years 1960-69 at Winters, California, show a mean rainfall of 20.64 inches a year, of which greater than 90 percent falls from November to April (Figure 3). Mean monthly temperature varies from the low eighties (°F) in July and August to the low forties (°F) in December and January. The lowest and highest temperatures range from below freezing in the winter to over 110°F in the summer. Summer temperatures, however, do not ordinarily exceed 100°F for more than a few days at a time. Winter temperatures rarely fall below 20 - 25°F.

General Geology

The generalized geologic map of the Dry Creek Drainage Basin (Plate I) shows the following stratigraphic units, from youngest to oldest: (1) alluvium, (2) Tehama formation and related continental sediments, (3) volcanic and sedimentary rocks (Thomasson *et al*., 1956). A brief description of the units is given on the geologic map.

The Dry Creek Drainage Basin can be divided into two geomorphic units: (1) the Coast Ranges, characterized by high relief; and (2) low foothills and dissected alluvial uplands of the Sacramento Valley, with relief ranging from 10 to 300 feet. Rocks which crop out in the Coast Range part of the basin are primarily Upper Cretaceous sandstones, shales,

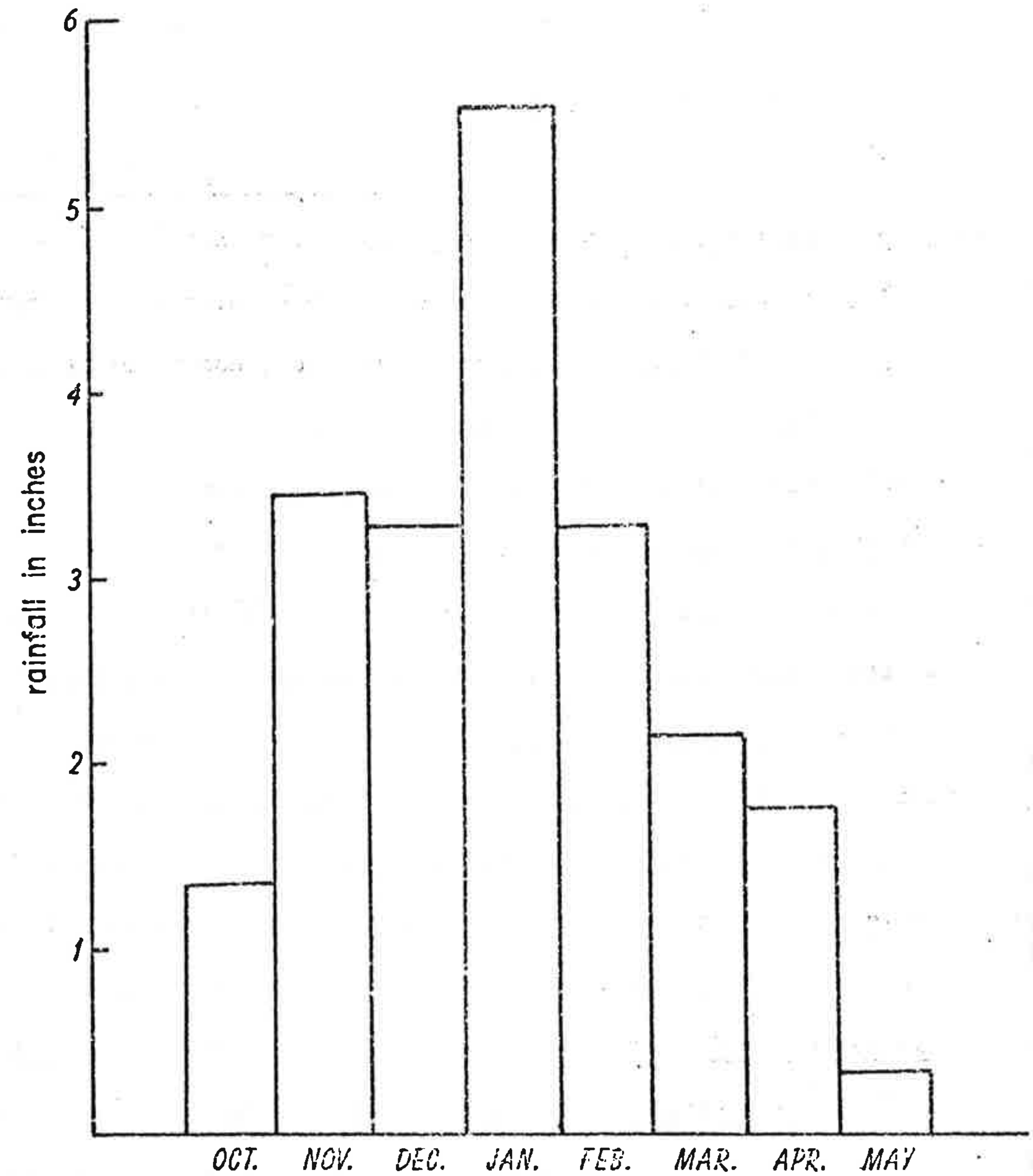


Fig. 3. Dry Creek mean monthly rainfall, water years 1960-69.

and conglomerates (Division of Water Resources, 1955). The low hills and dissected alluvial uplands in the basin are underlain by Tertiary and early Quaternary semi-consolidated alluvial sediments. A topographic break between the Coast Ranges and lower hills generally follows the contact between the Tehama Formation and underlying Cretaceous rocks (Thomasson et al., 1956).

Entrenchment of Lower Dry Creek

From Putah Creek to the gaging station one mile upstream, Dry Creek is entrenched approximately 25 feet into a gently undulating alluvial surface that is probably part of a compound fan of semi-consolidated, older Dry Creek and Putah Creek alluvium. The fan material is characterized by poorly delineated channels and overlies semi-consolidated Tehama sediments into which Dry Creek occasionally bottoms. Near Winters there are several older broad-channel banks above the present entrenched channel of Dry Creek which may indicate that Dry Creek was considerably wider before entrenchment than it is today. The entrenchment gradually decreases upstream (see sections on Plate 2) to about 10 feet two miles above the gaging station. The entrenchment is probably due partly to man's influence and partly to structural controls.

Putah Creek's channel was first diverted in the later part of the 19th Century. A story in the Woodland, California, Daily Democrat of November 6, 1968, states that in 1871 or 1872 farmers diverted Putah Creek as a flood control measure. A 100-foot wide, 6-foot deep channel is said to have been cut with slip scrapers pulled by horses and Chinese laborers. The article does not state where the channel was started, but it supposedly ended east of Davis. Thomasson et al. (1956) state that in the 1890's an artificial channel was cut with teams and fresno scrapers in Putah Creek three miles southwest of Davis. The channel then ran for four miles along a section line. The old channel, located 13 miles downstream from Winters, is now cut off by a flood-control levee, and the artificial channel is 15-20 feet lower than the old channel at the bifurcation. If it can be assumed that farmers did lower the base level of Putah Creek by 6 - 20 feet in the latter part of the 19th Century, then it might be expected that the base lowering would influence the upstream tributaries. The longitudinal profile of lower Dry Creek (Plate 2) does show a change in slope near the mid point of the profile that may represent a nick point resulting from downcutting due to the artificial lowering of the base level of Putah Creek. Some of the entrenchment might also be due to scour and resulting lower base level of Dry Creek below Monticello Dam. Scouring below the dam, however, is probably much less significant in terms of entrenchment of Dry Creek than is the earlier base lowering of Putah Creek.

Entrenchment of lower Dry Creek might also be partly attributed to structural control. If the two faults north and southwest of Winters (Plate I) are active, then lower Dry Creek could be entrenched upon a rising fault block. The fault north of Winters was first postulated by Bryan (1923). Marginal steepening of the strata becomes attenuated to the north, suggesting that the fault is a hinge fault whose displacement increases to the north (Thomasson et al., 1956). However, conclusive evidence for recent large scale fault movement is lacking.

The long profile of Dry Creek (Plate 2) is, in effect, convex upward. The reason for this is not completely understood, but it may suggest structural control of the channel. A straight line extension of the channel above the nick point (Plate 2) to the mouth at Putah Creek indicates 50-60 feet of entrenchment. This is twice the actual entrenchment at the mouth and may indicate that the surface into which the stream is entrenched must also have been convex up. This suggests slow upwarping or faulting across the stream.

The prevalence of bank caving in the lower few miles of Dry Creek has produced a bed load in which particle size does not significantly decrease in the downstream direction. Leopold and Miller (1956) found that less rapid decrease in bed-particle size in the downstream direction is associated with less concave upward profiles. Thus the slightly convex upward longitudinal profile of lower Dry Creek may owe in part to the fact that bed particles do not decrease in the downstream direction.

Upstream from the nick point the entrenchment continues to gradually lessen to about 10 feet. A large oak tree in the channel bottom approximately one mile above the nick point (Figure 4) indicates that with the exception of 6 feet of pool scour at the base of the tree, the channel has been relatively stable during the life of the tree.

CHANNEL FORM

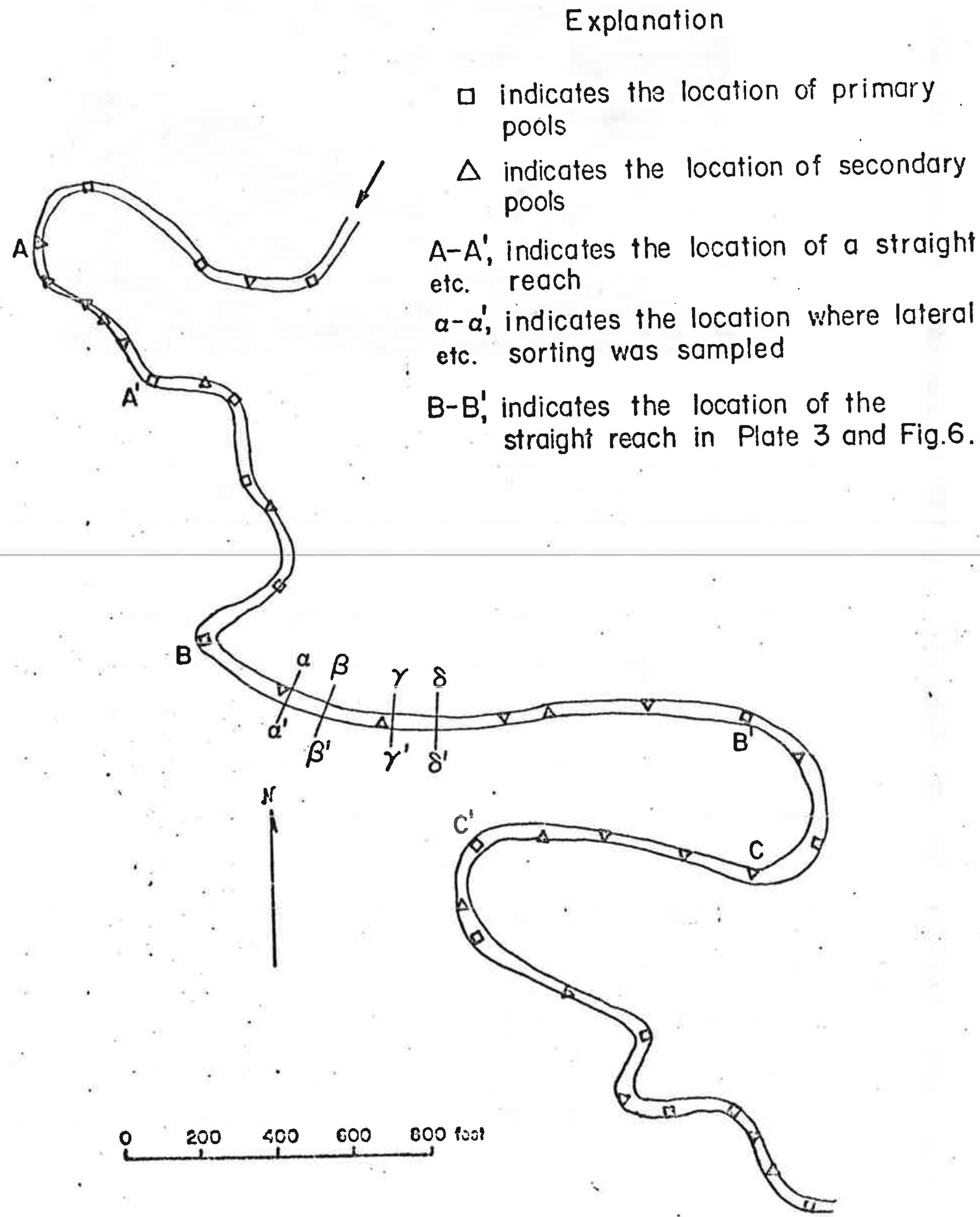
General

Dry Creek is an entrenched meandering stream with sinuosity (ratio

Figure 4. Oak tree indicating relative channel stability during the life of the tree. The location of the tree is in the vicinity of B in Figure 5.

of channel length to downstream valley distance) of about two. Leopold et al. (1964, p.281) define a meandering stream as having a sinuosity greater than 1.5. Streams with sinuosity less than 1.5 are designated as straight or sinuous. Leopold et al. (1964) have suggested that a channel should have a degree of symmetry in curvature before it is considered meandering, but to date symmetry has not been used as a criterion. Meandering channels, however, can have both straight reaches and braided reaches. Dry Creek has no braided reaches, but there are straight reaches; Figure 5 shows three straight reaches in about 1.3 miles of channel. All three straight reaches have length greater than ten times the channel width. This is considered rare by

Fig. 5. Portion of Dry Creek map showing location of pools. Location of the reach is shown by X-X' in Fig. 2.



Leopold and Wolman (1957).

Dry Creek meanders vary from long to short loops and generally lack symmetry. Wave lengths measured along the channel for 1.3 miles (Figure 5) vary from 20 to 59 times the channel width, with an average of 32 times the channel width. This is about twice that measured by Leopold _et al_. (1964), and by Brice (undated letter). The long wave lengths are probably a function of entrenchment and channel morphology. Dry Creek bank material is fairly cohesive and rapid entrenchment has developed a relatively low width to depth channel ratio. Thus stream width combined with long straight reaches in some meander loops is probably responsible for the relatively greater wave lengths in Dry Creek meanders.

For this report channel width is considered to be the width of the channel covered by bed material, measured at right angles to the channel banks. Dry Creek has very steep banks, so the width as defined above is probably nearly the bankfull width of Leopold _et al_. (1964). Channel widths determined from air photographs of Dry Creek tend to be greater than those measured in the field. These differences as measured for large streams would probably not be great, but with streams the size of Dry Creek (25-35 feet wide), the difference is significant.

Bed Forms

The predominant bed forms in Dry Creek are the gravel bar and associated pool and riffle sequence. Bed material in the creek is largely pebble and cobble gravel. Leopold _et al_. (1964) state that where gravel size bed materials are abundant the bar and pool-riffle sequence is the most common bed form.

At low flow pools are recognized by smooth slow water. At high flow pools are areas of fast current and scour. Pools are generally separated from other pools by lobate bars called riffles. The bars or riffles generally slope alternately first toward one bank and then toward the other. Pools also tend to alternate from one bank to the other, but there are exceptions. The bed material is significantly larger on the bars and riffles than in the pools. At low flow riffles can be recognized by shallow fast water flowing over a slope greater than that of the adjacent pools. The pool, at low flow, is simply a topographic depression which fills up and spills over a riffle to the next pool downstream. At high flow the pool-riffle sequence is "drowned out", and the water surface has a nearly constant slope. These observations on Dry Creek are consistent with those made on the pool-riffle sequence by Leopold *et al*. (1964).

In Dry Creek it is necessary to distinguish two types of pools which I have designated primary and secondary pools. Primary pools are those that show deep scour (often to bed rock), are generally found on bends, and are always associated with a point bar. Where the primary pool is on a bend, the point bar is on the inside of the bend and generally slightly upstream of the pool. Secondary pools are those that are scoured much less than the primary pools and are not always associated with a point bar. The bed profile (thalweg) of Figure 6 shows a series of pools, starting with a primary pool on a bend and progressing through a straight reach containing secondary pools. The pools alternate

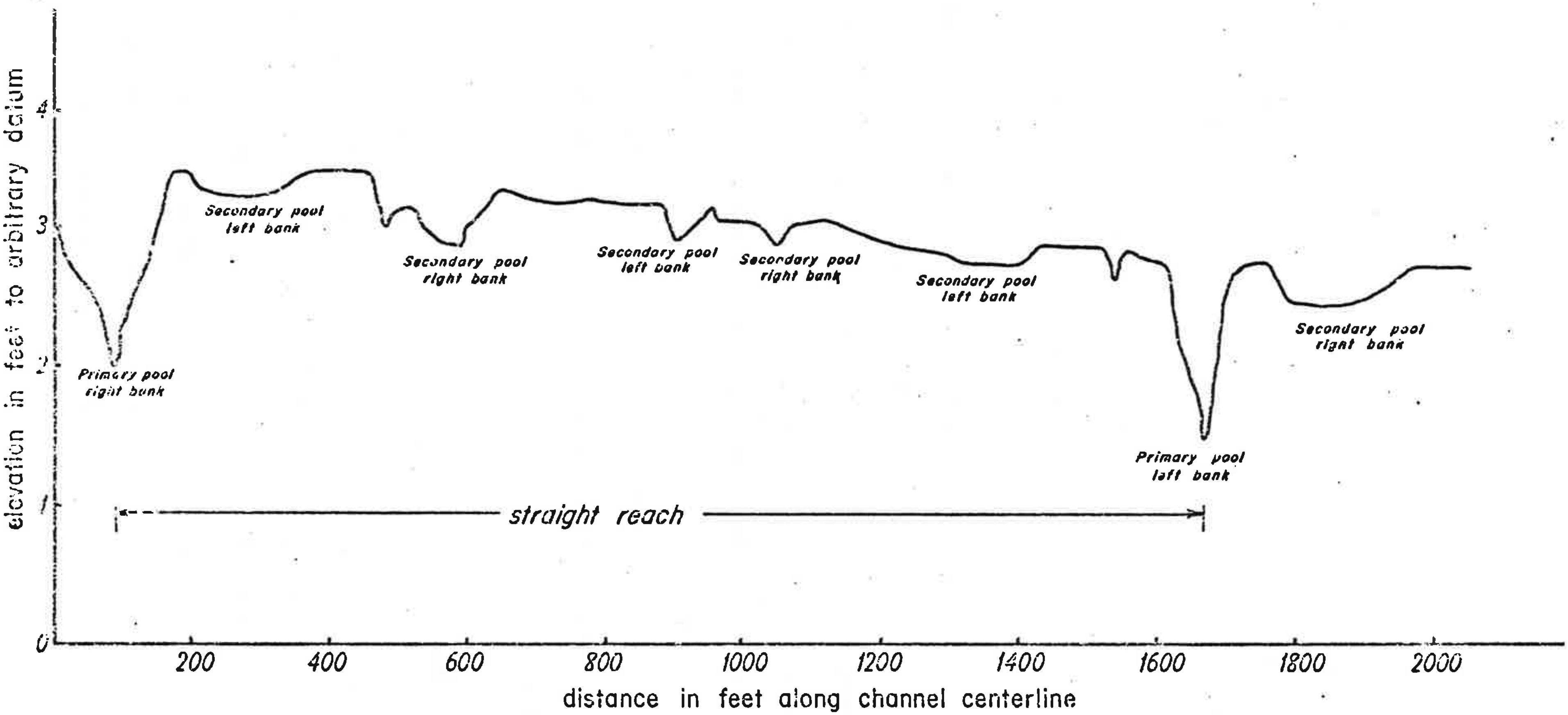


Fig. 6. Bed profile (Thalweg) of mapped channel, Dry Creek. The location of this reach is shown by B-B' in Fig. 5.

from bank to bank and the primary pools are significantly deeper than the secondary pools.

Bedforms that might be remnant antidunes were observed on the bottom of a long shallow secondary pool. One set of these forms was observed at low flow and measured when flow stopped. Each form has a wave length of about 15 cm and an amplitude of 0.5 cm (Figure 7). The surface of the trough is covered by sand and fine gravel (intermediate diameter 1-3 mm), and the crests contain finer sand, 0.5-1.0 mm in diameter. Since the fines are not distributed as a thin layer over the entire surface, it is assumed that they are not the result of a waning current. The sediment size is larger than commonly found in fluvial ripples. Wentworth (1967) describes a dish structure of 4-50 cm in length in turbidite deposits that shows reverse grading in the troughs. He postulated that the dish structure formed during the upper flow regime in antidune flow, and that the reverse grading is a result of grain dispersion. The Dry Creek structures of 15 cm are comparable in size and form.

Pool-Riffle Spacing

Pool-riffle spacing in Dry Creek was measured with a surveyor's level for 1.3 miles along the channel and by planetable surveying for 0.27 miles of straight channel. The distances measured were from center point to center point of consecutive pools. The deepest point in the pool was considered the center point. This helps remove some of the subjectivity of deciding where the pool or riffle starts or stops, and the periodicity is not affected so long as a consistant reference point

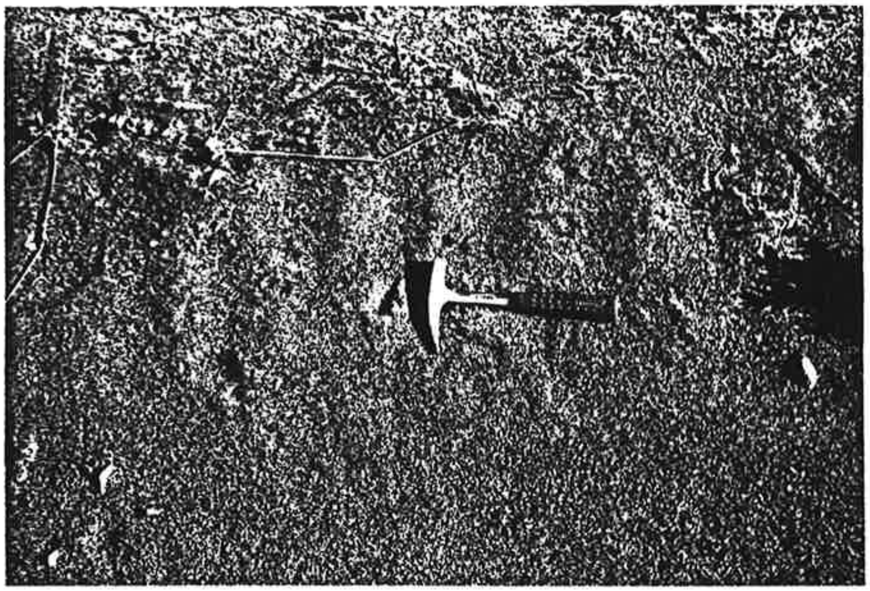


Figure 7. Possible remnant antidunes. Downstream to the right.

is used.

The 1.3 miles of measured channel (Figure 5) has a sinuosity of 2.4 and would be considered meandering by Leopold et al. (1964). The stretch contains both straight and curved reaches. In this stretch the average spacing of pools was 5.9 times the channel width for the straight and curved reaches inclusive, 5.7 for the straight reaches, and 6.1 for the curved reaches. These results generally agree with the 5 to 7 times channel width value proposed by the same authors. The similarity of the pool-riffle spacing in the straight and meandering reaches of Dry Creek may indicate that the same mechanism is operating in both as suggested by Leopold et al. (1964). In Dry Creek, however, the mean meander wave length, measured along the channel, averages 4 to 5 times the pool-riffle spacing, compared to a ratio of 2 obtained by Leopold et al. (1964).

The distribution of pool-riffle spacing (Figure 8) shows that although the mean spacing is 5-7 channel widths, the most frequent spacing for all types of reaches is 3 to 5 times the channel width. More than 80 percent of the pools are 3 to 9 channel widths apart, but only about 25 percent are 5 to 7 channel widths apart. The significance of the skewed distribution of pool spacing is largely unknown. Hypothetically, the abundance of pools in the 3-5 channel widths spacing and relative absence of pools at greater than 9 channel widths spacing might suggest that pools are not initiated at less than 3 channel widths and are unstable at greater than 9 channel widths. This highly hypothetical relationship suggests that once pools are initiated they tend to increase the spacing until new pools are added.

A portion of Dry Creek channel surveyed approximately 2 miles above the gaging station, shows a straight reach between two primary pools on meander bends (Plate 3, Figure 5). The secondary pools between the bends alternate from one bank to the other. The mean pool-riffle spacing in this reach is about 7 times the channel width.

The number of secondary pools between primary pools in Dry Creek is a function of the mean spacing and channel length between primary pools. The above function is shown graphically in Figure 9. The coefficient of correlation of 0.94 is high and a Student's "t" test of significance for n=15 at n-1 degrees of freedom yields a value of t=4.43

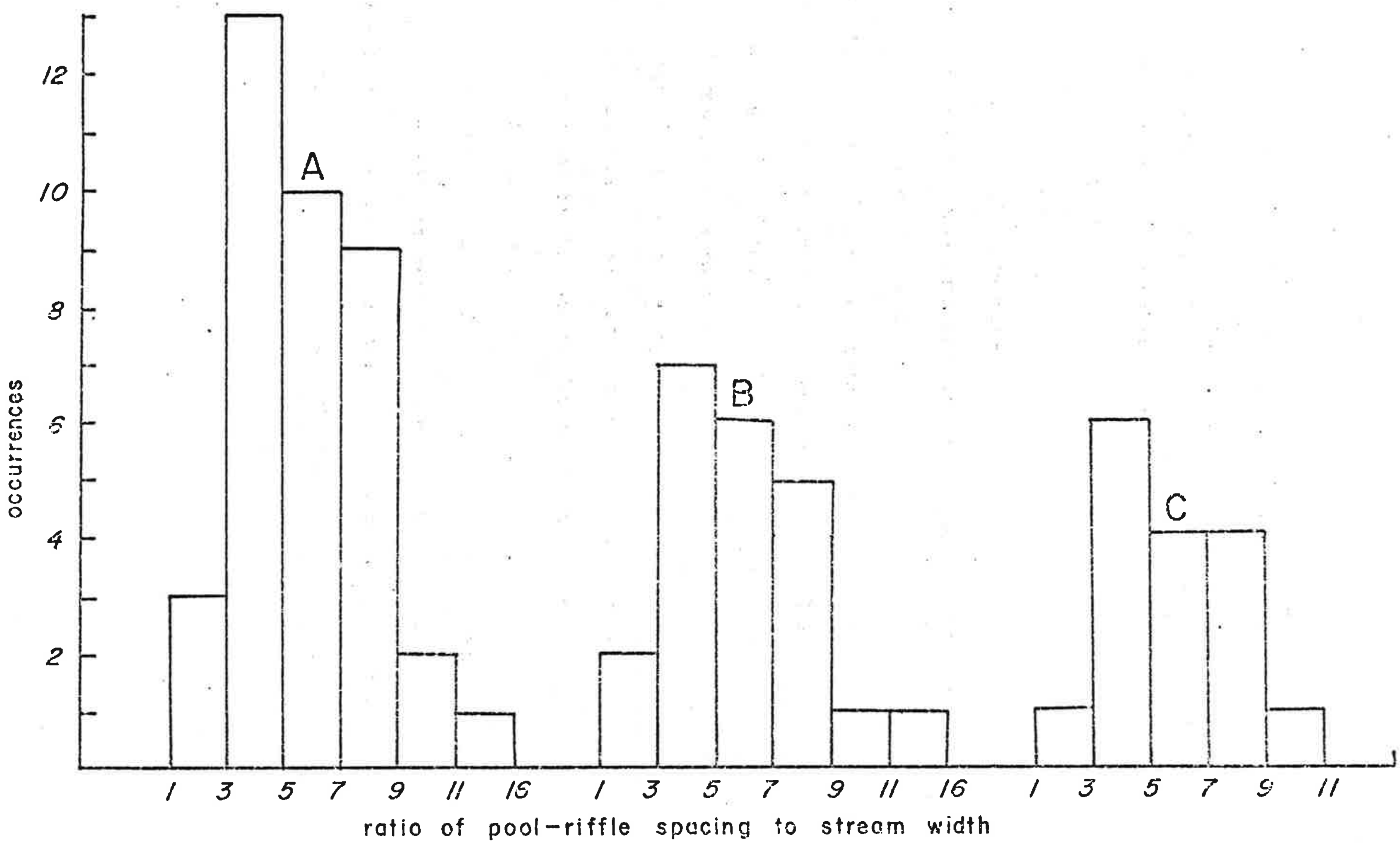


Fig. 8. Relationship of pool spacing to stream width for: A, straight and meandering reaches inclusive, B, meandering reaches, and C, straight reaches

which sets the confidence level at 99 percent. Figure 9 also suggests that when there are no secondary pools between consecutive primary pools, the spacing is 3 to 5 channel widths, and when there is one secondary pool between consecutive primary pools, the spacing is also 3 to 5 channel widths. This supports the idea that secondary pools may be initiated with spacing of about 3-5 channel widths.

The channel distance between primary pools in Dry Creek changes as the meander bends move laterally or the radius of curvature increases. Either of the above can lead to the formation of new secondary pools to maintain the mean pool-riffle spacing of approximately 6 times the channel width. Most of the channel lengthening in Dry Creek is due to lateral migration of meanders. A small scour area about 70 feet upstream from the downstream primary pool on Plate 3 is spaced at about two channel widths from the adjacent pools and will probably become a secondary pool as the meander continues to move laterally.

Information on the rate of lateral migration of meander bends in Dry Creek is scarce, but Mr. George Stotts, a local rancher, states that the fence shown in Figure 10 was on solid ground two years ago. It is now about 14 feet out over the stream. Allowing for some original curvature of the fence, the rate of lateral movement of this bend is about 2-3 feet per year for the past several years.

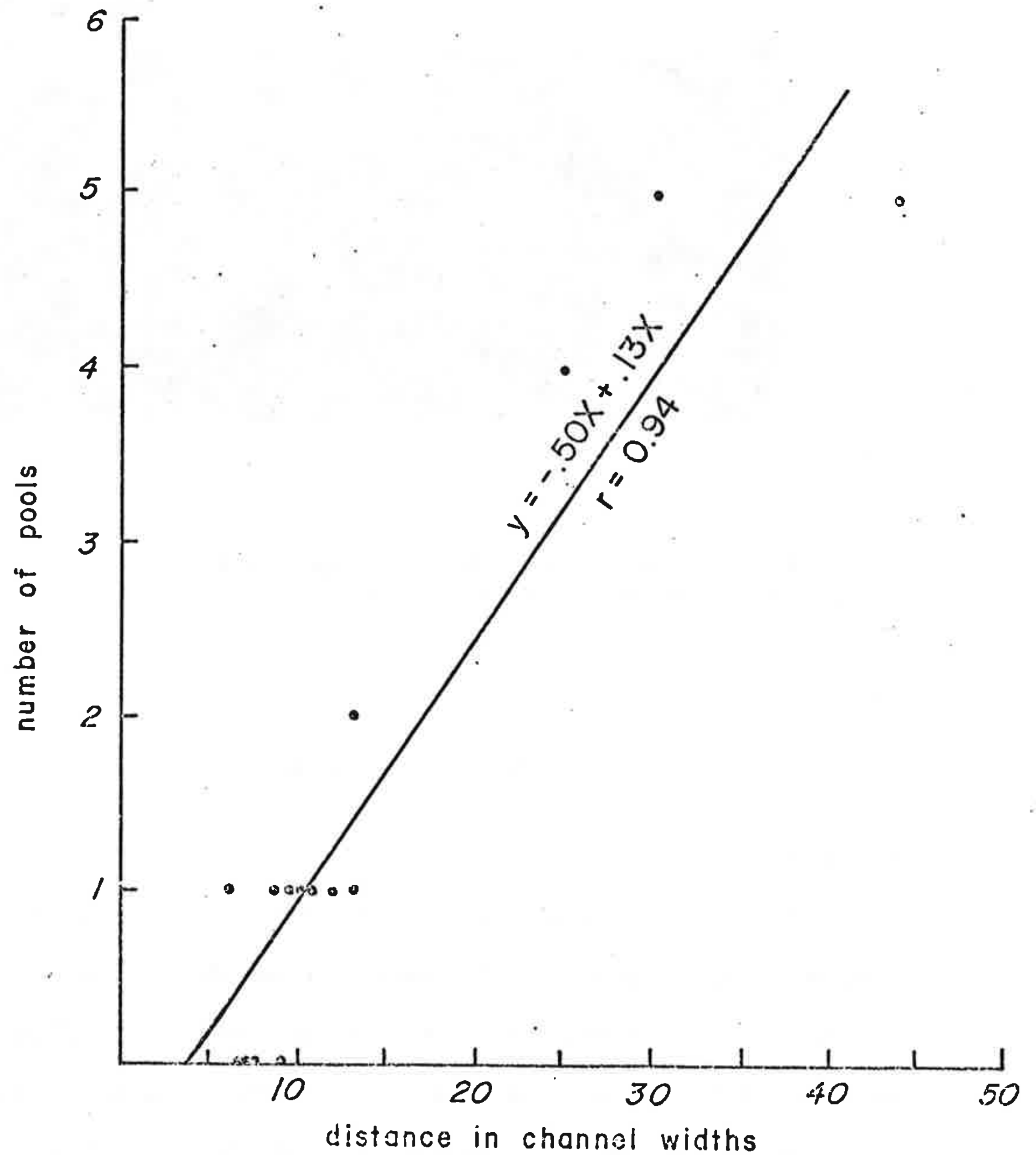


Fig. 9. Number of secondary pools between consecutive primary pools as a function of distance between consecutive primary pools in channel widths.

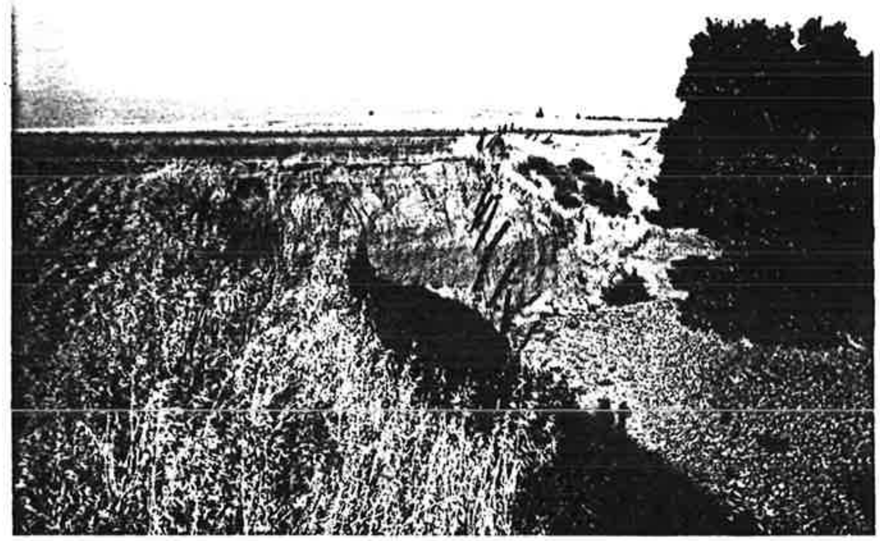


Figure 10. Hanging fence indicates recent lateral movement of meander bend in Dry Creek. View is to the southeast.

HYDRAULIC PARAMETERS

Streamflow

The only stream gaging station presently operating on Dry Creek is located approximately one mile upstream from the junction with Putah Creek. The station was established in early November 1958 by the U.S. Bureau of Reclamation. The gage is a recorder model A35-28199, and is sheltered by a wooden box. An outside staff (1.0' to 10.0') is attached to the stilling well (Figure 11). The recorder is run by a weight-driven clock, and produces a continuous record. Intake pipes project out of

Figure 11. Stream gage on Dry Creek during high flow. February, 1969.

the well and allow water to reach a float which, as the stream rises and falls with stage, moves a pen resting on a clock-driven chart. The resulting chart is called a hydrograph. On Dry Creek the record is collected and the recorder wound once a month.

The discharge and runoff data used in this report were obtained from Surface Water Monthly Reports for Dry Creek near Winters, California, 1960-69 (U.S. Bureau of Reclamation). Discharge measurements by Mr. John Harris of the U.S. Bureau of Reclamation indicate that the stream channel shifts considerably, and because of this, control is poor. Adjustments are made to the rating table by periodic field measurements of discharge and channel shift. The values of discharge obtained during the highest flows are estimated by extrapolation of the rating curve.

Figure 12 shows mean monthly discharge (runoff) for water years 1960-69. The water year is considered to be from 1 October to 30 September. The maximum runoff in January probably reflects the high rainfall in that month, and the rather high runoff in February to April is facilitated by a previously saturated drainage basin.

Dry Creek has measured flow 16 percent of the time from November to April, and averages 29 days of flow a year. Rare flows in October and June have been recorded. The nature of the flow in the vicinity of the gaging station is flashy--i.e., very sharp rise and fall of discharge with time. Discharge varies with storm strength and periodicity, and contribution by springs. The flashy nature of the discharge during a series of storms in February 1969 is shown on the hydrograph of Dry Creek (Figure 13). During the 18-day period, it rained 11 days (U.S. Department of Commerce climatological records for Winters, California). The largest storm was on February 15 and produced 2.24 inches of rain. The maximum discharge for the period was recorded on February 15 following the storm. On February 24, after intermittent rain since February 15, another high flow occurred. The 24 February rainfall of 0.76 inches was probably amplified by a previously saturated drainage basin to produce the high flow. A smaller peak flow on February 28 resulted from a saturated basin and 0.62 inches of rain.

Floods have long been considered as important geomorphic events. High flows can be considered as random occurrences because the meteoro-

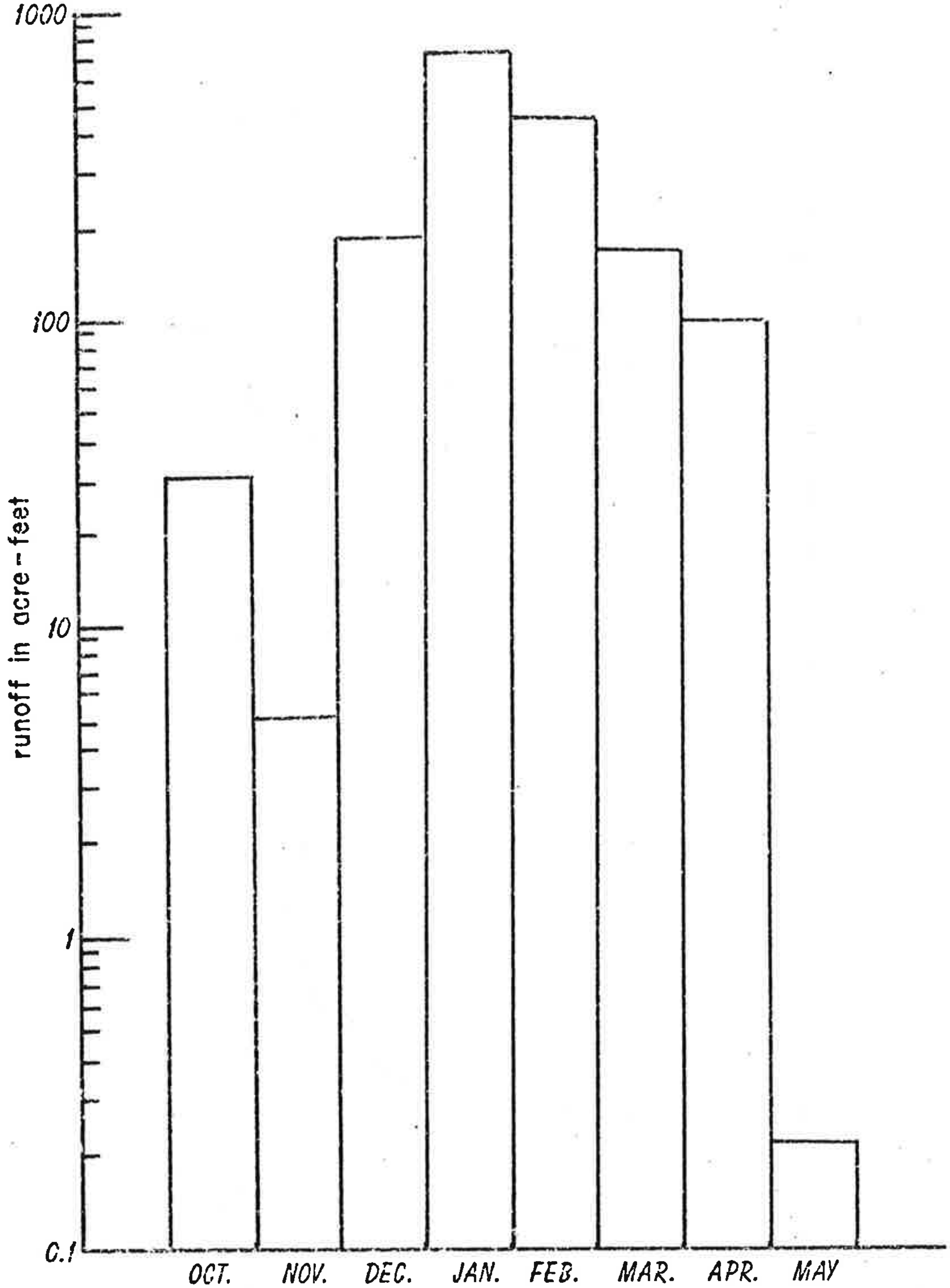


Fig.12. Dry Creek mean monthly runoff, water years 1960-69.

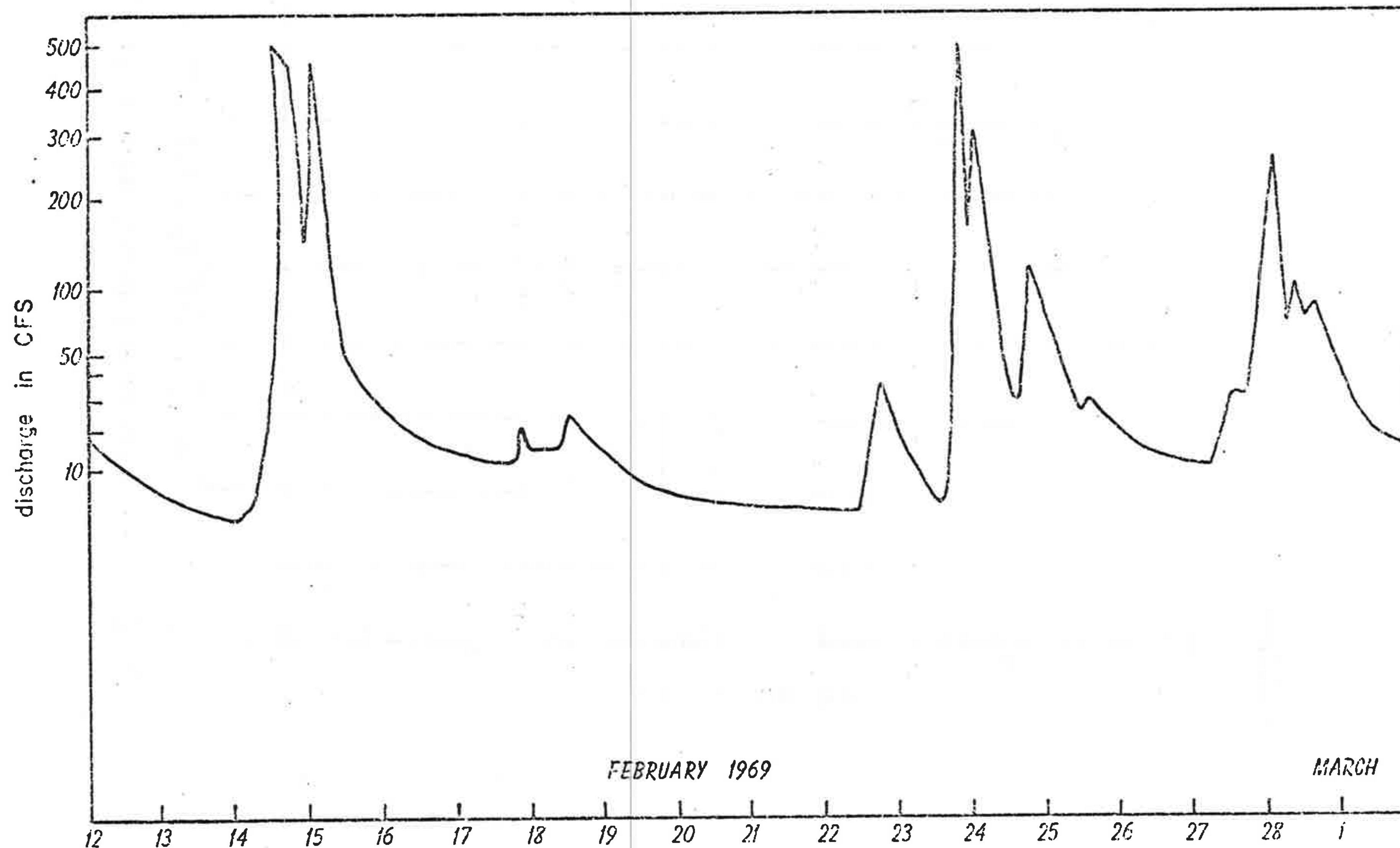


Fig. 13. Hydrograph of Dry Creek, February 12 to March 1, 1969.

logical and hydrologic factors that control floods vary with time sufficiently that the possible combinations are random events (Leopold, Wolman and Miller, 1964). The several methods available to compare flood frequency for a given station all assume that floods of a certain magnitude occurring over a given time are a valid sample of an infinitely large population (Helley, 1966). The method used in the study of Dry Creek is the Annual Series as described by Lindsley, Kohler and Paulhus (1958). This method ranks floods in numerical order (highest = 1). The Annual Series ranks the highest peak discharge in each water year. The order of frequency (return period) is then computed by the formula T = N+1/M where T is the recurrence interval in years, N is the number of years of record, and M is the rank of the flood. The Annual Series, with return periods, is shown in Table 1. It has been shown that the mean annual flood has a recurrence interval of 2.33 years. A recurrence interval of 2.33 means that, on the average, every 2.33 years the highest discharge of the year will equal or exceed the mean annual flood (Lindsley, Kohler and Paulhus, 1958). The mean annual flood for Dry Creek at the gaging station, computed by interpolation of Table 1, is 785 C.F.S.

When the annual runoff and rainfall are ordered by numerical ranking (highest = 1), it can be seen (Table 2) that in wet years with rainfall above normal, the runoff is directly related to the amount of annual rainfall. However, in dry years (orders 6-9 of Table 2), runoff is probably more closely related to storm frequency and strength than to total annual rainfall. This is because in dry years only closely

Table 1. Frequency Analysis of Annual Floods, Dry Creek near Winters, California.

Water Year Nov.-April	Month	Day	Discharge CFS	Annual Floods Order M	Return Period, yr.
1960-61	Jan	31	125	9	1.1
1961-62	Feb	14	958	4	2.5
1962-63	Jan	30	996	3	3.3
1963-64	Jan	21	316	7	1.4
1964-65	Dec	22	449	5	2.0
1965-66	Jan	5	364	6	1.7
1966-67	Jan	21	1090	2	5.0
1967-68	Jan	30	274	8	1.2
1968-69	Jan	26	1360	1	10.0

Table 2. Comparison of Runoff and Rainfall, Dry Creek Drainage Basin near Winters, California.

Water Year Nov.-April	Runoff in Acre-feet	Order M	Rainfall in inches	Order M
1960-61	86	9	14.07	7
1961-62	1787	5	18.96	5
1962-63	2779	3	27.71	3
1963-64	285	8	10.92	9
1964-65	2247	4	23.25	4
1965-66	517	6	14.02	8
1966-67	4805	1	33.52	1
1967-68	333	7	14.64	6
1968-69	3819	2	28.67	2

spaced storms which would saturate the drainage basins produce much surface runoff. In wet years with many storms, the basin probably never dries out and the spacing of storms is not as significant a factor in producing surface runoff.

Hydraulic Characteristics

Hydraulic characteristics at a given cross section were first described by Leopold and Maddock (1953) as "at-a-station hydraulic geometry". Mean velocity, mean depth, and width change with discharge as power functions:

$$w = aQ^b \qquad d = cQ^f \qquad v = kQ^m$$

where w is width, d is the mean depth, v is the mean velocity, and Q is discharge. The exponents b, f, and m and constants a, c, and k can be calculated from stream gage data used to formulate the rating curve. A simple logarithmic transformation where $\log W = \log a + b \log Q$ can be solved by linear regression to yield the constant a and slope b. The exponents b, f, and m have been used by Leopold _et al_. (1964) to describe the geometry of the channel and the resistance to erosion of the bed and banks. When the channel material can be moved at all stages of discharge b will be large and f will approach zero; with a fixed bank of cohesive material, b will be low and f high (Leopold _et al_., 1964).

The data for the at-a-station hydraulic geometry of Dry Creek (Figure 14) were obtained from U.S. Bureau of Reclamation records. The values at high discharge (above 100 CFS) were not used because the measurements were probably made from a bridge approximately 100 feet upstream from the gaging station. The stream there is controlled and

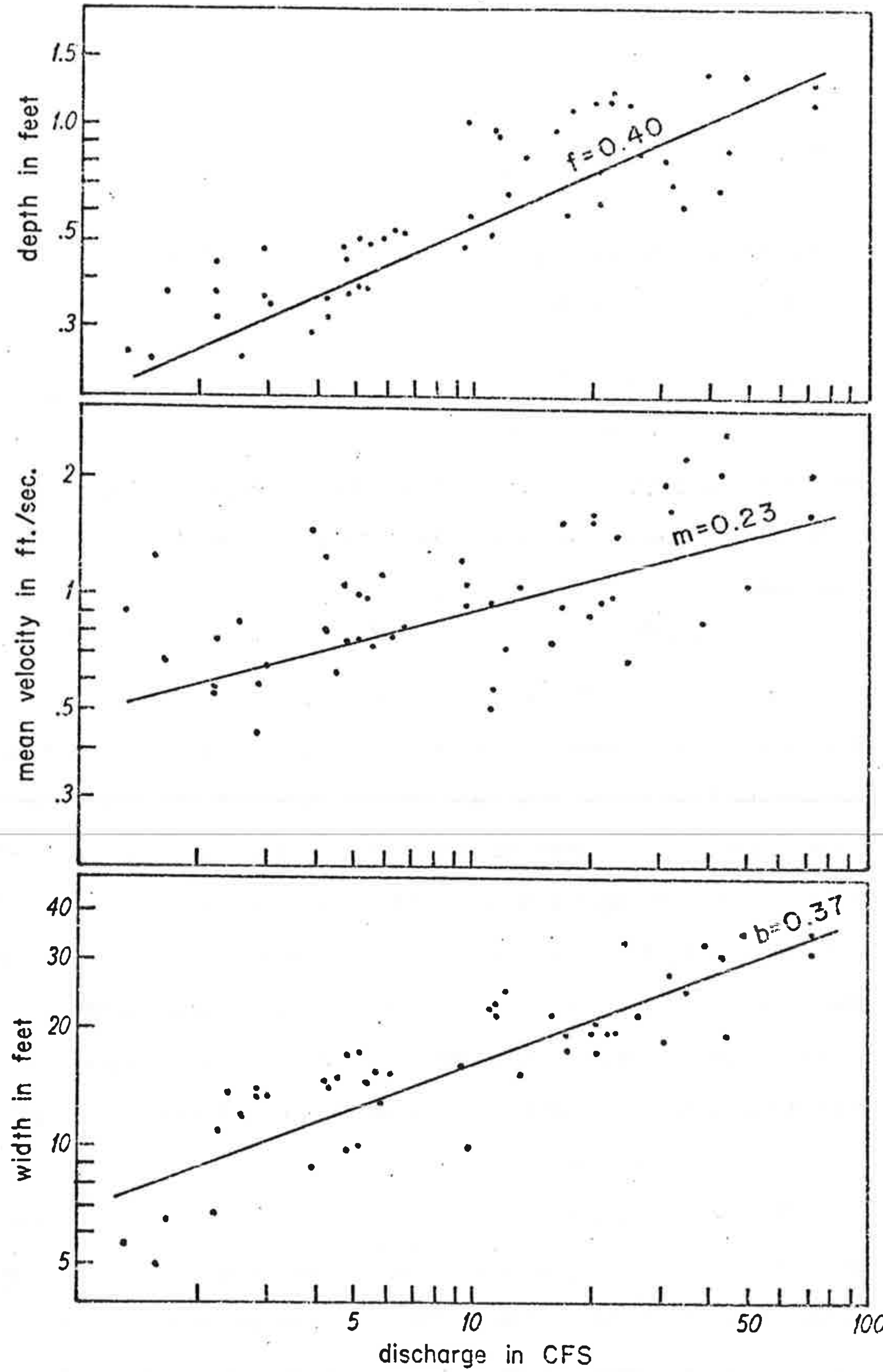


Fig. 14. At a station hydraulic geometry, Dry Creek near Winters.

the rate of change of the hydraulic characteristics is artificial. The high scatter of the graphs may also indicate that the location of the cross section used for the measurements varied a short distance up and down stream from the gaging station.

The exponential values (slope) of b=0.37, f=0.40, and m=0.23 may indicate several channel characteristics: 1) The relatively high value of f may indicate that channel material cannot be moved at all stages of discharge, but only at high flow. This was confirmed by observation. 2) The relatively high values of b and f may indicate that the steep banks of Dry Creek lose some cohesiveness when saturated. Field observations confirm that the banks do lose some cohesiveness when water loosens the clay cement that holds most of the bank material together. The loss of the clay cement facilitates bank caving, although the banks are still cohesive enough so that lateral widening of the channel is not rapid.

SEDIMENT TRANSPORT

General

Sediment transport in the Dry Creek Drainage Basin begins with downslope movement of weathered rock material to the channel network. Sheet wash and bank caving are the primary processes which contribute sediment to the lower few miles of Dry Creek. The former contributes primarily fines while the latter is responsible for most of the pebbles and cobbles in the bed load.

Sheet wash is most significant where natural grasses have been replaced by row crops and orchards. In the latter areas large amounts of fine sediment (silt and clay) were observed moving downslope into the channel during a storm. In vegetated areas containing natural grasses the amount of surface runoff is very small and little sediment is transported downslope by sheet wash.

Bank caving during high flow in Dry Creek is very common, and most of the large material in the bed load is probably derived from this process. Figure 15 shows a large block (approximately 8 feet in diameter) of semi-consolidated conglomeratic alluvium which was undercut by stream action and slumped into the channel. Figure 16 shows the same block after the flow receded; much of the block was broken up and added to the bed load by stream action.

Bed-Load Movement Experiments

The primary objective of the bed-load movement experiments in Dry Creek was to determine the relative importance of bottom velocity and bed-load particle parameters such as shape, volume, specific gravity, weight in water, and A-C axis ratio in movement of bed-load material. A secondary objective was to investigate the movement of bed-load particles through the pool-riffle sequence.

The experiments were conducted in February and early March, 1969. The area selected was a straight reach which has a well-developed pool-riffle sequence (Plate 3, B-B' in Figure 5).

The section lines of Figure 17 were surveyed and 134 samples of the bed material were randomly selected at one foot intervals along the

Figure 15. Bank caving 200 feet below the gaging station before a high flow on February 15, 1969.

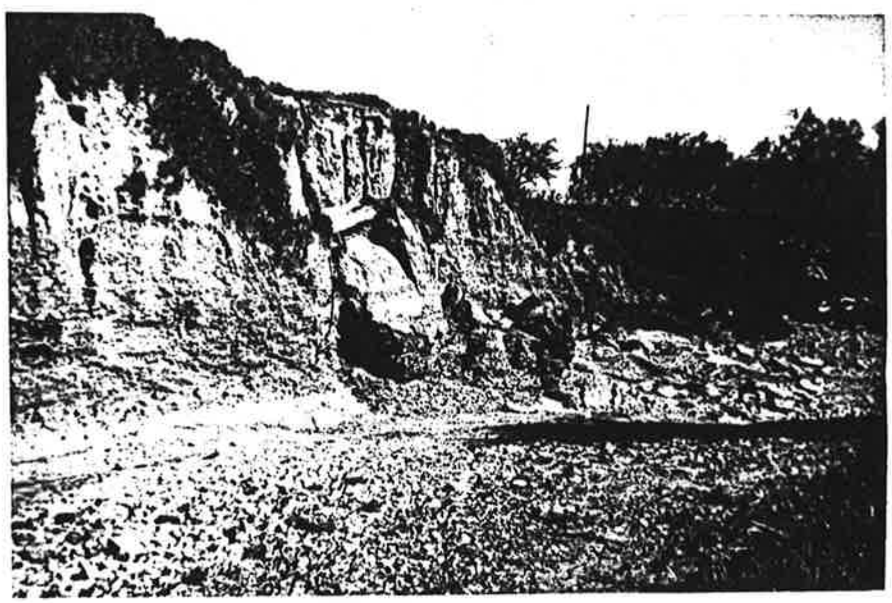
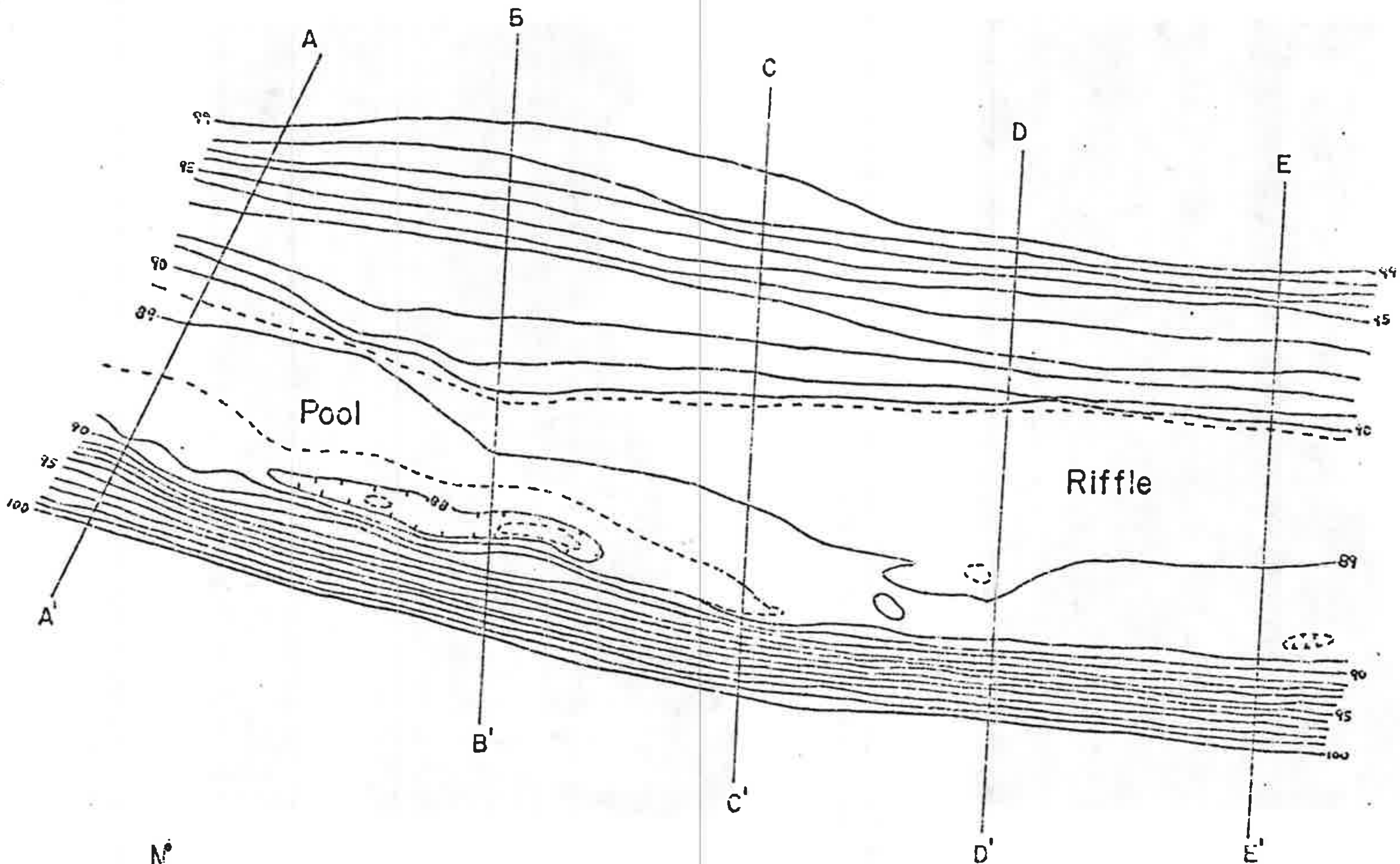


Figure 16. Eroded block of bank material after a high flow on February 15, 1969.



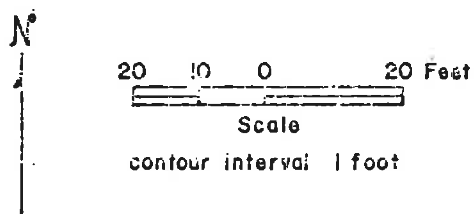


Fig. 17. Dry Creek pool-riffle sequence. Section lines indicate area where bed-load material was sampled and bottom velocity measured. The location of this area is in the vicinity of $\gamma-\gamma'$ in Fig. 5.

section lines. At the time of sampling there was very little flow and no bed material was moving. The samples were numbered in the field and their position recorded. They were then taken to the laboratory where they were weighed, measured, and painted. Yellow oil-base enamel was used to paint the rocks, and the sample location number was painted on in black. The rocks were then placed back in the stream in their original order and location. This was to ensure that the natural sorting of the stream was disturbed as little as possible. Bed material sampled varied in size, by Wentworth's scale, from pebbles to cobbles. The painted samples remained in the stream for approximately three weeks. During that time there were two storms which resulted in high flows (February 15 and 24 of hydrograph, Figure 13). After each storm the position of the painted rocks was marked and the distance they moved was measured by telescopic alidade. Throughout the experiment, the yellow paint and black numbers remained plainly visible on most of the rocks.

The three bed-load movement experiments were:

> Experiment 1: The measured movement of painted bed-load material resulting from the storm and high flow on February 15, 1969. In this experiment 43 painted rocks were recovered.
>
> Experiment 2: The measured movement of painted bed-load material resulting from the storm and high flow on February 24, 1969. In this experiment 33 painted rocks were recovered.
>
> Experiment 3: The total measured movement of painted bed-load material resulting from the combined storms and high flows on February 15 and 24. In this experiment 76 painted rocks were recovered.

The velocity near the bed of a stream is a significant factor in bed-load movement, but particle movement is almost always compared to the mean velocity of the entire stream. Many authors have assumed that velocities near the stream bed are proportional to mean velocities, but Rubey (1937) points out that there is apparently no adequate basis for such an assumption. Bed velocity, as defined by Rubey, is the velocity at the boundary between the thin film of laminar flow on the stream bed and the main mass of turbulent water above. The bed velocity of Rubey is a function of mean velocity, hydraulic radius, slope and coefficient of friction of the stream bed. The bed-velocity concept, as proposed above, has not been readily accepted by hydrologists and engineers. Gilbert, in his classical flume experiments (1914), attempted to measure the velocity close to the channel bed. However, his attempts were not successful because the current meter rested on the bed, caused the bed material to form a hollow, and destroyed the normal velocity of the bed. Further, Gilbert stated that he regretted not being able to measure the velocity close to the bed because he believed that bed velocity was a prime factor in traction and that slope and discharge exert their influence chiefly through bed velocity.

Velocities near the bed were measured in Dry Creek. The trouble Gilbert experienced with the current meter was not encountered because the large size of the bed material in Dry Creek allowed the instrument to remain stable and not disrupt the normal velocity. A Price Current Meter (propeller type) was used to make the measurements of the "bottom velocity". The instrument is calibrated such that one revolution per second of the propeller is equal to a velocity of one foot per second.

Velocity is then measured by counting the revolutions per second. The "bottom velocity" for the purpose of this report is the velocity of the water approximately 0.05 feet above the stream bed. This is above the laminar layer described by Rubey (1937), but it is as close as the instrument will measure. The author believes that this bottom velocity is much more significant in analyzing bed-load movement than the mean velocity of the entire stream.

Figures 17 and 18 show the locations and times that bottom velocities were measured on Dry Creek. Velocity measurements were taken at 3 foot intervals along the section lines through the pool-riffle sequence (Figure 17). Weather and hazardous water conditions allowed bottom velocity measurements at only 5 stages during the experiments. On particularly wet and high-water days only two sections could be completed (one through the pool and the other through the adjacent riffle).

The independent variables used in analyzing the bed-load movement experiments are:

Volume - volume of the bed-load particle in cm^3.

Weight in water - weight in water of the bed-load particle in gm.

A-C axis ratio - ratio of longest to shortest axis of bed-load particles.

Specific gravity - ratio of weight in air to difference between weight in air and weight in water of bed-load particles.

Diameter × specific gravity - mean diameter times specific gravity for bed-load particles.

Shape - a subjective value ranging from 0.1 for

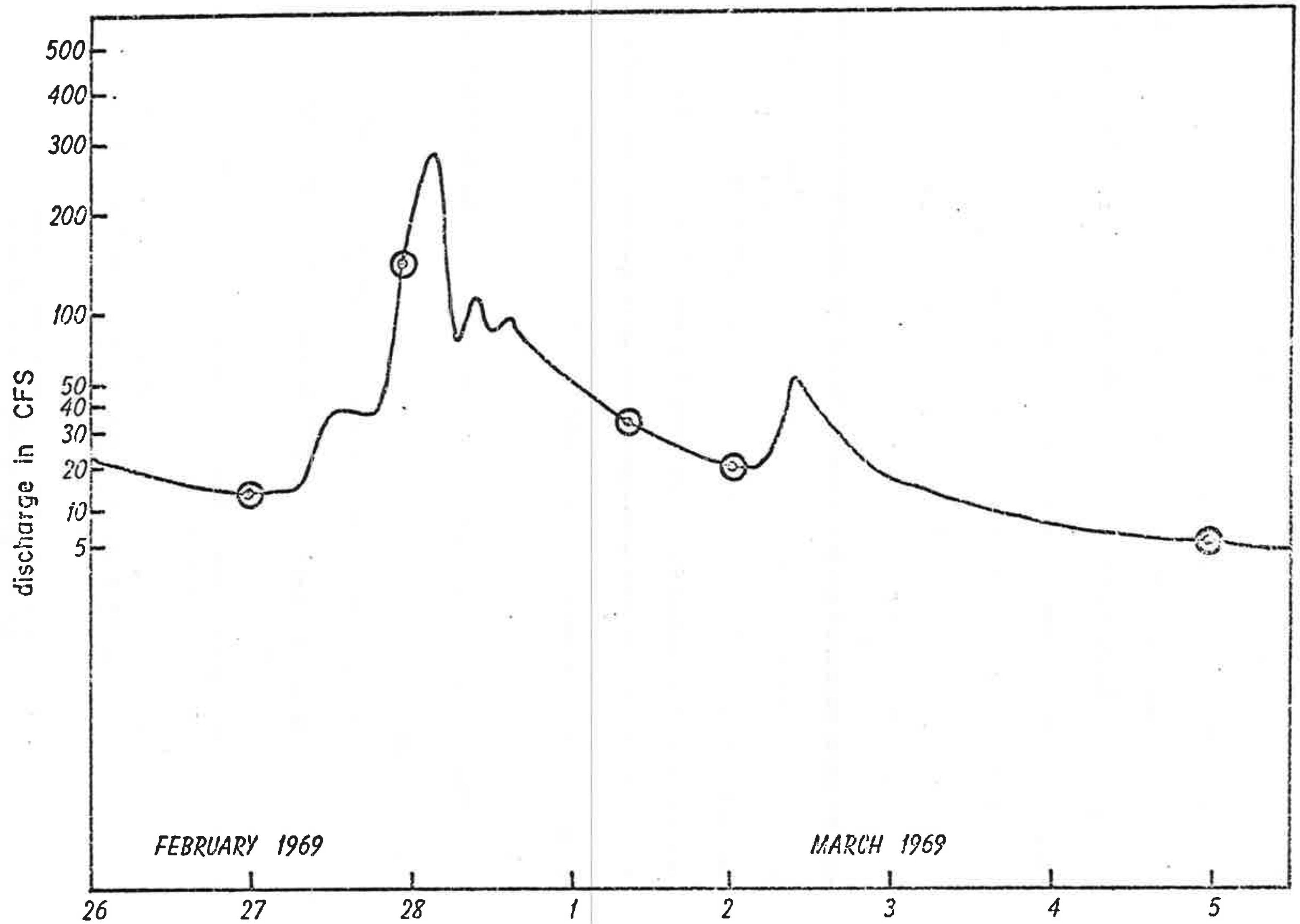


Fig. 18. Hydrograph of Dry Creek. Circles indicate times and stages at which velocity was measured.

angular to 0.9 for well rounded.

Effective bottom velocity - the average maximum bottom velocity that a bed-load particle experiences during transport from one point to another, i.e., assuming that most bed-load movement in Dry Creek takes place at nearly maximum flow (for a particular storm), a bed-load particle moving downstream through a number of pools and riffles will experience different bottom velocities along the way. These bottom velocities at each point will be near the maximum bottom velocity for that point (assuming nearly maximum flow), and an average of these at-a-point maximum bottom velocities is the "effective bottom velocity" that provides the tractive force to move the bed-load particle.

Effective bottom velocity squared - the square of the above-defined effective bottom velocity.

Maximum starting bottom velocity - the maximum bottom velocity that is experienced at the location where the bed-load particle started (before movement) during experiment 1 only.

Not all of the painted bed-load particles moved during the experiment--two in experiment 1, four in experiment 2, and one in experiment 3 did not move. This indicates that scour during the experiments was shallow. The bed-load particles that did not move during the experiment were excluded from the regression analysis; because they did not move it was impossible to determine at what bottom velocity they would have moved. The maximum bottom velocity at each location from which a pebble started (Figure 19) was determined by graphing measured bottom velocities and discharge for each location on Figure 19 and the extrapolating the curve to the peak discharge.

The at-a-point maximum bottom velocities in Figure 19 show a ten-

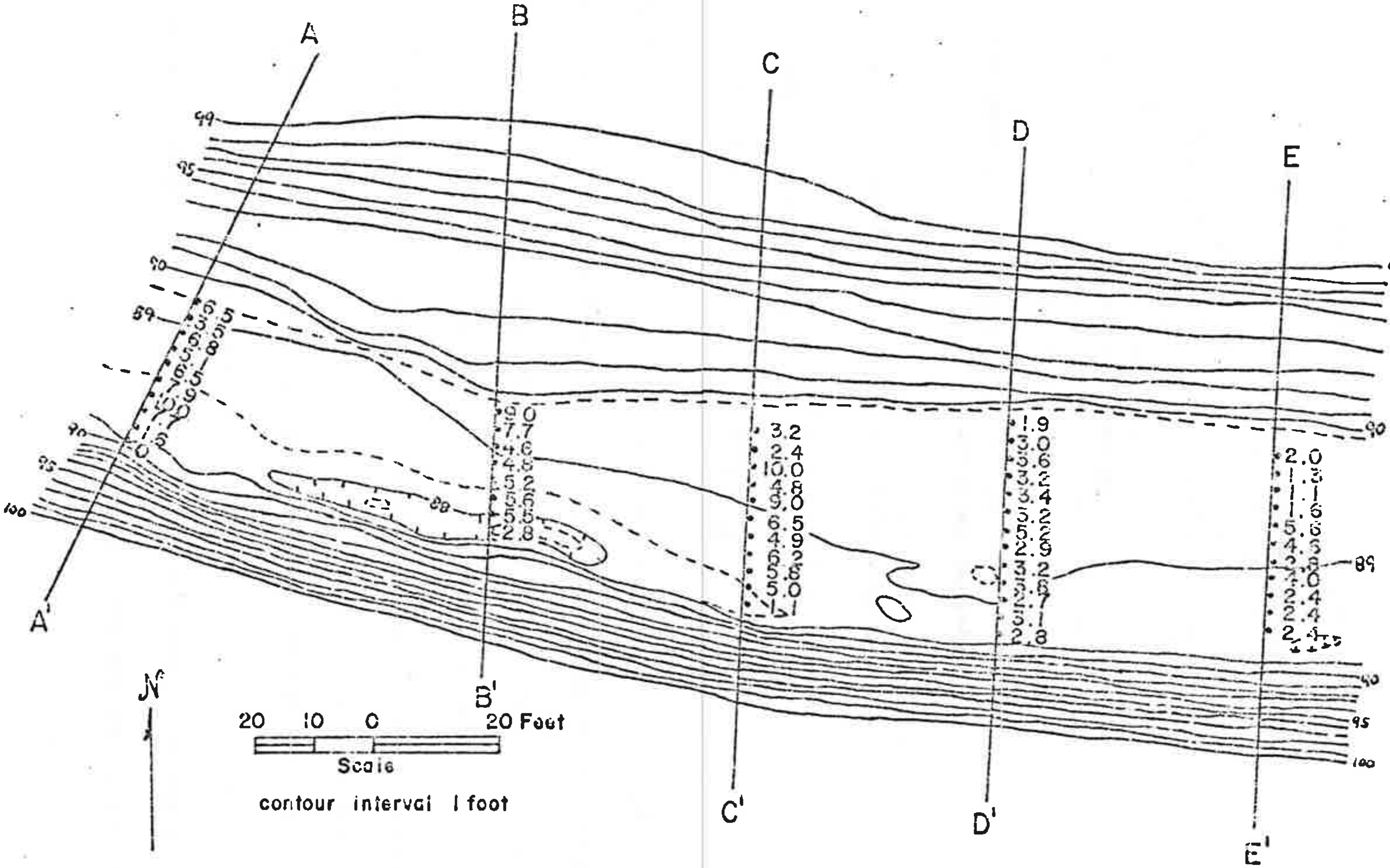


Fig.19. Distribution of maximum bottom velocity in ft/sec during bed-load movement experiments, Dry Creek. The location of this area is in the vicinity of $\gamma-\gamma'$ in Fig. 5.

dency for the highest velocities in the pool to be located on the point bar side of the pool rather than in the center of the pool. Bottom velocity measurements in Dry Creek suggest that the area of high bottom velocity is never in the center of the pool. With increasing velocity there is a tendency for the area of high bottom velocity to migrate toward the point bar side of the pool. The significance of this observation is not well understood, but the current meter used might be partly responsible for the phenomenon because it measures the net downstream velocity. Thus, if there is less turbulence over the point bar than the bottom of the pool, the net downstream velocity of the former might exceed the latter. Field observations suggest that there is considerably more turbulence at high flow in pools than in adjacent point bars, and some pools in Dry Creek appear to be formed by vertical vortexes scouring the pool bottom.

From Figure 19 a value of average maximum bottom velocity for the pool and riffle can be calculated. For Dry Creek these are 6.32 and 3.69 ft/sec respectively. The effective bottom velocity that a bed-load particle experiences during transport from one point to another can be calculated from the formula:

$$EBV = \frac{Mxs + Np\ 6.32 + Nr\ 3.69}{Np + Nr + 1}$$

where EBV is the effective bottom velocity, Mxs the maximum starting bottom velocity, Np the number of pools the particle moved through, and Nr the number of riffles the particle moved through. For example, if a particle had a maximum starting bottom velocity of 4 ft/sec and moved 200 feet through 1 pool and 2 riffles, then:

$$\text{EBV} = \frac{4 + (1)(6.32) + (2)(3.69)}{1 + 1 + 2}$$

$$\text{EBV} = \frac{17.70}{4} = 4.42 \text{ ft/sec}$$

Each recovered bed-load particle has a unique set of independent variables that possibly determine how far the particle moved. The average movement, excluding the bed material that did not move at all, was 146 feet in experiment 1, 48 feet in experiment 2, and 214 feet in experiment 3. The results of the linear regression and correlation analysis are given in Table 3. The confidence limit is determined by the "t" test and indicates the significance of the variables. A confidence limit of 0.95 or greater is generally considered significant. Table 3 shows that the independent variables--diameter × specific gravity, effective bottom velocity squared, and effective bottom velocity--consistently have high coefficients of correlation. The independent variable diameter × specific gravity was found to yield a high confidence level and coefficient of correlation, and about 25 percent of the variability of the dependent variable--distance a bed-load particle moves--can be explained by the variability of diameter × specific gravity (Figure 20). The effective bottom velocity squared is proportional to the shear stress and would be expected to be a significant variable in bed-load movement. Low confidence levels for effective bottom velocity squared, however, indicate that shear stress is not as signi-

Table 3. Linear Regression Analysis.

Note: The dependent variable, distance moved, was used in all runs. The independent variable changes with each run.

Experiment Number	Dependent Variable	Independent Variable	Coefficient of Correlation	Confidence Level	N
1	distance moved	volume	-0.423	0.98	41
1	"	weight in water	-0.410	0.97	41
1	"	A-C axis ratio	-0.158	0.75	41
1	"	specific gravity	-0.030	0.97	41
1	"	diameter × s.g.	-0.522	0.99	41
1	"	shape	-0.258	0.99	41
1	"	effec. bot. vel. sq.	0.692	0.80	41
1	"	max. st. bot. vel.	0.592	0.10	41
1	"	effec. bot. vel.	0.701	0.99	41
2	"	volume	-0.276	0.54	29
2	"	weight in water	-0.278	0.78	29
2	"	A-C axis ratio	-0.085	0.33	29
2	"	specific gravity	-0.225	0.99	29
2	"	diameter × s.g.	-0.386	0.99	29
2	"	shape	-0.340	0.99	29
2	"	effec. bot. vel. sq.	0.491	0.55	29
2	"	effec. bot. vel.	0.450	0.99	29
3	"	volume	-0.305	0.99	65
3	"	weight in water	-0.327	0.99	65
3	"	A-C axis ratio	-0.057	0.50	65
3	"	specific gravity	-0.286	0.99	65
3	"	diameter × s.g.	-0.528	0.99	65
3	"	shape	-0.291	0.99	65
3	"	effec. bot. vel. sq.	0.438	0.61	65
3	"	effec. bot. vel.	0.470	0.99	65

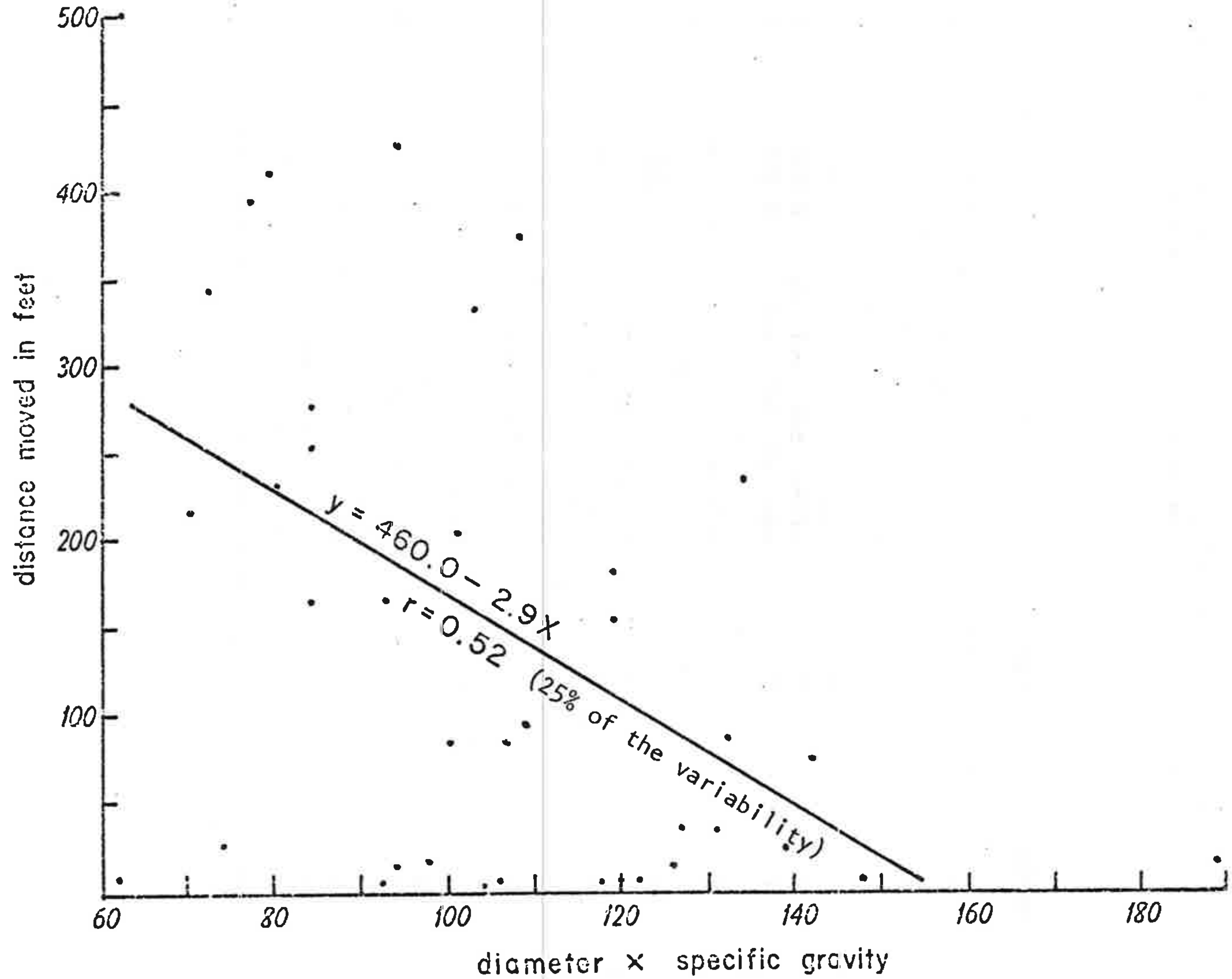


Fig. 20. Diameter × specific gravity vs. distance moved for Experiment I.

ficant as would be expected in Dry Creek bed-movement. The effective bottom velocity has a high coefficient of correlation and a high confidence level, and approximately 30 percent of the variability of the dependent variable--distance a bed-load particle moves--can be explained by the variability of the effective bottom velocity (Figure 21). The differences between the effective bottom velocity squared (shear stress) and effective bottom velocity indicate that the latter is a more significant factor in the movement of the coarse bed-load material of Dry Creek. This is consistent with Gilbert's (1914) experiments from which he concluded that large particles are most sensitive to changes in velocity. The A-C axis ratio is a shape factor; the greater the ratio the flatter the particle. The experiments indicate that this ratio is not a significant factor in bed-load movement. The dependent variables, volume and weight in water, generally correlated about 0.3 to 0.4 with high confidence levels. Shape of the particles consistently correlated about 0.25 to 0.34 with a very high confidence level, and indicated a tendency for angular particles to move farther than rounded particles. Specific gravity also correlated low with a high confidence level indicating that there is a slight tendency for the less dense material to move a greater distance than particles of higher density.

Multiple regression analysis was applied to different combinations of the independent variables (Table 4). The results indicate that about 33 percent of the variability of the distance a bed-load particle will move can be explained by the variability of shape and diameter times specific gravity. Volume, weight in water, and shape in combination

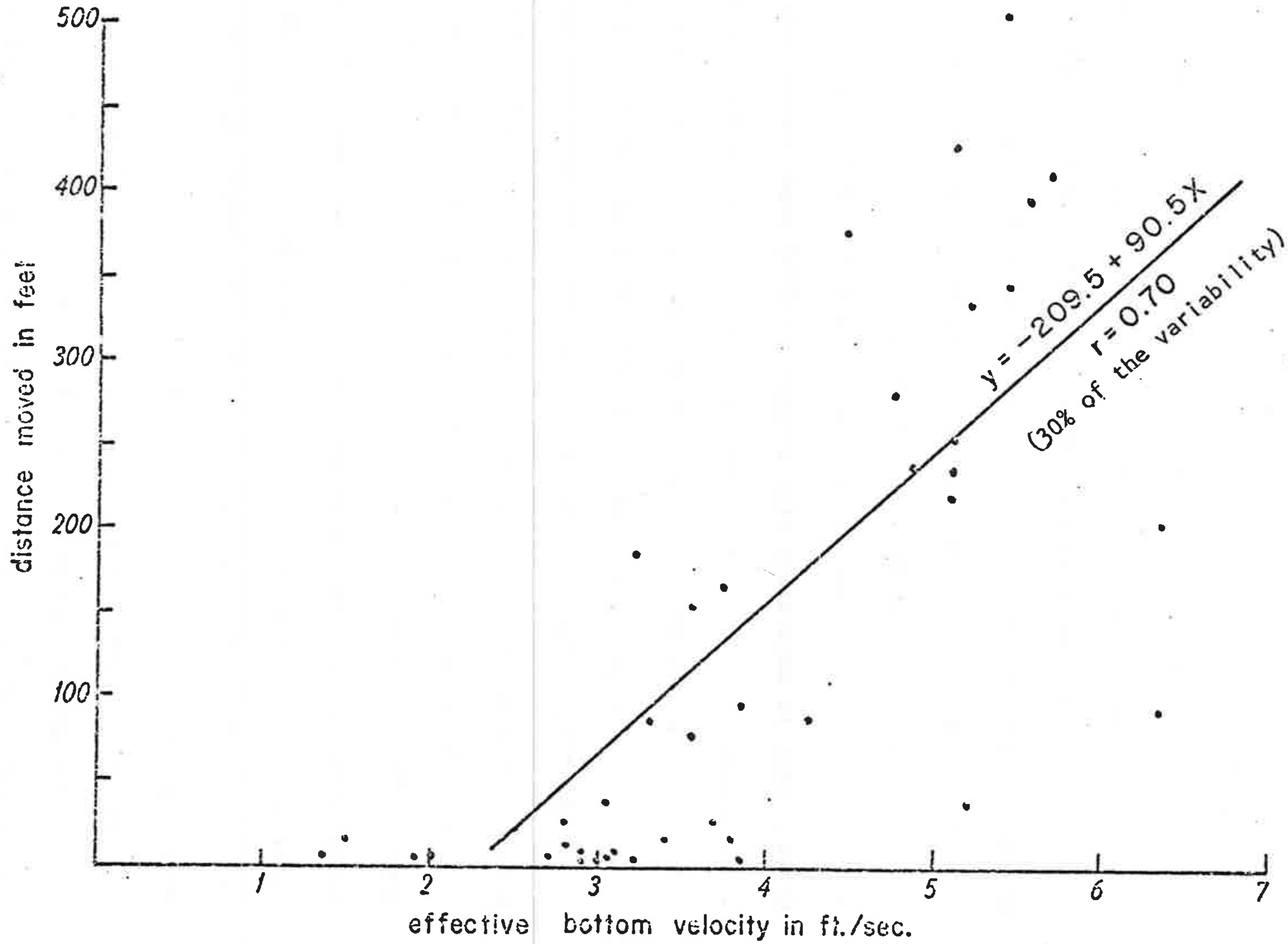


Fig. 21. Effective bottom velocity vs. distance moved in Experiment I.

Table 4. Multiple Regression Analysis, with Dependent Variable as Distance Transported and Independent Variables Consisting of Pebble Parameters. The significance of the variables is shown in Table 3.

	Particle Parameters	
	Coefficient of Determination	Coefficient of Correlation
Dependent Variable		
Distance moved		
Independent Variables		
Volume		
Weight in water		
Shape		
Experiment no. 1	0.275	0.524
Experiment no. 2	0.183	0.428
Experiment no. 3	0.238	0.487
Dependent Variable		
Distance moved		
Independent Variables		
Volume		
Weight in water		
Shape		
Diameter × Specific gravity		
Experiment no. 1	0.356	0.596
Experiment no. 2	0.223	0.473
Experiment no. 3	0.372	0.610
Dependent Variable		
Distance moved		
Independent Variables		
Shape		
Diameter × Specific gravity		
Experiment no. 1	0.350	0.592
Experiment no. 2	0.223	0.472
Experiment no. 3	0.329	0.573

[continued]

Table 4. Multiple Regression Analysis [continued]

	Effective bottom velocity and Particle parameters	
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel. squared		
Diameter × Specific gravity		
Experiment no. 1	0.628	0.793
Experiment no. 2	0.423	0.650
Experiment no. 3	0.467	0.683
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel.		
Diameter × Specific gravity		
Experiment no. 1	0.663	0.814
Experiment no. 2	0.417	0.646
Experiment no. 3	0.485	0.697
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel. squared		
Diameter × Specific gravity		
Shape		
Experiment no. 1	0.648	0.805
Experiment no. 2	0.440	0.663
Experiment no. 3	0.505	0.711
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel.		
Diameter × Specific gravity		
Shape		
Experiment no. 1	0.678	0.824
Experiment no. 2	0.446	0.668
Experiment no. 3	0.517	0.719

[continued]

Table 4. Multiple Regression Analysis [continued]

	Effective bottom velocity and Particle parameters	
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel. squared		
Volume		
Weight in water		
Diameter × Specific gravity		
Shape		
Experiment no. 1	0.649	0.806
Experiment no. 2	0.440	0.663
Experiment no. 3	0.517	0.719
Dependent Variable		
Distance moved		
Independent Variables		
Effective bot. vel.		
Volume		
Weight in water		
Diameter × Specific gravity		
Shape		
Experiment no. 1	0.681	0.825
Experiment no. 2	0.452	0.672
Experiment no. 3	0.529	0.727

can also explain about 33 percent of the variability of the distance moved. Up to 68 percent of the variability of the distance moved can be explained by the variability of effective bottom velocity, shape and diameter × specific gravity or effective bottom velocity, shape, weight in water and volume in combination.

The movement of bed-load particles starting in a pool compared to particles starting in a riffle was investigated by separately analyzing each group. In experiment 3 there were 31 particles that started in a pool and 34 that started in a riffle, and it is the only experiment with sufficient data to study the pool and riffle separately. The results (Table 5) show that particle parameters--i.e., volume, weight in water, specific gravity, and shape--are considerably more important than velocity for particles starting in a pool. For particles starting in a riffle velocity is apparently more important than particle parameters. A plot of distance moved for bed-load particles as a function of effective bottom velocity (Figure 22) shows the lower coefficient of correlation and greater scatter for particles starting in a pool than those starting in a riffle.

Particle movement through a pool and riffle has been discussed by Langbein and Leopold (1968) in terms of a kinematic wave theory. Their idea is that the spacing of particles is very important in bed-load movement, and that particles move quickly through pools where the concentration of coarse material is less and slower through riffles where the concentration of coarse material is greater. In Dry Creek (experiment 3) the average distance moved for bed-load particles was 199 feet for par-

Table 5. A & B Linear Regression Analysis of Bed-Load Movement. All pebbles started in pool (A) or riffle (B). The dependent variable, distance moved, was used in all runs. The independent variable changes with each run.

A

Experiment Number	Dependent Variable		Independent Variable	Coefficent of Correlation	Confidence Level	N
3	distance	moved	Volume	-0.407	0.99	31
3	"	"	Weight in water	-0.432	0.99	31
3	"	"	A-C axis ratio	-0.002	0.01	31
3	"	"	Specific gravity	-0.403	0.99	31
3	"	"	Diameter × S.g.	-0.624	0.98	31
3	"	"	Shape	-0.291	0.99	31
3	"	"	Effec. bot. vel. sq.	0.178	0.69	31
3	"	"	Effec. bot. vel.	0.217	0.99	31

B

3	distance	moved	Volume	-0.260	0.66	34
3	"	"	Weight in water	-0.280	0.67	34
3	"	"	A-C axis ratio	-0.100	0.37	34
3	"	"	Specific gravity	-0.242	0.99	34
3	"	"	Diameter × S.g.	-0.532	0.99	34
3	"	"	Shape	-0.286	0.99	34
3	"	"	Effec. bot. vel. sq.	0.783	0.99	34
3	"	"	Effec. bot. vel.	0.765	0.99	34

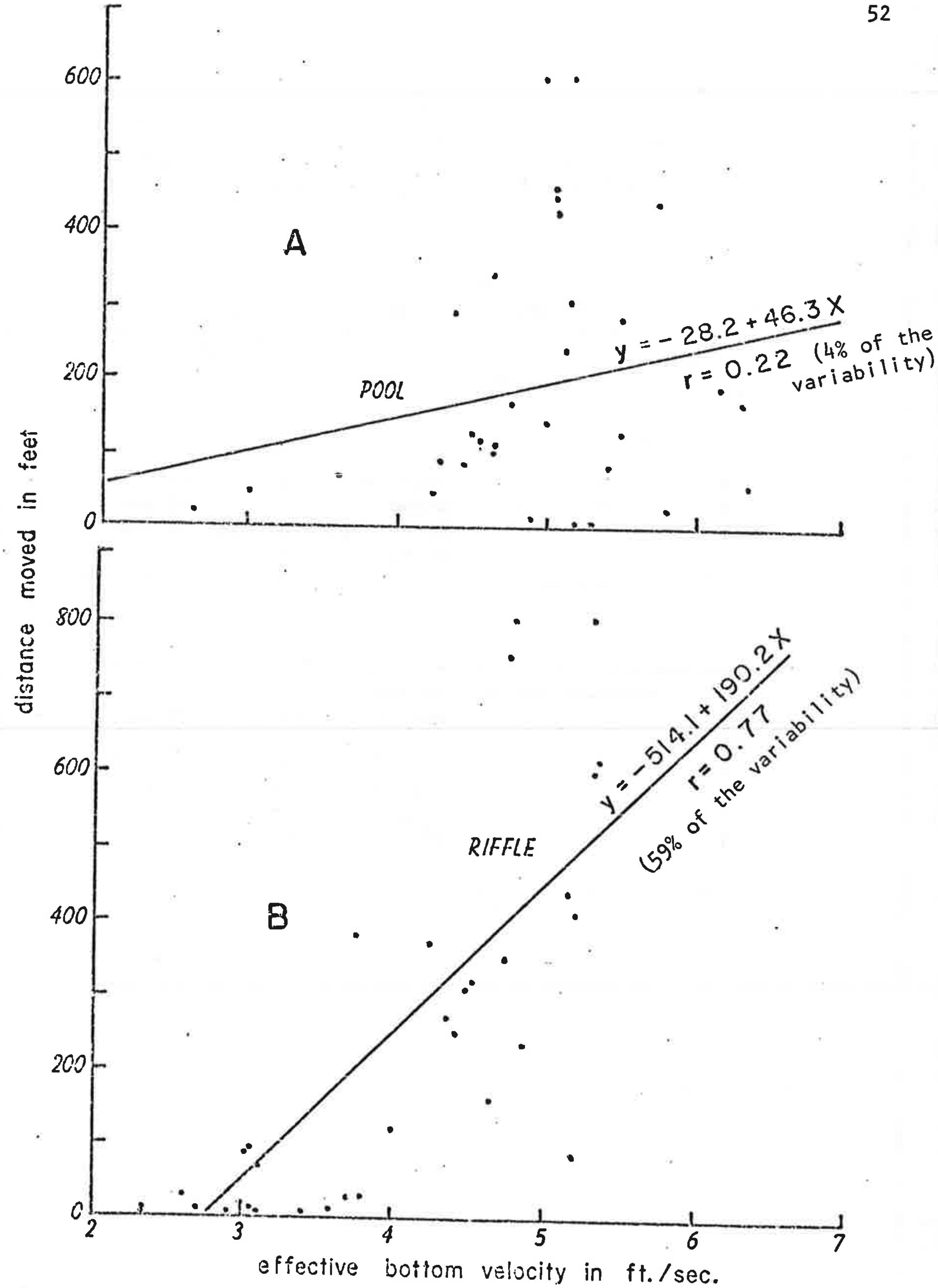


Fig. 22. Effective bottom velocity vs. distance moved for bed load material; A starting in a pool and B starting in a riffle from Experiment 3.

ticles starting in pools and 229 feet for those starting in riffles. The analysis has shown that two-thirds of the variability of bed-load movement in Dry Creek can be explained by the variability of particle parameters and maximum bottom velocity. The importance of particle spacing (especially coarse material) is certainly significant, and is probably a function of the velocity and particle parameters. Intuitively bed-load particles must be moved before they are sorted or spaced in pools and riffles.

FLUVIAL SORTING -- THE HYPOTHESIS OF VELOCITY REVERSAL

General

Geomorphologists have long known that stream action sorts the bed-load material in a channel. The heterogeneous bed material of Dry Creek is well sorted (areally) in pools and riffles. The largest bed material is generally concentrated in the riffles (Figures 23, 24) and point bars, and the fines in the pools (Figures 25, 26) and occasionally in point bars. The detailed topographic map of Dry Creek channel (Plate 3) shows mean diameters of bed-load particles, as determined by Wentworth's (1954) areal method of sampling coarse bed-load material. The tendency for coarse particles to accumulate in riffles and fines in pools is shown by the areal frequency distributions in Figures 27 and 28.

Lateral areal sorting across the pool and riffle characterizes Dry Creek. This was determined by measuring the ten largest bed-load particles at three foot intervals along section lines (α-α', etc., Figure 5).

Figure 23. Upstream view of point bar associated with a primary pool in the vicinity of B' in Figure 5.

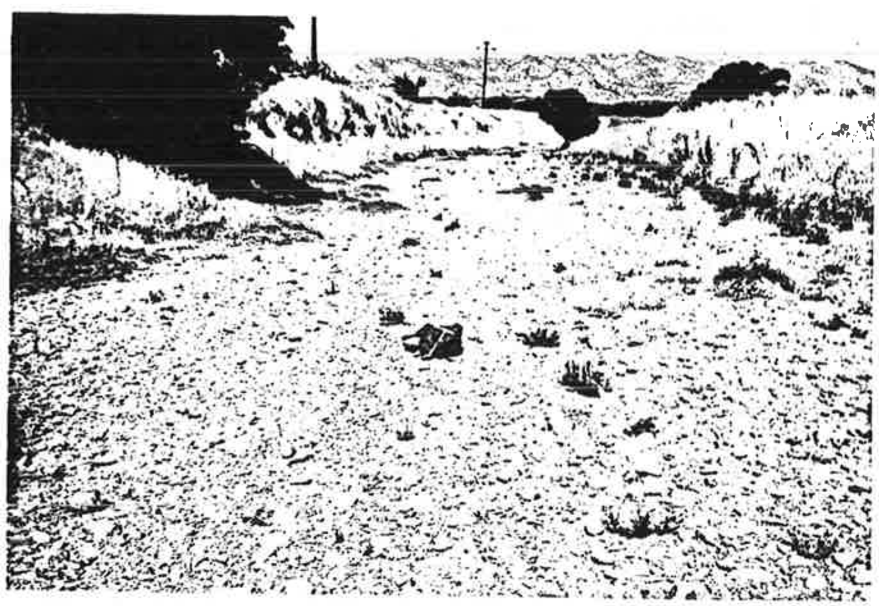


Figure 24. Upstream view of riffle between two secondary pools in the vicinity of δ' in Figure 5.

Figure 25. Upstream view of primary pool in the vicinity of B' in Figure 5 with finest bed material on pool bottom (lower right) and coarsest on point bar (upper left).

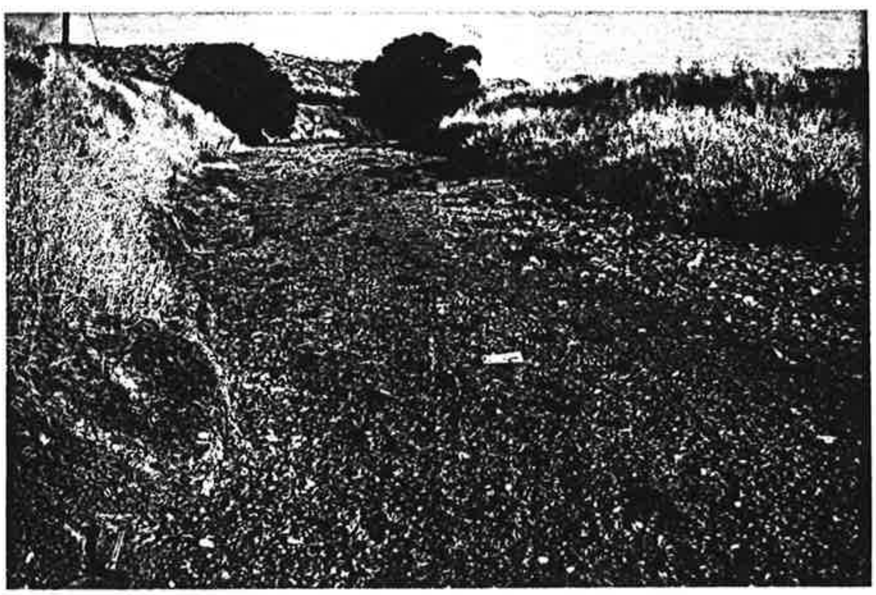


Figure 26. Upstream view of secondary pool in vicinity of γ' with finest bed material on bottom (center) and coarsest on point bar (upper right).

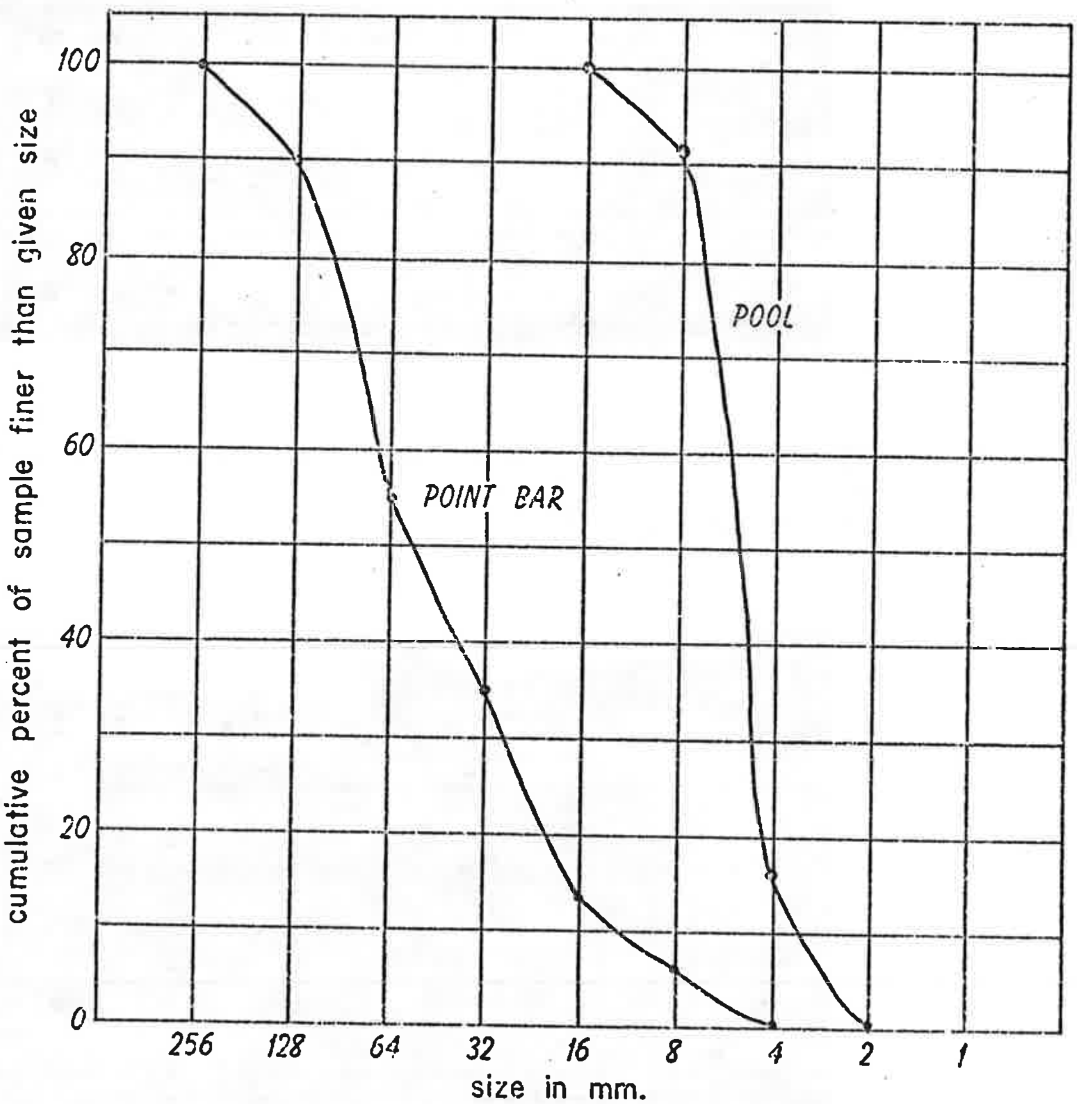


Fig. 27. Frequency distribution of bed material over a pool and adjacent point bar. The location of the sampled area is in the vicinity of B' in Fig. 5.

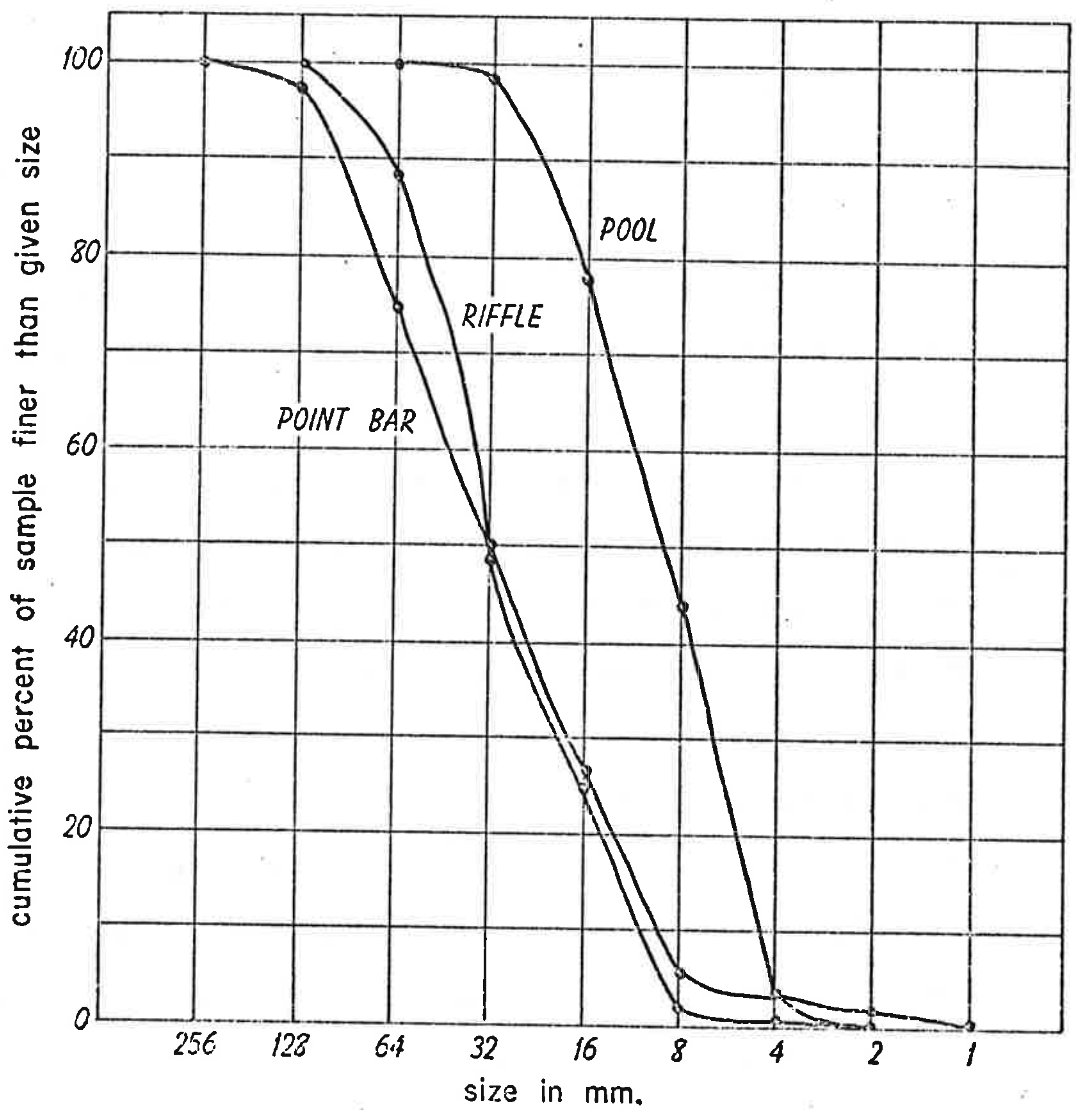


Fig. 28. Frequency distribution of bed material over a pool, adjacent point bar and downstream riffle. The location of the sampled area is in the vicinity of γ--γ' in Fig. 5.

The average size of the ten particles in each interval is shown in Figures 29 and 30. The graphs show that the large material on the point bar gradually decreases in size across the stream to the bottom of the pool. The riffle forms a lobate shaped structure, with the largest material in the center of the channel.

Four trenches, two in pools and two in riffles, were excavated in Dry Creek channel. In the riffles the largest material is on the surface (Figures 31, 32). Figure 31 shows the largest material forming a single layer on the surface, while in Figure 32 large material is also scattered below the surface. Bagnold (1968) has explained the tendency for large material to be found on the surface of riffles by the Dispersive Stress. The stress is proportional to the square of the particle size, and the relatively large particles will drift towards the region of least shear at the upper surface of the bed. In the pools (Figures 33, 34) there is an abundance of relatively fine bed material on the surface. The fines near the surface of the pools are probably the result of deposition by a waning current. The coarser material below the fines is sharply defined in Figure 33 and only weakly in Figure 34, but the coarsest material found in the pool is significantly smaller than the largest material at the surface of the riffles. These observations in Dry Creek are consistant with those reported by Gilbert (1914).

Hypothesis of Velocity Reversal

The velocity reversal hypothesis, which is here proposed to explain the areal sorting of bed-load material in Dry Creek, is based upon the

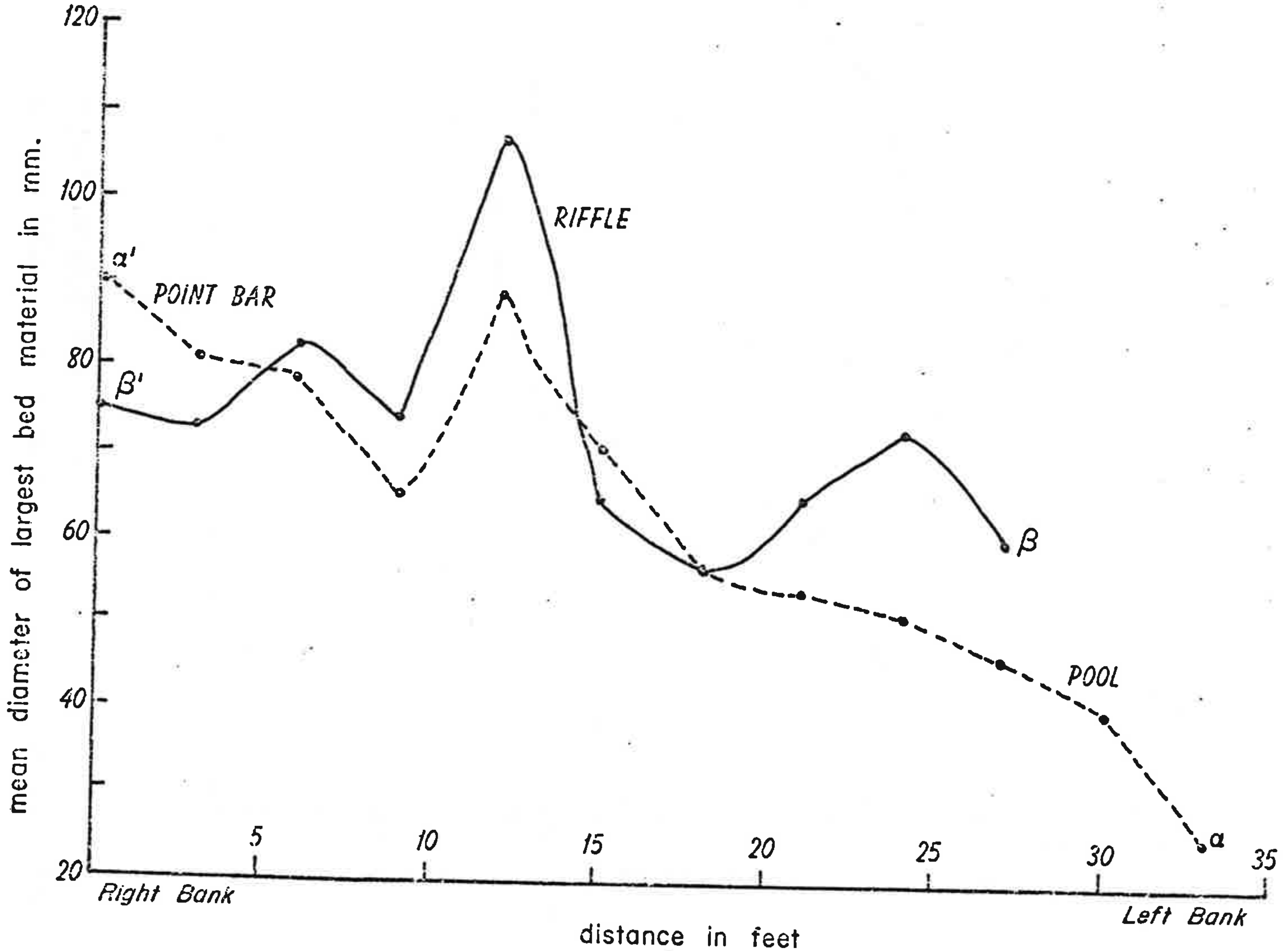


Fig. 29. Lateral sorting of largest bed material through a point bar – pool and adjacent riffle. The location of the sampled area is shown in Fig. 5.

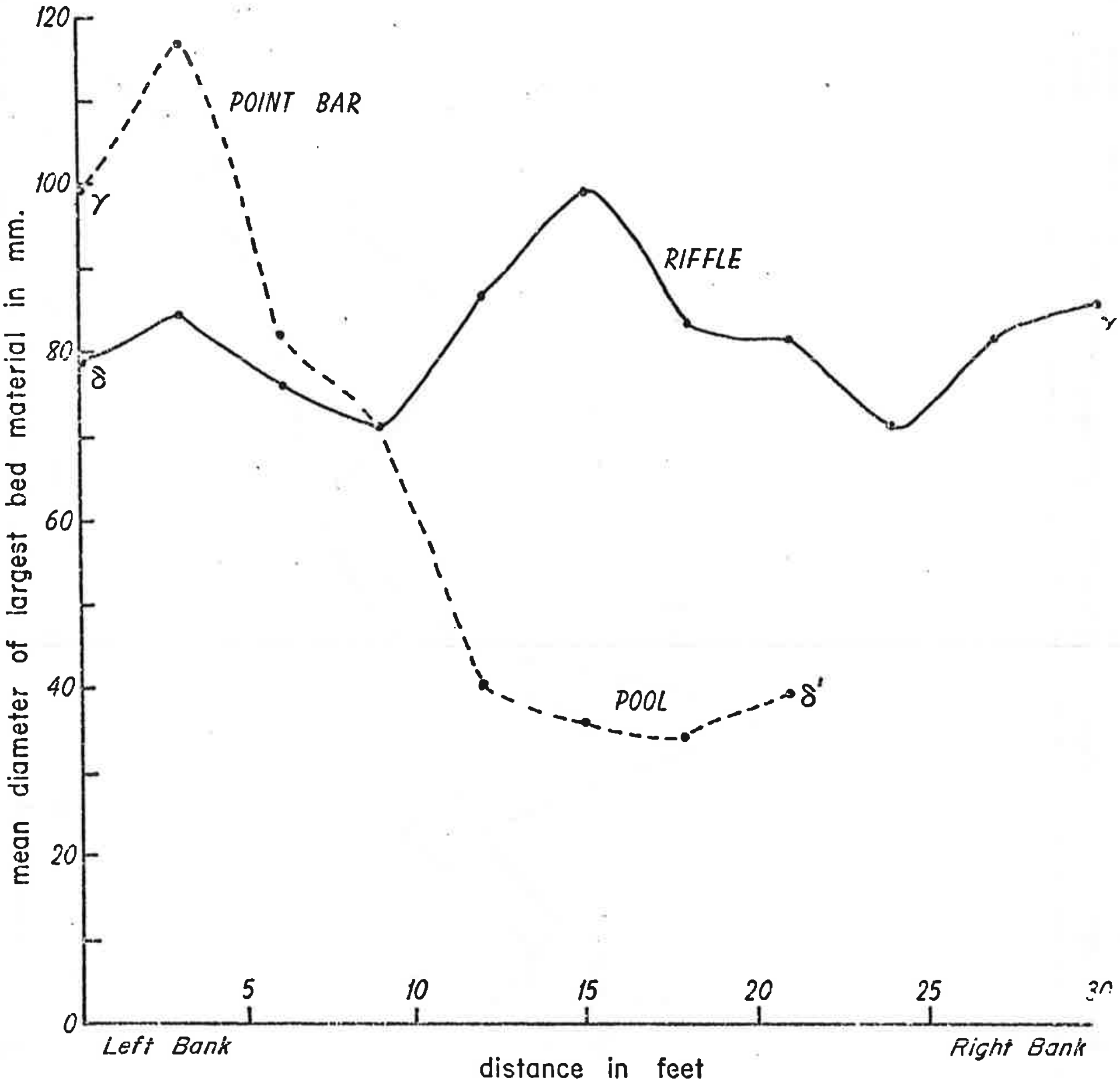


Fig. 30. Lateral sorting of largest bed material through a point bar – pool and adjacent riffle. The location of the sampled area is shown in Fig. 5.

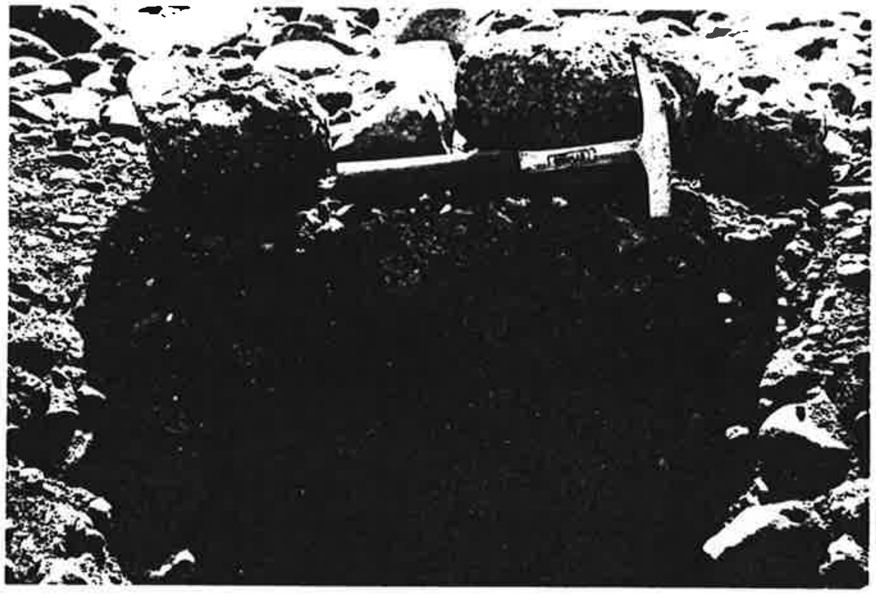


Figure 31. Excavated riffle in the vicinity of B' in Figure 5 showing a veneer of coarse material at the surface.

Figure 32. Excavated riffle in the vicinity of δ' in Figure 5 showing the abundance of coarse material at the surface.

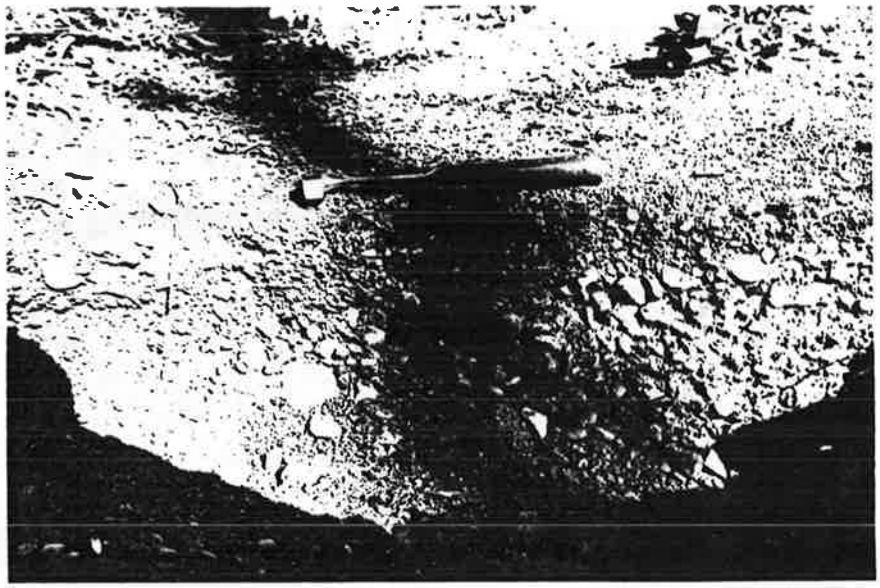


Figure 33. Excavated primary pool in the vicinity of B in Figure 5 showing the abundance of fine material at the surface.

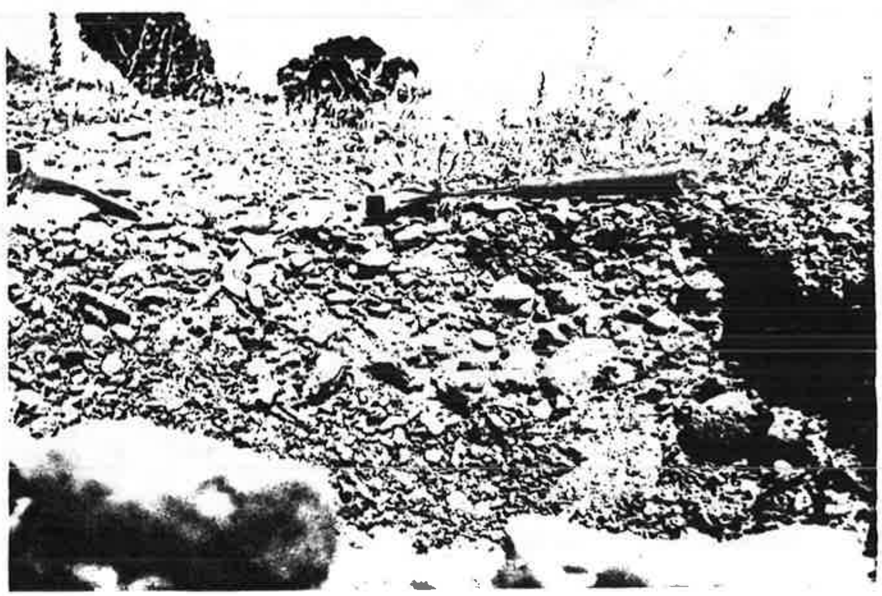


Figure 34. Excavated secondary pool in the vicinity of γ' in Figure 5 showing the general tendency for the fine material to be at the surface.

following observations:

(1) At low flow the bottom velocity is less in the pool than in the adjacent riffles;

(2) With increasing discharge the bottom velocity in pools increases faster than in riffles.

The reversal velocity occurs when the bottom velocity of the pool is equal to that of the riffle. With continued increase in discharge beyond the reversal, the bottom velocity of the pool exceeds that of the riffle. Large bed-load material on riffles cannot be moved at low flow; at high flow, beyond the reversal, bed material that can be moved through a riffle and into a pool will be quickly transported through the pool by the greater bottom velocities and tractive force there. As a result, the largest bed-load particles will be generally found on the riffles and relatively finer particles in the pools.

Gilbert (1914) first observed the reversal of bottom velocity, but he thought that the largest particles would be trapped in the bottom of the pools as the velocity decreased. Leopold _et al_. (1964) concluded that bottom shear, which is proportional to the velocity squared, increased more rapidly with discharge over a pool than over a riffle, but did not further explore the phenomena.

The location and stage of measured bottom velocity is shown on Figures 17 and 18. The measurements for the pool-riffle sequence (Figure 35) indicate that the reversed velocity of about 4 ft/sec was reached at a discharge of approximately 300 C.F.S. Bottom velocities above the reversal point were not measured in Dry Creek due to hazardous conditions at high flow, but at one measurement (Figure 36) the bottom velocities over the pool and riffle were equal. The reversal velocity of 2 ft/sec reflects a single section in comparison to a reversal velocity of 4 ft/sec of the entire pool and riffle. Near the downstream end of the pool the slope of the bottom velocity vs. discharge line approaches that of the riffle (Figure 37) indicating that the process which caused the reversal has dissipated by the end of the pool.

The length of time that the process operates depends upon the duration of high flow. The change of bottom velocity as a function of time (Figure 38, derived from the hydrograph and velocity measurements) shows that the velocity reversal during the high flow on February 24 lasted only a few hours at peak flows near 6:00 a.m. and 12:00 a.m. This suggests that large bed material is only transported for a relatively short time during the peak flow.

The areal sorting produced by the velocity reversal occurs at discharge of 300 CFS, which, from Table 1, has a return period of about 1.4 years. This suggests that the sorting is produced by relatively low flows of moderate frequency. This seems consistent with Wolman and Miller's (1960) conclusion that most sediment in streams is transported by flows with return periods of one to two years.

The surface distribution of bed material at low flow is probably destroyed with rising stage, and the distribution at high flow is modified during a falling stage. In Dry Creek these changes are rapid, due to the flashy nature of the discharge. The relative lack of fines in the surface layer on riffles and the abundance of fines in the pools suggests that the fines in the pools may be derived from the riffles.

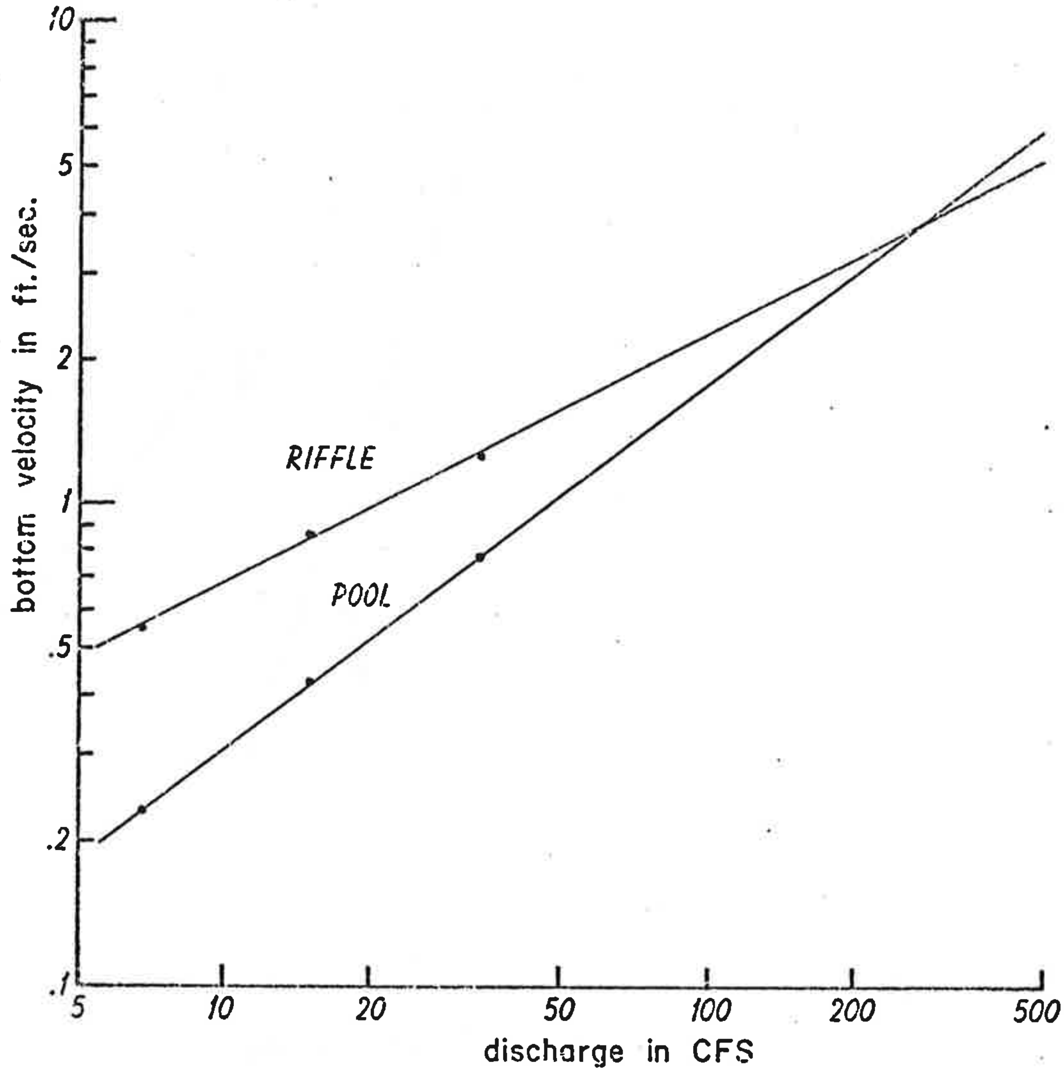


Fig.35. Mean bottom velocities in a pool (A-A', B-B', C-C') and riffle (D-D', E-E') vs. discharge. The location of the pool and riffle is shown in Fig. 17.

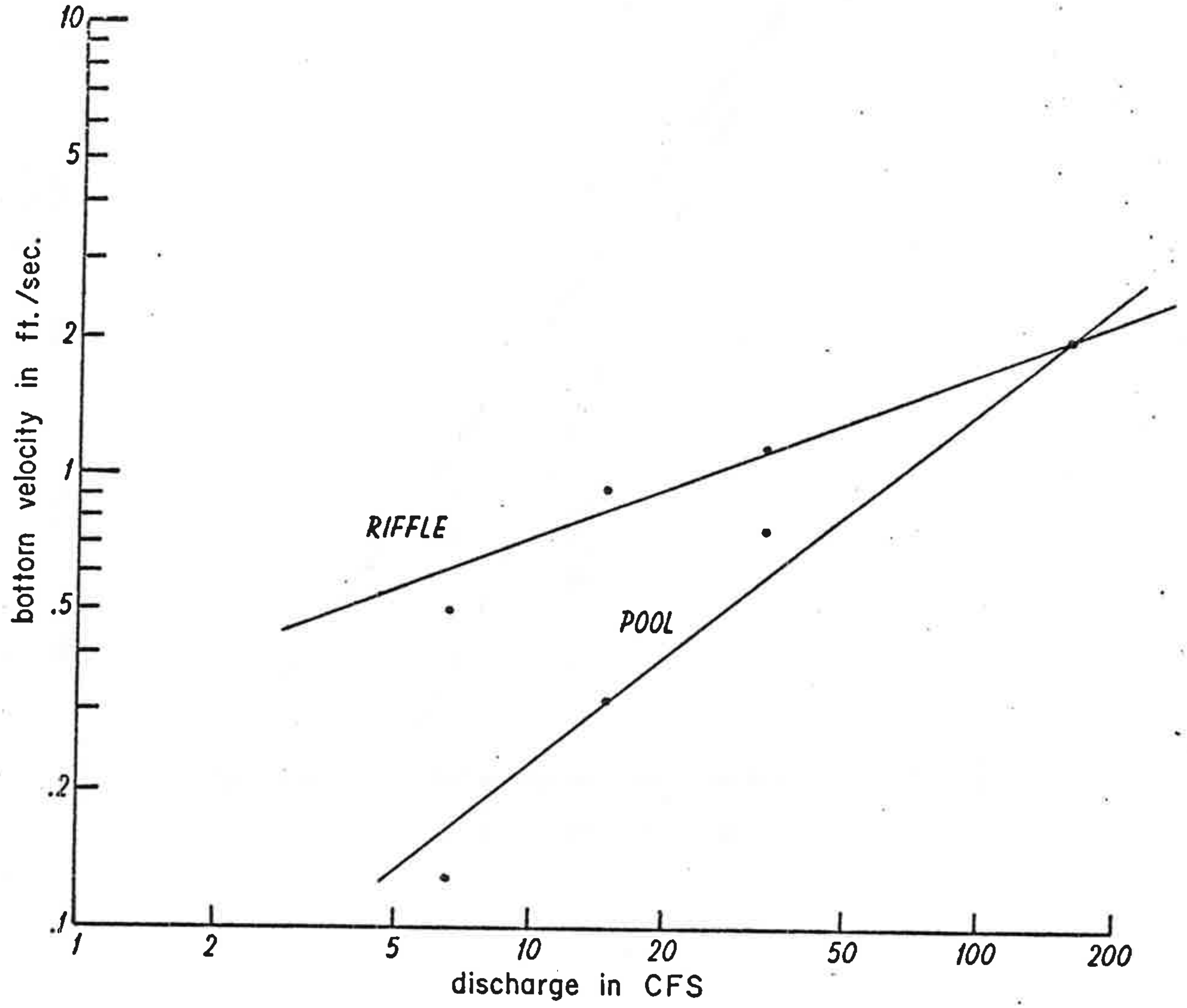


Fig. 36. Mean bottom velocities for pool (B-B') and riffle (D-D') vs. discharge. The location of the pool and riffle is shown in Fig. 17.

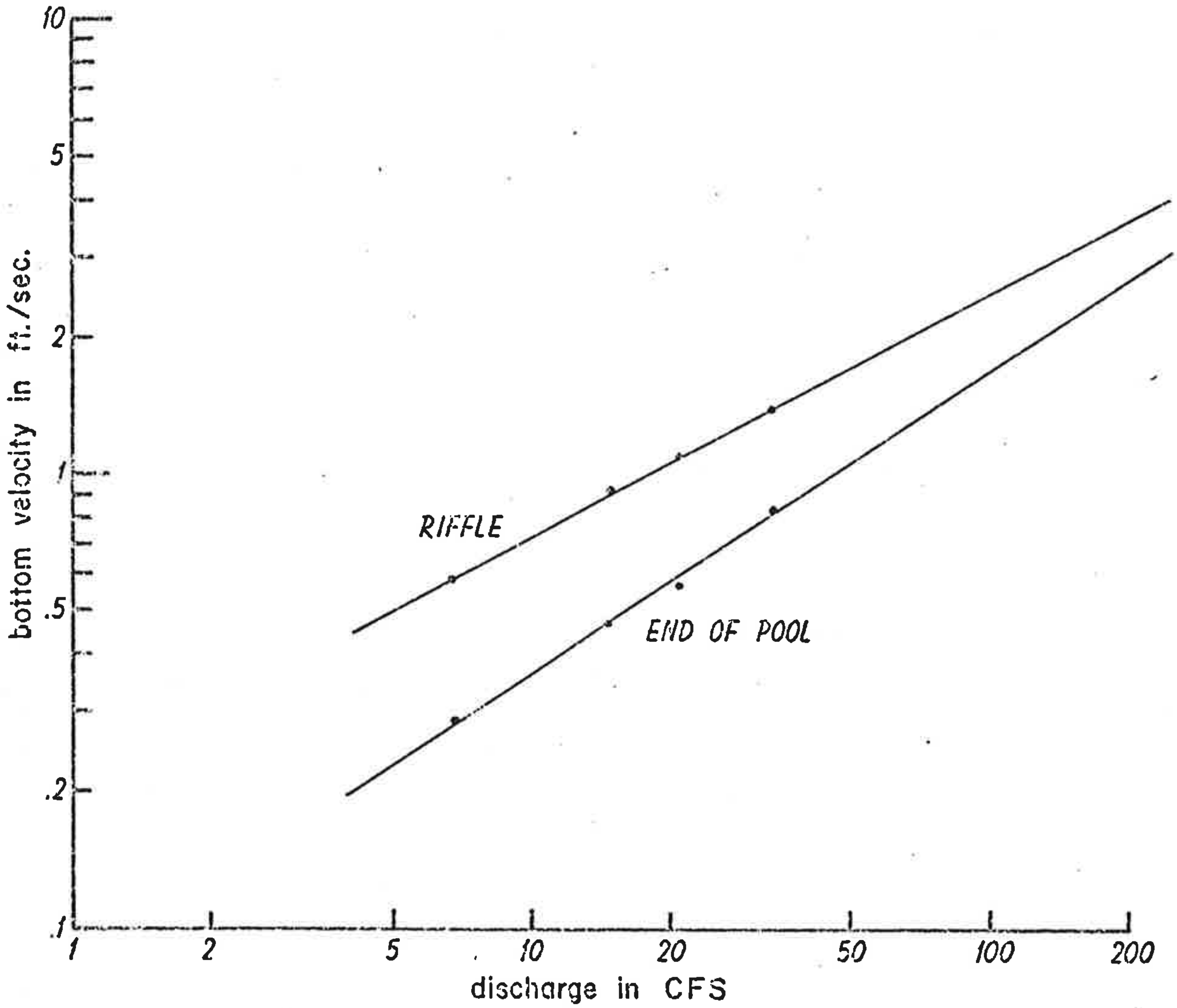


Fig. 37 Mean bottom velocities for end of pool (C–C') and riffle (E–E') vs. discharge. The location of the pool and riffle is shown in Fig. 17.

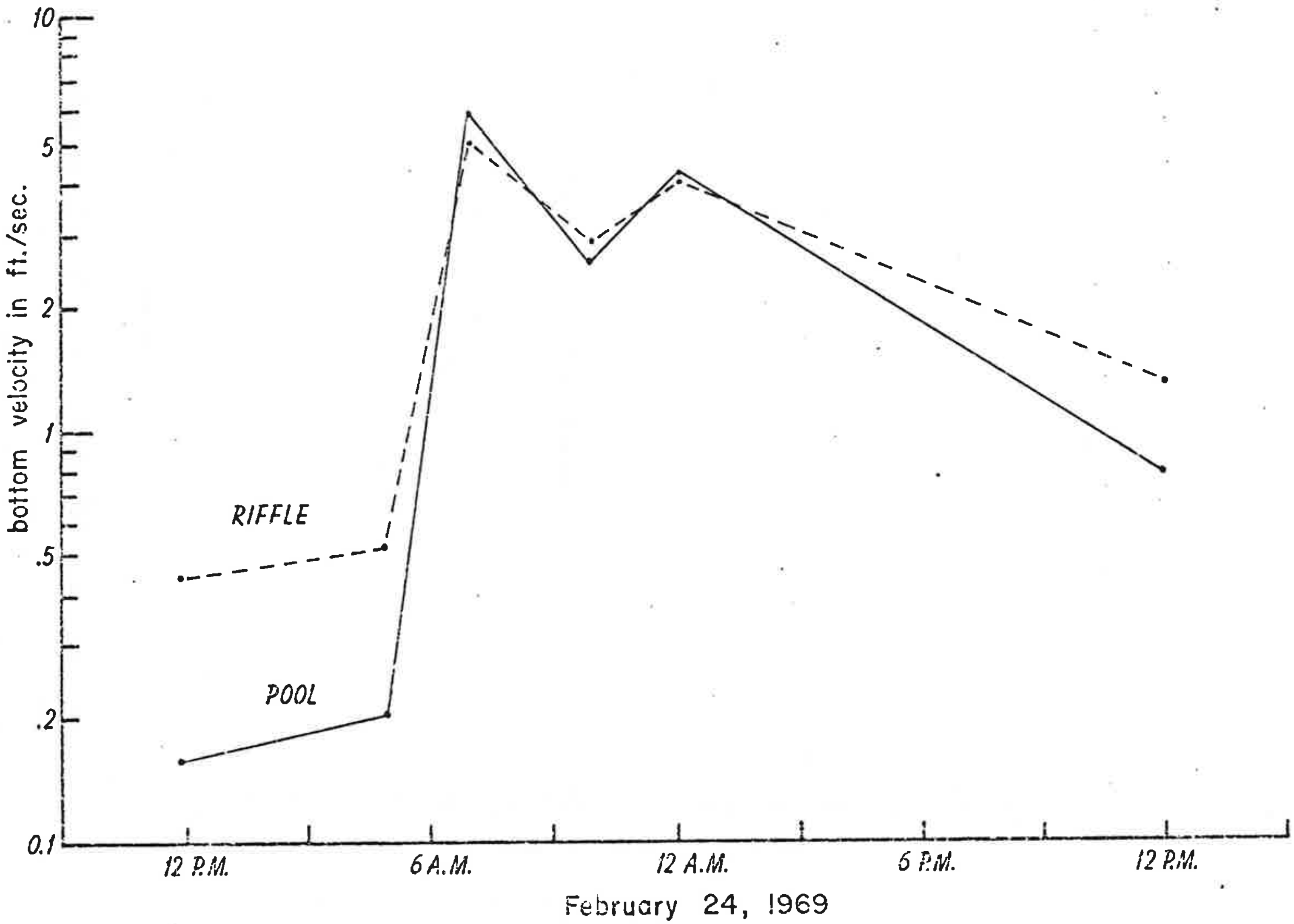


Fig. 38. Calculated change of bottom velocity as a function of time in a pool–riffle sequence during a rise and fall of stage, based on hydrograph and velocity measurements. The location of the pool and riffle is shown in Fig. 17.

At low flow the bottom velocity of the riffle exceeds that of the pool, so if fine material--sand and silt--is transported through the riffles it may be trapped in the pools.

Bed-load movement through a pool-riffle sequence in Dry Creek would be as follows: After a storm, discharge increases rapidly, but below the velocity reversal only relatively fine material is transported. The bottom velocity of the pool is less than that of the riffle, so the largest material able to be moved through the riffle is trapped in the pool. With increasing discharge a transitional point is reached where the bottom velocity of the pools equals that of the riffle; at this point material that can be transported through the riffle is also transported through the pool. Beyond the the reversal velocity the bottom velocity of the pool exceeds that of the riffle. The largest bed material moves only at flood stage, and at this point the pools can transport any bed-load particle that moves into the pool. Therefore, at very high flow the only stable areas for large bed-load material are on bars and riffles, where there is less tractive force. With decrease in discharge following the peak flow, the largest bed-load material is left on bars and riffles. Below the reversal velocity some of the particles moving through a riffle would be unable to move through the pool, and if the velocity fell rapidly, as in Dry Creek, there could be an abrupt change from relatively coarse to fine material in some of the pools (Figure 33). The size of the largest bed material in the pools beneath the fines is dependent on the reversal velocity. The higher the reversal velocity, the larger the material that will be left in the pool with decreasing discharge and velocity.

The cause of the velocity reversal is dependent upon the interaction between channel morphology, discharge, slope, bottom velocity and bed roughness, but the relative significance of each is not completely understood. Hypothetically, the reversal is primarily associated with convergence of the channel through pools, bed roughness, and water slope. The bed slope of the pool and riffle, where movement was measured, is 0.002 and 0.005 respectively. Bed roughness can be defined as the ratio of particle size to depth of water (Leopold and Miller, 1956). At low flow bed roughness in the pool-riffle sequence studied is 0.04 for the pool and 0.42 for the riffle. Bed roughness probably changes with discharge, because the distribution of surface bed material changes (Bagnold, personal communication, 1969). Leopold et al. (1964) conclude that with increased discharge the water slope increases over a pool, and decreases over a riffle. The steeper bed slope of the riffle probably accounts for the greater bottom velocity at low flow, but with increasing discharge, slope becomes less significant, and the convergence-divergence of the channel and bed roughness become significant. The bed roughness is probably of secondary importance because it is essentially a product of the surface sorting caused by the changes in bottom velocity.

It is assumed that discharge is constant through a pool and adjacent riffle. The variables there are cross-sectional area of the channel and velocity. At low flow the cross-sectional area of the pool is greater than the riffle, but the mean velocity is less (the bottom velocity is also less). Since the pool is a topographically low part of the channel, water flow tends to be convergent at the pool. The point bar, which is slightly upstream, also tends to converge water into the pool. This is not significant at low flow, but may be very important in producing fast bottom velocities at high flow. Water coming out of the pool diverges on the riffle, and this probably is responsible for the slower bottom velocity in the riffle at high flow. Figure 39 shows a primary pool with no large bed material and a fan shaped deposit of large bed-load material downstream adjacent to the pool. It is assumed that at high flow the convergence of the pool produces fast bottom velocity which has a jetting action on the bed material; when the material reaches the divergent and slower bottom velocity of the riffle, the coarser material may be dropped from the moving traction load.

Figure 39. Upstream view of primary pool showing convergence of pool, divergence of downstream riffle (foreground), and associated areal sorting of bed material.

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