Channel and Hillslope Processes in a Semiarid Area New Mexico

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By LUNA B. LEOPOLD, WILLIAM W. EMMETT, *and* ROBERT M. MYRICK

EROSION AND SEDIMENTATION IN A SEMIARID ENVIRONMENT

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ABSTRACT

Ephemeral washes having drainage areas from a few acres to 5 square miles are shown by actual measurement to be accumulating sediment on the streambed. This aggradation is not apparent to the eye but is clearly shown in 7 years of annual remeasurement.

A similar aggradation was in progress in the same area some 3000 years ago as evidenced by an alluvial terrace later dissected by the present channel system. At that time as well as at present, aggradation occurred even in tributary areas draining a few acres. Colluvial accumulations merge with channel deposits and blanket the valleys and tributary basins even up to a few hundred feet of the drainage divides.

The present study concerned the amounts of sediment produced by different erosion processes in various physiographic positions in the drainage basins. Measurements show that by far the largest sediment source is sheet erosion operating on the small percentage of basin area near the basin divides.

Mass movement, gully head extension, and channel enlargement are presently small contributors of sediment compared with sheet erosion on unrilled slopes. As in previous studies, not all of the erosion products could be accounted for by accumulations on colluvial slopes and on beds of channels. The discrepancies are attributed primarily to sediment carried completely out of the basins studied and presumably deposited somewhere downstream.

Aggradation of alluvial valleys of 5 square miles area and smaller both in the present epicycle, and in prehistorical but post-glacial times in this locality, cannot be attributed to gullying or rill extension in the headwater tributaries but to sheet erosion of the most upstream margins of the basins.

Studies of rainfall characteristics of the 7 years of measurement compared with previous years in the 100-year record do not provide a clear-out difference which would account for the presently observed aggradation of channels. Longer period of measurement of erosion and sedimentation will be necessary to identify what precipitation parameters govern whether the channels aggrade or degrade.

ACKNOWLEDGMENTS

This study was conceived and initiated by Dr. John P. Miller and the senior author in the summer of 1958, and fieldwork was continued during each succesive summer for periods of 1–3 weeks. Immediately following the field season of 1961 Dr. Miller died from bubonic plague contracted during that fieldwork. We resolved to prosecute the work thereafter with especial diligence.

An important part of the observations made during the first 5 years consisted of the data on the movement of the hundreds of individual cobbles which had been painted for identification. Emphasis was gradually shifted to the observations on rates of erosion and sediment movement which had been begun as only an auxiliary part of the original investigation. It is with these observations that the present paper is primarily concerned.

For permission to work on the property known as Las Dos and for many other courtesies we are grateful to the late Mrs. Adelina Otero-Warren. Dr. Bergere Kenney has kindly encouraged the work to continue on that property.

The slope-area measurements of discharge and many other observations when we were not in the area were made under the direction of Wilbur L. Heckler, district engineer for the U.S. Geological Survey in Santa Fe. Louis J. Reiland, Leo G. Stearns, Charlie R. Sieber, Leon A. Wiard, and others of the Santa Fe office contributed materially to these observations.

Field assistants and technical associates during various seasons included Brandis Marsh, Peter Sparks, Macklin Smith, Olav Slaymaker, Thomas Detwyler, Garnett Williams, and Lehn Franke.

The C^{14} analysis of the charcoal sample was run by Dr. Meyer Rubin in the laboratory of the Geological Survey in Washington, D.C.

For their review, comments, and suggestions, we are indebted to Stafford C. Happ, Asher P. Schick, George H. Dury, S. A. Schumm, R. F. Hadley, M. R. Collings, W. L. Heckler, and L. J. Reiland.

ALLUVIAL FILLS IN WESTERN VALLEYS

To cross any valley in the foothills of a large part of the western conterminous United States is to traverse a flat floor of stream-deposited alluvium. Many such floors, once smooth and undissected, are now trenched by arroyos or troughlike gullies. Abandoned flood plains or alluvial terraces can be seen in many such valleys, representing the surfaces of previous valley fills.

A large literature describes the local sequences of alluviation and erosion in such valleys, and there appears to be considerable contemporaneity in the timing of these alterations in post-Pleistocene time over an area that stretches from Wyoming to Texas. When grazing by cattle reached peak intensity about 1880, the most recent epicycle of valley trenching began in what is now believed to be a coincidence of climatic conditions conducive to erosion and degradation of the vegetative cover by overuse.

The alluvium which now fills these valleys and which is being trenched is usually similar in texture to that representing the fills of previous epicycles, though in some places the recent fill material is somewhat coarser. This alluvium is predominantly silt, often fine sandy silt, sometimes silty fine sand. The amount of clay is generally not great. The fills may be only a few feet deep in ephemeral tributaries draining several acres, and can be at least 50-feet thick through long distances. The latter figure applies to the alluvial valley, 150 miles in length, of the Rio Puerco, a tributary to the Rio Grande.

Three periods of late Pleistocene and recent alluviation are recognized in many places in Western States. The most recent fills now being eroded are less deep than those of previous periods of aggradation represented by the terraces which stand above the present valley floors, so even larger amounts of alluvium were stored in valleys in the past than are now observed.

Thus an immense amount of silty and fine-sandy alluvium has been produced by ephemeral drainage basins in the five states—Arizona, New Mexico, Utah, Colorado, and Wyoming—and has been deposited in valleys. When a period of valley trenching occurred, much was eroded out, carried downstream, and the process repeated.

It is logical to suppose that the source of sediment which would contribute to such aggradation during the periods of alluviation would be rill and gully erosion in the headwater tributaries. Deposits in the valley must have been derived from the basin upstream. But alluviation, when it occurred in the main valleys or master streams, also affected minor tributaries as well. The ground surface seems to sweep from valley floor up to the adjacent hills and up tributary valleys in concave-to-the-sky profiles. The topography of the adjacent hills seems to have been drowned in a sea of alluvium, softening and smoothing the surface configuration of the whole landscape. This phenomenon occurs widely and is the general rule in Nebraska, Kansas, Missouri, and the driftless area as well as in New Mexico, Wyoming and other parts of the Rocky Mountain area.

So widespread has been the phenomenon of valley aggradation with silty alluvium and so large are the volumes of sediment involved that the geomorphologist may wish to see examples of present-day streams currently undergoing such alluviation, and to discern the areal sources of the material being deposited. But, interestingly, it is difficult to designate channels undergoing such a process—at least any that are identifiable by visual or qualitative criteria. The processes which were so important even in the historic past cannot easily be observed at present.

Furthermore, if Leopold and Miller (1954) were correct in their assertion that the source of the valley alluvim was not in channel and gully erosion of the headwaters, then the processes of such sediment production must have been mass wasting and sheet erosion. The first of these is a process little studied and the second is a process studied far more on agricultural than on grazing or uncultivated areas. Little is known about rates of such processes on nonagricultural land, nor have the effects of relief, land slope, vegetation density, or other relevant factors been observed.

The present investigation was initiated to study both process and rate of aggradation and degradation in the channels, rills, and on the hillslopes of a drainage basin typical of many parts of the semiarid West. This paper is a progress report on that study.

Investigations of the kind described here involve the operation of field stations and specific experiments over a period of several years. Results can be obtained only at infrequent intervals because of the sporadic character of the precipitation. The general method, then, was to establish observation stations which could be visited for resurvey during a period of a few weeks in summer each year, and to maintain a more restricted number of observations after each important storm. The area chosen, Arroyo de los Frijoles near Santa Fe, N. Mex., was one in which previous work had been done by Leopold and Miller (1956), and for this reason it provided a familiar geographic and geologic background on which to base further investigations.

Our objective was to integrate several aspects of fluvial processes operating in the area: specifically, to study sheet erosion on the divide and interstream areas, slope retreat adjacent to steep-walled gullies that prevail in the uplands, and in particular, the movement of coarse and fine sediment down the arroyos of various dimensions. To this end, various kinds of measuring devices were gradually developed and installed. The results reported here represent information collected during 7 years of observation, but some measurements have been made for only a part of the 7-year period.

GEOGRAPHIC SETTING

Arroyo de los Frijoles and the other ephemeral channels discussed here are a few miles west-northwest of Santa Fe, N. Mex. (figs. 138 and 139). They are typical of many small arroyos or dry channels in the lowlands of the Rio Grande Depression at the base of the Sangre de Cristo Range. As one approaches Santa Fe from the west, the Sangre de Cristo Mountains appear to be abutted by a broad sloping surface underlain by poorly consolidated sand and gravel. There are actually several surfaces differing but slightly in elevation. However, the local relief is considerable, with rolling hills dissected by gullies, rills, and broad sandy-floored washes. As is typical of arid regions everywhere, these channels present almost endless variety. They range from tiny rills near the drainage divide to deep, wide arroyos incised in flat alluvial valleys. Vegetation is sparse, both adjacent to the channels and on the interfluves between them. In general the area is a woodland association, including juniper, piñon, sage, and a low-density understory of grasses.

Because of its geological character and climate, the area studied is characterized by huge amounts of both fine and coarse sediment readily available for transportation. During runoff sediment may be derived from the unconsolidated country rock or from recent alluvium adjacent to the channels.

An arroyo discharges water only when a moderately heavy rain falls on the drainage basin. This is a summer phenomenon because heavy rains fall only from thunderstorms. No flow occurs during the winter. Ordinarily during a summer there are about three rainstorms of sufficient magnitude to produce runoff. However, only exceptional rains affect an entire drainage basin the size of the Arroyo de los Frijoles at Sand Plug Reach (drainage area=3.75 sq mi).

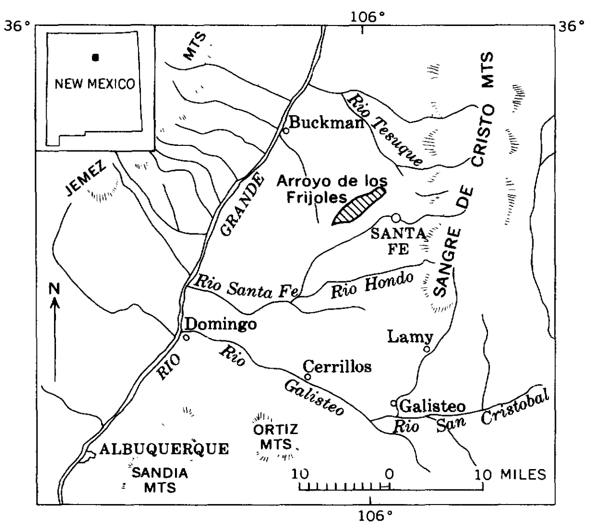


FIGURE 138.—Area in New Mexico where detailed studies were made.

VALLEY ALLUVIUM

Many widely separated areas in southwestern United States have undergone three periods of alluviation followed by erosion, and there is evidence of approximate simultaneity of the respective events from one area to another. That some or all of these events should have occurred in the study area would be a logical supposition.

Arroyo de los Frijoles through most of its length is incised into an alluvial fill of silty sand which at present has a surface configuration characterized by two terraces, and paired remnants of each are common along the principal drainage ways. The higher terrace stands about 5 feet above the channel bed in upper tributaries and tends to remain about the same height downstream along the 7-mile reach which we have studied in detail. The terrace tread is uniform and flat, and vegetated, as are the hills, with piñon and juniper and an understory of grass. Along much of the stream length the terrace is bounded by a vertical wall, at least on one side of the channel, but elsewhere it slopes down to the lower terrace in a subdued S-shaped profile which may have a maximum slope of 1 : 5. Such a rounded scrap is generally vegetated with bunch grasses of low density. The terrace tread grades in a smooth curve to the adjacent hills, and its whole width seldom is more than 300 feet.

The low terrace averages about 1–2 feet above the present streambed and is seldom bounded by vertical banks. Its surface tends also to be somewhat irregular and can usually be recognized by the occurrence of rabbit brush, locally called chamiso [*Chrysothamnus nauseosus* (Pall.) Britt.], which occurs neither on the higher terrace nor on the presently active point bars.

Typical aspects of the valleys and the terraces are shown in figure 140.

The stratigraphic relation of the alluvium of the high terrace to the bedrock underlying the adjacent hills is commonly seen in the vertical banks. The valley fill was laid in a shallow U-shaped trough cut into the friable and poorly consolidated bedrock, and the bed of the present channel lies very near the bottom of this trough in the smaller valleys and probably close to it even in the main stream. That is to say, the present stream has cut nearly through the valley alluvium and most of the depth of alluvium can be seen in the cut banks or vertical walls.

The relation of the alluvium underlying the tread of the lower terrace to that of the upper terrace is difficult to decipher. So nearly the same is the alluvium under the two terrace treads that even when a vertical bank cuts through both, no stratigraphic contact is obvious, though an inset relation is suggested by the contacts seen. The same difficulty is often observed in alluvial fills of western valleys. We have concluded after inspection of many sections, that the lower terrace represents the top of an inset fill and that Arroyo de los Frijoles is an example of a two-fill, two-terrace alluvial valley (see Leopold and Miller, 1954, p. 5, for a discussion of the classification of terraces and fills). A diagrammatic cross section is presented of this valley in figure 141. We here apply the name Coyote terrace deposits to the alluvial deposit under the higher terrace so prominent along streams in the vicinity which will be referred to as the Coyote terrace.

The type locality for the Coyote terrace deposits will be along the Arroyo de los Frijoles at what we will

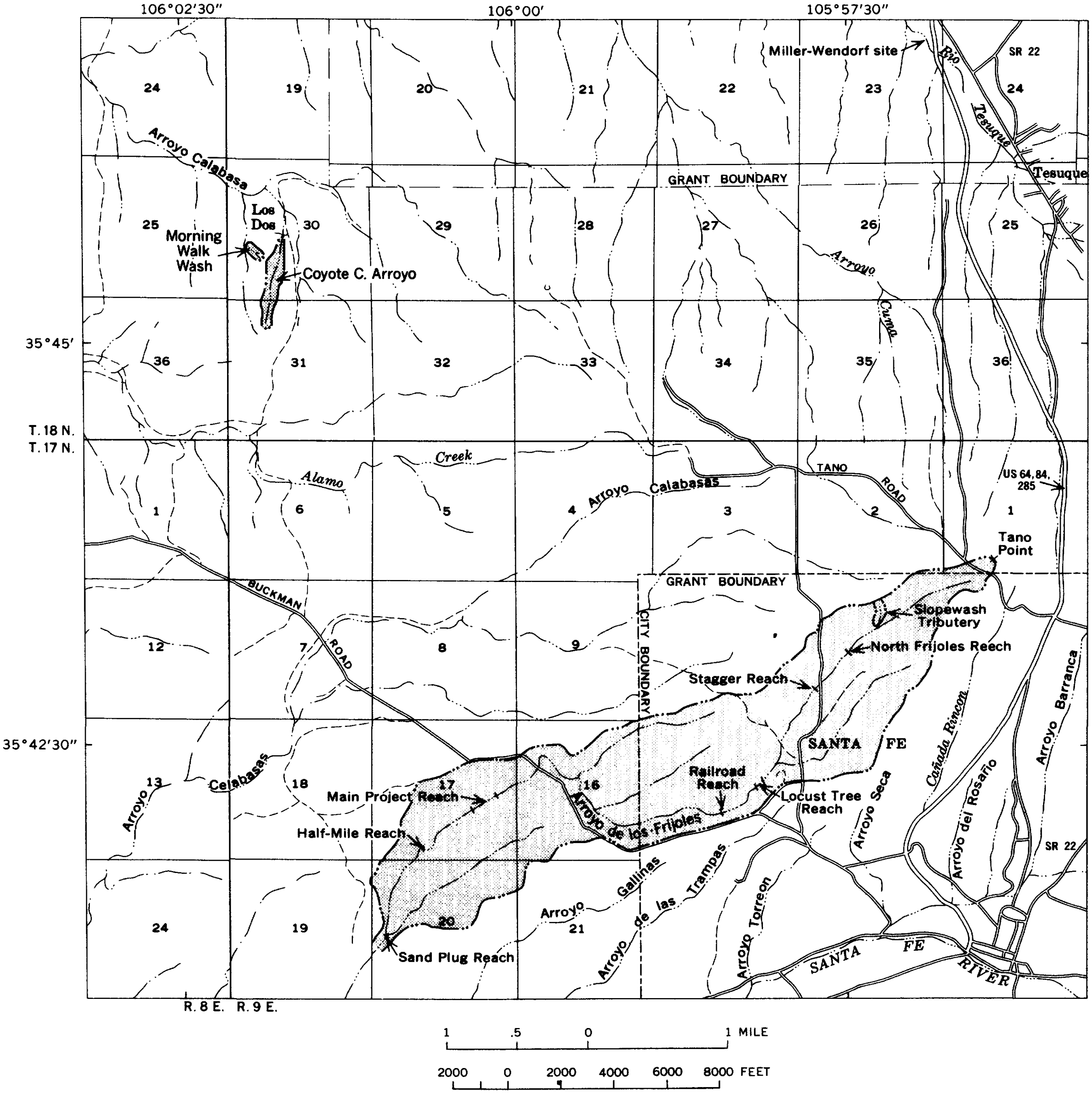


FIGURE 139.—Drainage basins of Arroyo de Los Frijoles, Coyote C. Arroyo, and Morning Walk Wash. Named reaches are locations where detailed studies were made. Also included are principal stream channels and roadways within the area.

A

B

C

FIGURE 140.—Typical aspects of the valleys and the terraces. *A*, Drainage basin of Coyote C. Arroyo; the man is standing on a flat surface of alluvium or colluvium. *B*, Two terrace levels along Arroyo de los Frijoles; the lower terrace, about 18 inches above the channel bed, is in the foreground; at the tree near the channel edge, the upper terrace stands 5 feet above the present bed and grades smoothly to adjacent hills. *C*, Arroyo de los Frijoles; the channel is cutting into the upper terrace material that here stands 8 feet above the present bed elevation; the view is on the left bank just downstream from Fence Line Headcut; bedrock crops out in the channel bed at this place, dipping downstream.

describe here as our main-project reach, in the NW¼ SE¼ sec. 17, T. 17N., R. 9E., 4.2 miles from Santa Fe. The name is derived from Coyote C. Arroyo at Las Dos (see p. 205), where a sample of charcoal buried in this deposit gave a date of 2800±250 years B.P. (USGS sample W1328).

Coyote terrace deposit is alluvium consisting of red-brown, slightly indurated silty sand or fine sand, sometimes fine sandy silt, with occasional discontinuous lenses of fine gravel. When dry, the cut banks stand vertically and are hard to dig with a shovel. The alluvium is 5–10 feet thick and rests on bedrock, which here is unconsolidated sand and gravel. The top several inches may contain more fine sand or silt than at greater depths. No soil zonation is apparent though the upper 6 inches are slightly darker from the admixture of humus and incipient soil development.

The Coyote terrace forms a curving surface as it rises away from the valley floor and joins the hillslopes underlain by the Santa Fe Group. The alluvium interfingers with colluvium at the valley sides and extends upstream in minor tributary valleys, where the distinction between valley alluvium and colluvium at the base of the slope often cannot be made.

In the Tesuque Valley just 4 miles to the north, similar alluvial terraces have been studied by Miller and Wendorf (1958) at a location shown on figure 139. There, two terraces occur at 18–20 feet and 8–10 feet above the present channel; the alluvium underlying the higher one contains dateable artifacts and charcoal. A C^{14} date of charcoal lying 130 inches below the surface of the upper terrace was 2230±250 years. Between the

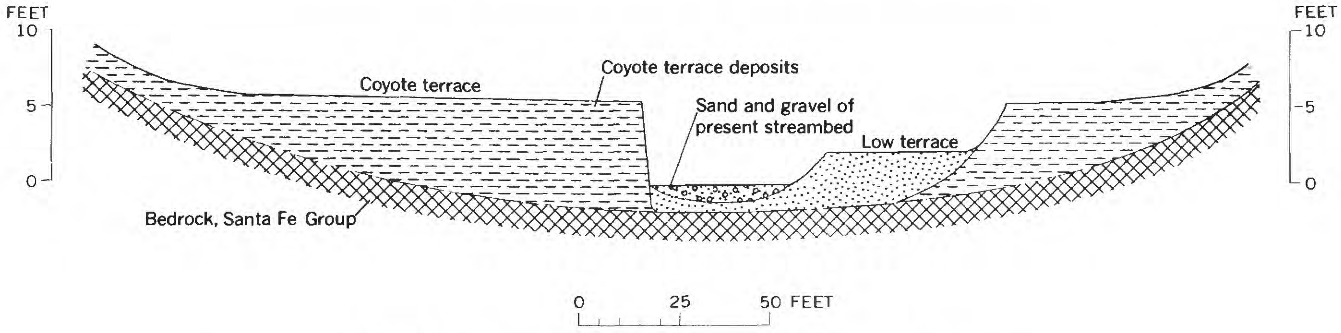


FIGURE 141.—Diagrammatic cross section, Coyote terrace deposits.

Tesuque area and Arroyo de los Frijoles, the agreement of dates, the similarity in form, the comparable character of the alluvial materials, and the geographic proximity of the areas suggest that the respective periods of deposition and erosion in the valleys of the whole area are correlative and may be considered Coyote terrace deposits.

Though the terrace heights and the depth of alluvium of the Coyote terrace deposits differ somewhat from valley to valley as indicated by the comparison between Arroyo de los Frijoles and Tesuque Creek, such a valley fill is ubiquitous in all the ephemeral valleys in the area. It typifies all the drainages rising in the foothills which lie west of the Sangre de Cristo Range and east of the escarpment of La Bajada, a distance of 11 miles or more in most places, and extending north-south at least from Cuyamungue, 12 miles north of Santa Fe, to San Cristobal, 25 miles south of the city. This area of more than 100 square miles has been seen, at least in reconnaissance, during this study, and our impression is that similar relations would be observed over a much larger area in central New Mexico. The Coyote terrace deposits correspond to Deposition 2 in the regional alluvial chronology of Kirk Bryan. (See Leopold and Miller, 1954, p. 58.)

THE LOCAL BEDROCK

The hills being drained by the network of ephemeral channels are composed of the upper beds of Santa Fe Group. The whole group is at least several thousands of feet thick, but that part with which we are concerned includes the upper zones only, principally the Tesuque and Ancha Formations (Miller, and others, 1963, especially p. 50–51 and pl. 1). The geologic map by these authors includes similar landscape 3 miles north of our study area which they mapped as Tesuque Formation described as follows (p. 50):

The Tesuque Formation of the Santa Fe Group, as defined here, consists of poorly consolidated, water-laid silt, sand, and gravel, mostly tan in color. . . . Abrupt changes in texture, both vertically and horizontally, are the rule. Bedding is locally distinct, but few beds can be traced more than a mile or two. Some of the sandstone beds are fairly well sorted and locally crossbedded. Their coherence is due to cementation by calcium carbonate. At most places, even in unconsolidated materials, the sediments are highly calcareous.

The Tesuque Formation was derived from Paleozoic and Precambrian rocks of the mountains. The presence of a considerable quantity of quartzite pebbles, for example near Tesuque, indicates drainage southward from Rio Santa Cruz or Rio de Truchas, which requires a radical difference from the present drainage pattern.

Miller, Montgomery, and Sutherland (1963) consider the Tesuque Formation to be Tertiary. They identify a Pleistocene or upper Pliocene Ancha Formation consisting of remnants of a once-continuous sheet of unconsolidated gravel which extended originally from the western part of the Sangre de Cristo range to the Rio Grande. The gravels were considered to be laid down as fan deposits derived from glacial action and carried out to cover the older Tesuque beds as glacial outwash deposits.

Those workers did not map as Ancha Formation any of the deposits in the area just to the north; the bedrock materials with which we deal are probably entirely Tesuque Formation. Because, as Miller, Montgomery, and Sutherland stated (1963, p. 51), 100–300 feet of dissection has occurred since deposition of the fan gravel comprising the Ancha Formation, the concentration of gravel on many hilltops which we observe in our study area may represent a lag concentrate of gravel derived from Ancha beds which now have been removed.

Other than the gravel concentrate on hilltops, the decription given by Miller and his associates fits the bedrock materials. Those authors, as well as we, observed many places where the upper surface of the Santa Fe beds is weathered. A zone of caliche, 2–3 feet thick locally, permeates the sandy, or elsewhere the gravelly, bedrock materials. This caliche where it crops out does not affect the alluvium or colluvium and indicates processes of soil formation and weathering related to events prior to the deposition of the Coyote alluvium.

RELATION OF VALLEY ALLUVIUM AND COLLUVIUM TO HEADWATER AREAS

The surface of the Coyote terrace can be followed as remnants along the main valley of Arroyo de los Frijoles and other washes upstream to where the present channel is only a few feet wide. Similarly, the surface can be followed up lateral tributaries where it grades to the adjacent hills. Colluvium deposited by rills and unconcentrated wash merges and interfingers with alluvial deposits of the main valleys and tributaries. Excavation by shovel in the bed of any small, even any steep, tributary reveals alluvial-colluvial material within a few hundred feet of the watershed divide. The same relation of alluvium to headwater slopes was found in eastern Wyoming by Leopold and Miller (1954) who summarized their findings in these words (p. 83):

> The terraces of master streams can be traced directly into many tributaries of moderate size, indicating that erosion of alluvium in the master streams was accompanied by gully erosion in tributaries, even the ephemeral ones.
>
> * * * likewise, aggradation in the main stream valleys was accompanied by deposition in tributary valleys and draws. Probably these deposits were derived by mass movement and sheet erosion on upland slopes.
>
> It seems logical that the shift in relations between runoff and vegetation which caused erosion of all major streams would also affect the smallest tributary valleys in a similar way at the same time. . . . As the deposit in the main valley gradually increased . . ., the wash slopes that were graded to the main river accumulated material which blanketed all except the most prominent hills and uplands. The area of upland from which alluvial materials were being derived by erosion shrank, while the area of deposition increased.

The percentage of area of a small basin blanketed with alluvium-colluvium is exemplified in Coyote C. Arroyo. (See fig. 139 for location.) This typical drainage basin has an area of 0.064 sq mi (40.8 acres) of which 0.022 sq mi (14.4 acres) is covered by alluvium-colluvium, the remainder being hillslope and hilltop area of Tesuque Formation. In this example, then, 34 percent of the surface area was alluviated, and the average distance from the head of deposition in small swales to the watershed divide was 190 feet. The alluviation extends headward astonishingly close to the drainage divides. The proximity of the colluvial-alluvial deposits to drainage divide can be seen in figure 140*A*.

The relation of the small tributary draws to the headwater slopes may be typified by the two examples in figure 142. Profiles of the surface of the alluvium-colluvium merge smoothly into the unrilled hillslope underlain by bedrock. Cross profiles drawn nearly parallel to the contours of the side hills demonstrate, in conjunction with the stratigraphic evidence seen in the channel walls and in pits dug in the plane of the profile, that alluvial and colluvial material fill a former channel system cut into the bedrock and that subsequently the present channels have reevacuated parts of the earlier system. The present channel network incised into the alluvium makes a present topography similar to that existing before the Coyote terrace deposition.

This conclusion is supported by observations of the extent of gravel which more or less covers many of the rounded hilltops of the area. In the Slopewash Tributary example in figure 142, section *B–B′* crosses from west to east a gravel-covered hilltop, a gravel-free area, and again a gravel-covered hilltop. At the base of the channel on the right bank the bedrock is permeated with a white cement, presumably $CaCO_3$.

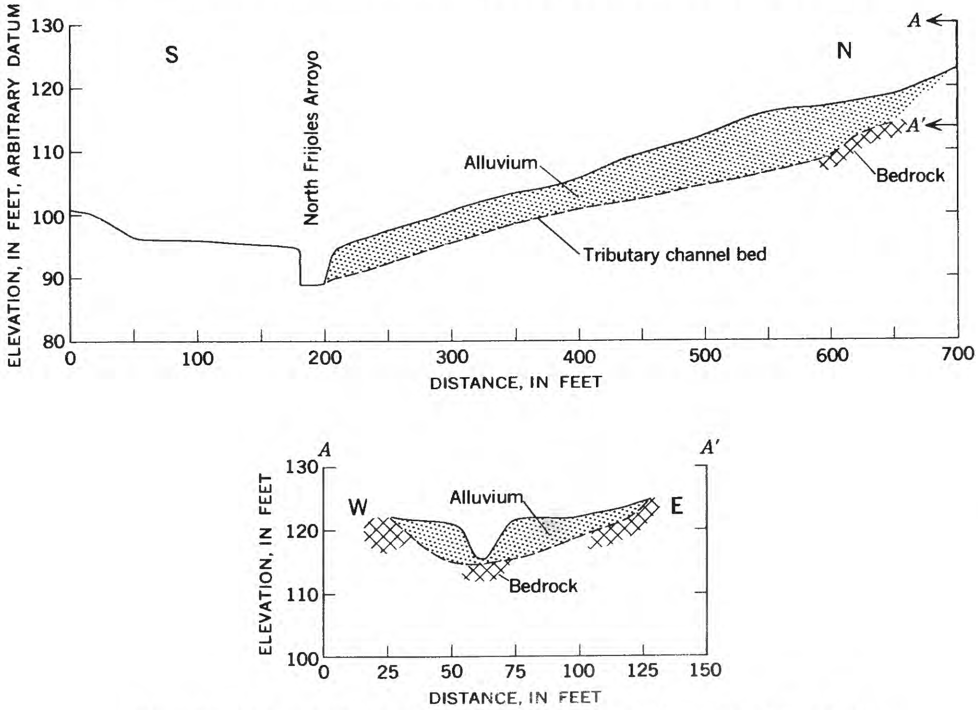
Exposures elsewhere also indicate that hilltops covered with lag gravel are usually underlain by bedrock. Thus the deep layers of silt exposed in present channel walls were deposited in channels which dissected the bedrock. The alluvium lapped up against the gravel-covered slopes and in places covered the gravel.

Investigations of the relation of the alluvium to the bedrock topography showed that the underlying Tesuque Formation generally appears no more weathered at the contact than elsewhere. In some places, however, alluvium was deposited over a surface heavily cemented with caliche. The caliche appears as a hard cement where the Tesuque was gravel, and where the Tesuque was silty, as a whitish calcification of a zone extending 3–4 feet below the contact, and especially concentrated on fracture planes. Hard nodules of caliche in the silt are seldom seem, but amorphous soft masses without sharp boundaries are common.

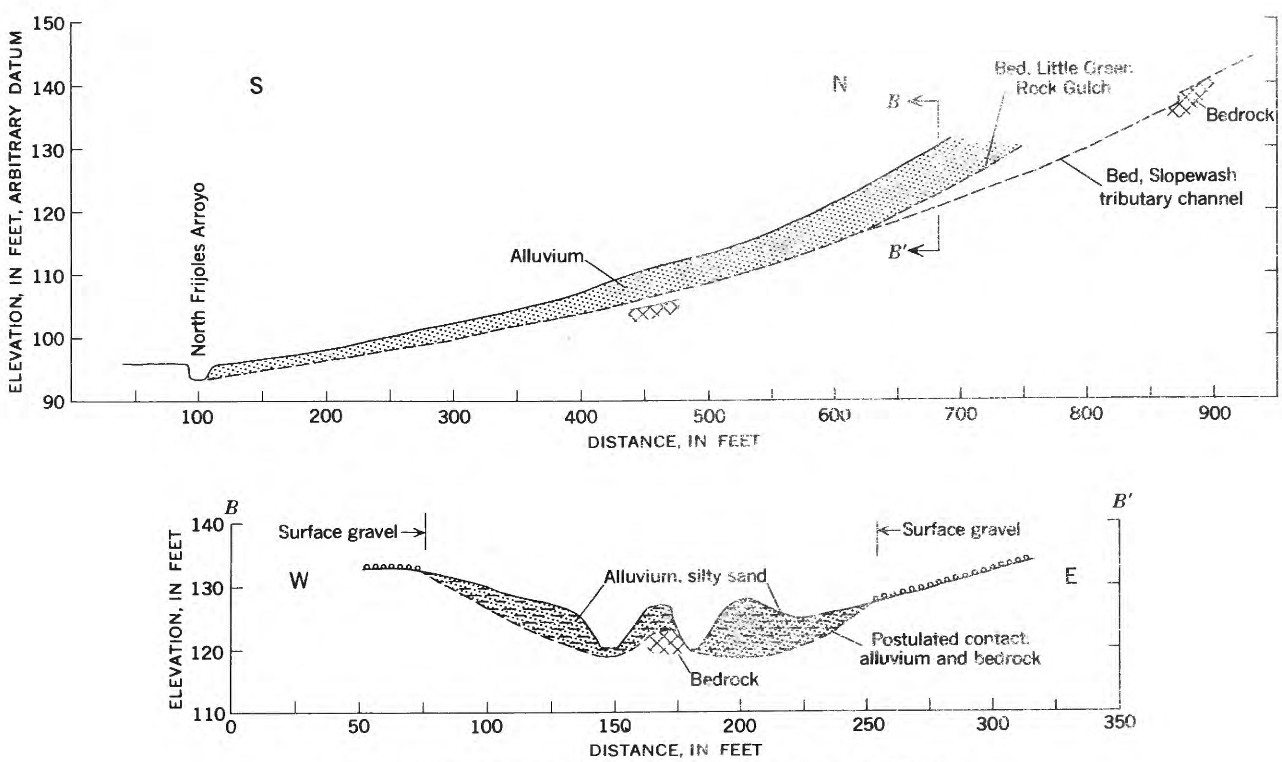
These facts support the conclusion reached by Miller, Montgomery, and Sutherland (1963), that a long period of weathering under subhumid conditions was followed by a semiarid climate during which caliche permeated an undulating topographic surface. Our observations add the additional postulation that, subsequently, this topography was first alluviated and later erosion developed a drainage network similar to and about the same depth as the present one; the erosion removed part but not all of the materials which had undergone calichefication.

To summarize, alluviation during Coyote terrace time aggraded not only the main valleys but small tributary draws as well. Post-Coyote terrace erosion reexcavated much of the earlier topography. The problem posed by this sequence of events is the following:

If alluviation took place in all the headwater draws at the time the main valleys were being aggraded, where did all the debris come from, and by what processes?



A.—UNNAMED TRIBUTARY TO NORTH FRIJOLES ARROYO AT STAGGER REACH



B.—SLOPEWASH TRIBUTARY TO NORTH FRIJOLES ARROYO

FIGURE 142.—Two examples of small tributaries showing stratigraphic and topographic relation of alluvium to bedrock.

Clearly, the sediment was derived from the hills above the areas of alluviation but not from rills or gullies on these hills, as evidenced by the absence of gullies or rills of any depth or importance outside of those which were being alluviated. Thus the sediment must have been derived from processes other than rill and gully erosion, specifically, sheet erosion or mass movement. This hypothesis attributes to the latter processes greater efficacy than we at least would have supposed. We were led, then, to devise methods of measurement which would allow the construction of a sediment budget, however approximate, to ascertain whether relative importance of present processes would shed light on these events of the past.

Another problem is highlighted by the postulates stated. It is usual to suppose that alluviation of a master stream would provide a rising base level for the tributaries which enter into it. Then the aggradation in the tributary would similarly provide a rising base level for its own subtributaries. Though this scheme is a simple one and would lead to field relations here observed, it also implies that the alluviation of the headwater tributaries would lag in time that of the main stem. But these inferences do not agree with field observations in the Arroyo Frijoles area.

It seems much more likely that in our study area the relation of runoff to vegetation which would lead a main stream to aggrade would similarly have the same result on the tributaries. We believe that control by base level is a relatively minor factor in alluviation of the valleys studied.

The remainder of this paper is organized around the measurement program instituted to investigate these questions. The sample areas studied will be described, the measurement methods outlined, and the results summarized. These measurements will then be discussed in terms of the problems outlined (see p. 236). We begin with a discussion of the study areas.

STUDY AREAS

The areas of special study shown in figure 139 include Arroyo de los Frijoles through its uppermost 7 miles and some smaller basins of several acres in an area 4 miles distant, near Las Dos. The principal basin, Arroyo de los Frijoles, has a channel width which ranges from the smallest recognizable rills a few inches wide to an arroyo 100–200 feet wide. All channels more than a foot wide have a flat predominantly sandy surface dotted in places with scattered gravel.

Larger scale maps, figures 143–45, show details of the areas of intensive study and will be referred to in later discussions.

Figure 146 illustrates the character of the country and the aspect presented by main and tributary channels. Figure 146, *A* and *B*, shows a small tributary within a few hundred feet of the headwater divide, a subbasin we called Slopewash Tributary.

At a point 1.1 miles from the furthest divide the North Frijoles Reach is typical, figure 146. One mile farther downstream the channel is larger, as shown at Locust Tree Reach (fig. 146*D*). Main Project Reach, 4.9 miles from the headwater divide and at a place where the drainage area is 2.87 sq mi, is illustrated in figures 146*E* and *F*.

Some characteristics of each of the study areas are indicated in table 1.

TABLE 1.—*Characteristics of locations studied*

Location	Drainage area (sq mi)	Elevation (ft above msl)		Relief (ft)	Length (ft)
		At headwater	At downstream point		
Arroyo de los Frijoles:					
Slopewash Tributary	0.05	7,280	7,200	80	1,200
North Frijoles Arroyo:		7,388			
At gaging station	.56	--------	7,159	229	5,800
At Stagger Reach	.70	--------	7,111	277	8,200
At mouth	1.36	--------	7,048	340	11,750
At Locust Tree Reach	1.49	--------	7,037	351	12,400
At Railroad Reach	1.61	--------	6,987	401	15,400
At Main Project Reach	2.87	--------	6,790	598	28,000
Sand Plug Reach:					
At Stump section	3.18	--------	6,696	692	33,600
At Rocky Nose section	3.75	--------	6,672	716	34,800
Gunshot Tributary, at mouth	--------	6,798	6,723	75	1,150
Arroyo Falta	.12	6,800	6,620	180	5,000
Coyote C. Arroyo, at dam	.064	6,735	6,550	185	3,600
Morning Walk Wash:					
South gully	--------	6,633	6,540	93	700
North gully	--------	6,615	6,540	75	870

METHODS OF STUDY

Observations of nearly all the types described here began in the period 1958–61 and are continuing as this paper is written. Water stages of flow are measured by recorders at gaging stations installed on North Frijoles Arroyo and at Main Project. The duration of individual flows is generally two hours or less and current-meter measurements for the construction of stage-discharge rating curves are impracticable without a full-time resident hydrographer. Stage-time hydrographs are obtained from the stage recorders, but maximum discharge for each flow is computed using a survey profile of high-water marks. This, combined with cross-sectional areas of flow determined by scour chains (described below), permits the computation of discharge using an estimated value of flow resistance.

A network of 12 nonrecording rain gages is observed after each significant summer rain.

Depths of scour and fill in channels are measured by chains set vertically in a dug hole in the streambed. At maximum depth of scour the chain is bent over by the flow and is usually covered by fill on the receding stage (Emmett and Leopold, 1964).

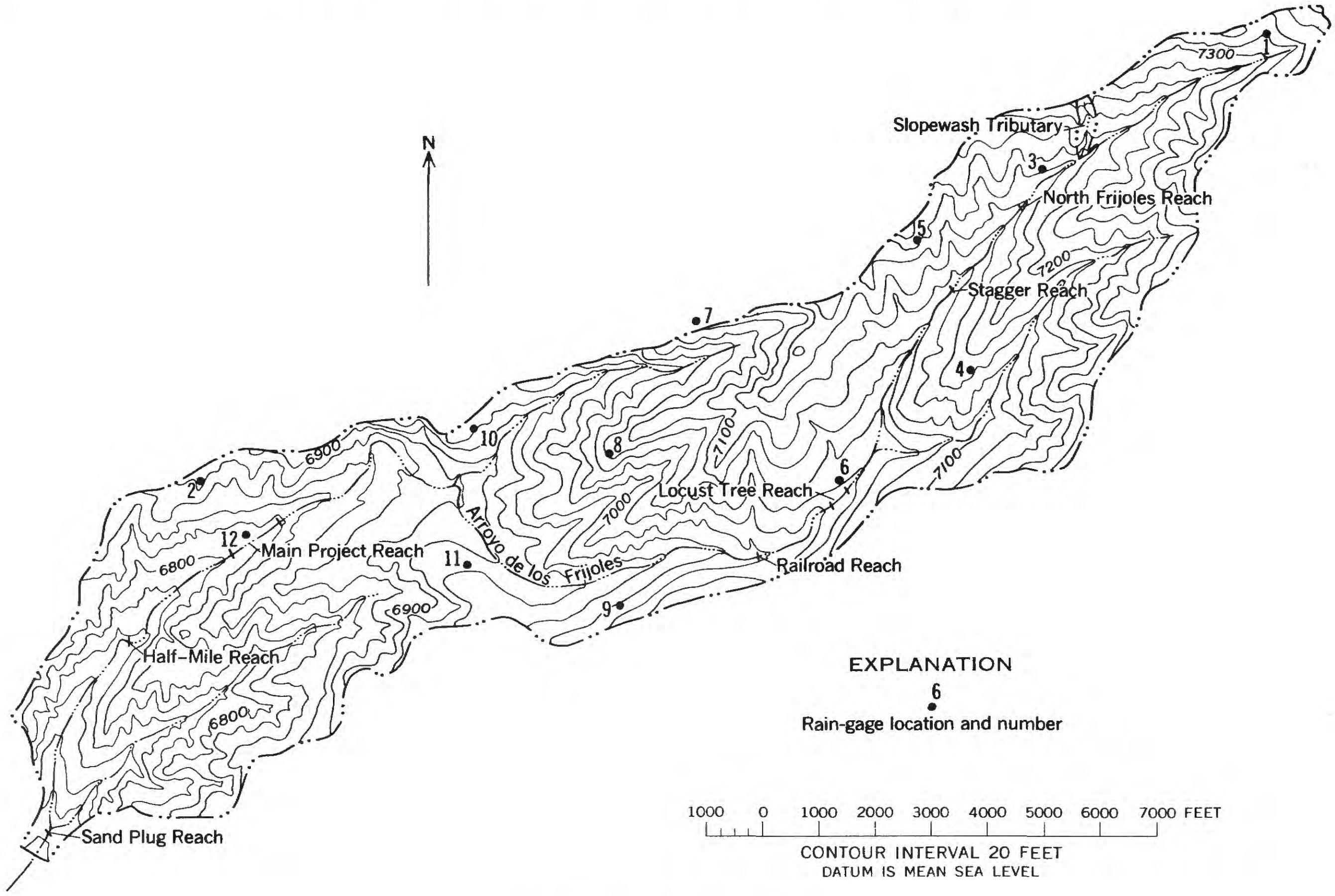


FIGURE 143.—Arroyo de los Frijoles.

Erosion pins, consisting of a 10-inch nail put through a washer, driven flush with the ground surface, are used to record increments of surface erosion. Some of these pins are arranged in a grid over certain plots, but generally the nails are in a line as a transect from hilltop to base or across a channel as a cross-section.

Mass-movement pins are set on a line between immovable bench marks, and are surveyed for alignment by transit.

Many rocks have been painted for identification and observed for movement after each flow.

The individual plants on some 3×3-ft quadrats have been mapped and are to be remapped periodically to observe changes with time.

Although the methods are simple, the labor after each storm (about 3 per summer) and during the annual resurvey of all observation points is rather great.

MAGNITUDE AND FREQUENCY OF RAINFALL AND STREAMFLOW, 1958–64

Rainfall has been measured since 1959 at 12 locations within the drainage basin, as shown in figure 143. Summary of data A (p. 247) contains a partial summary of the data collected from these sites.

The gages were not read after each shower, but efforts were made to read them at least after every flow-producing storm. The sporadic nature of storms is indicated by the unequal distribution of rainfall among stations.

At the Main Project Reach a recording rain gage has been installed at the location of the water-stage recorder. Precipitation data (summary of data B) collected here allow a better indication of the rainfall characteristics. The record is too incomplete to show the mean annual precipitation which at that location must be about 12 inches per year.

The 1,300 cfs (cubic feet per second) flow of July 25, 1962, the second highest flow recorded at the Main Project Reach, was caused by a storm which registered 1.5 inches in 25 minutes at the Main Project gage.

Channel discharge is measured or estimated at three places in Arroyo de los Frijoles: Main Project, Locust Tree, and North Frijoles. Gaging stations are installed at the Main Project and at North Frijoles reaches. During the period 1958–63, runoff occurred at the three measuring stations on the dates indicated in table 2, in which are presented values of peak discharge. Spaces in the table usually refer to no flow; however, in a few instances some flow may have occurred but was of negligible magnitude. Flow data discussed in this report are all peak values.

TABLE 2.—*Summary of peak discharges, in cubic feet per second, at three locations along Arroyo de los Frijoles, 1958–63*

[(a) and (b) refer to separate flows or different peak flows occurring on the same day]

Date	North Frijoles	Locust Tree	Main Project
1958			
August 18			20
September 6	15–20		10–15
September 13	194	1,320	3,060
1959			
May 23	140	50–75	3–5
June 15			2–4
July 23			10–15
August 17		20–25	20–25
August 24	50	15	
October 29	.5		1
1960			
July 14	67	360	35
August 4			152
September 15(a)	1		10–20
(b)			10–15
October 9	3–5		
October 16(a)	5–7		
(b)	9–10		10–15
October 17			10–15
1961			
June 26			1
July 8	58	498	98
August 12	85	300–400	80–90
August 23	3–5	3–5	.3
September 18 (a)	10		40
(b)			60
September 19	230	650	250
1962			
June 30	.3	30	
July 5	6–8	150	40
July 6	.3		10
July 18			3
July 22	.5		
July 25	85	450	1300
July 30	90	450	300
September 19	1		
1963			
July 20	10	5	15
September 21	5	391	316

Most storms are intense and so local that only a part of the drainage basin is affected by each. Only twice (September 13, 1958, and July 25, 1962) was there increasing discharge in the downstream direction due to heavy rainfall over the entire basin, and these two storms caused the greatest flows during the period of record.

For each of the three measurement locations, the peak flows experienced were arranged according to rank and recurrence intervals were computed. These are plotted against their corresponding discharge and are shown as dashed lines in figure 147. Recurrence intervals are determined by the U.S. Geological Survey method, $T=\frac{n+1}{m}$, where T=recurrence interval in years, n=number of years of record, and m=magnitude or rank of flood, the highest being number one.

Excepting the two storms just mentioned, the spotty distribution of precipitation implies that data collected at each of the three reaches may be considered as independent flows. If this were in fact true, a type of station-year analysis might be attempted by combining 5-years of record for each of three locations into a synthetic 15-year record. The solid line on figure 147 gives this average frequency of the three reaches. The solid circles on this graph represent all flows at the three stations, arranged in order of magnitude.

For small flows all moderate-size drainage areas are capable of receiving sufficient rainfall to produce a similarity in flow frequency. For drainage areas larger than some given size, further increases in area would not increase the size of flood of a given frequency. This feature is indicated by the fact that a flow of 2-year recurrence interval is about the same at Locust Tree and Main Project Reaches despite the fact that the drainage area of the latter is about twice that of the former.

The present data exceed by fivefold the values presented by Leopold and Miller (1956, fig. 21, p. 24). The latter values should not be considered applicable to the foothill area of ephemeral streams though they were so considered in that report. It is now obvious that flow frequencies of the gaged streams emanating from the high mountains are not comparable with and are smaller than values for ephemeral washes in the foothills, despite the lower mean annual precipitation of the latter areas.

The problem of flow frequency is of paramount importance to evaluation of erosion and sediment transport processes. Though the method of determining frequency is still open to further study in ephemeral basins, figure 147 expresses the occurrence of events in the studied basin during the period of observation.

CHANNEL FORM AND BED MATERIALS

A salient aspect of the change in channel characteristics downstream is the increase in width, shown in figure 148. As defined here, channel width refers only to the active channel which is swept free of vegetation except for annual plants. In some places the actual width between the steep banks is greater than indicated on figure 148. Such reaches usually include remnants of the lower terrace, which not only supports some vegetation but also stands 1–2 feet above the presently active bed.

The variability of channel width quite evident in figure 148 seems large, but one does not realize how large the variance is in the usual channel until he begins to make quantitative measurements. On a perennial eastern stream not much larger in drainage area than Arroyo de los Frijoles, the ratio of the standard deviation to mean channel width averages about 0.25 (data from Wolman, 1955, fig. 37), whereas for a reach of Arroyo

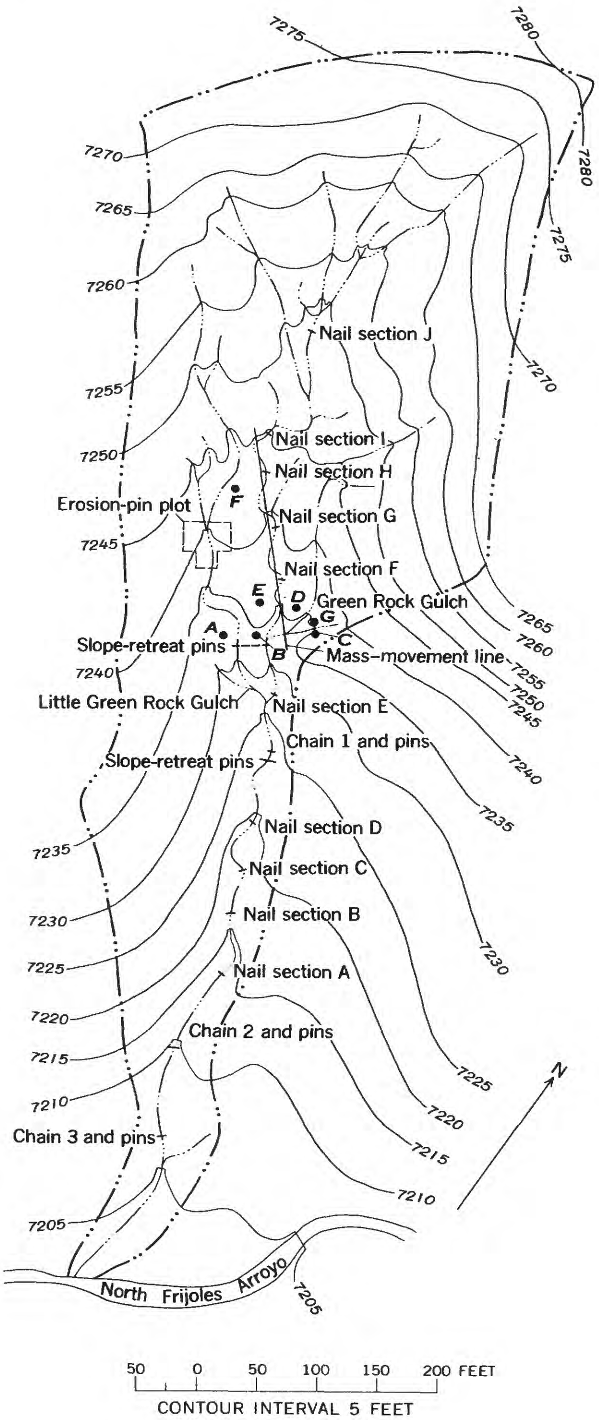


FIGURE 144.—Slopewash Tributary

de los Frijoles below the junction of North and South Frijoles it is about 0.39. Also, the variability of width is not so great above that junction where the drainage area is less than 1 sq mi. In an ephemeral basin, it appears that when the drainage area exceeds the size of the usual summer thunderstorm, only parts of the basin contribute runoff. Thus different reaches of channel experience different sequences of flows, and this probably tends to increase the variance of channel width.

The increase in drainage area with channel length is shown in the top part of figure 148. At three places, sudden increases in drainage area occur where relatively large tributaries enter the main channel. However, as mentioned above, it appears that these increases in drainage area affect channel width only incidentally, as the size of a given storm may or may not extend over the whole contributing area.

The bed of Arroyo de los Frijoles is predominantly sandy with scattered fine gravel and cobbles, but there are local concentrations of rocks. Considering first the nongravelly areas which predominate, sieve analyses are shown in figure 149*A*. The median diameter for all surface samples are within the limits of medium to coarse sands.

Three samples from Arroyo de los Frijoles provide comparison of median grain diameter at points downstream in the same basin.

Location sampled	Drainage area (sq mi)	Median grain size (mm)
Slopewash Tributary	0. 05	0. 56
North Frijoles Reach	. 56	. 78
Main Project Reach	2. 87	. 72

Though a larger number of samples may have yielded a more uniform set of values, at least it can be said that there is no progressive decrease of the size of sand downstream.

Figure 149*B* illustrates the composition within the area of a gravel concentration or bar. Clearly, the majority of the larger particles are in the top 2 inches (discussed in more detail on p. 212) and the composition over the full depth of the concentration is more coarse than in a nonbar area. Downstream tips of gravel bars are characterized by material a little finer than in nonbar areas. This is an expected pattern and is observed in other depositional phenomena such as mudflows.

The largest particle occurring in each 100-foot segment of the channel of Arroyo de los Frijoles was measured, and the results are plotted in figure 150. The size of the material in the Slopewash Tributary is as large as that in North Frijoles and, indeed, almost as large as that anywhere in the whole length of the stream. Maximum particle size actually increases somewhat downstream, and local variations from section to section are commonly two to threefold.

In gravelly perennial streams the occurrence of pools and riffles is characterized by considerable bed relief.

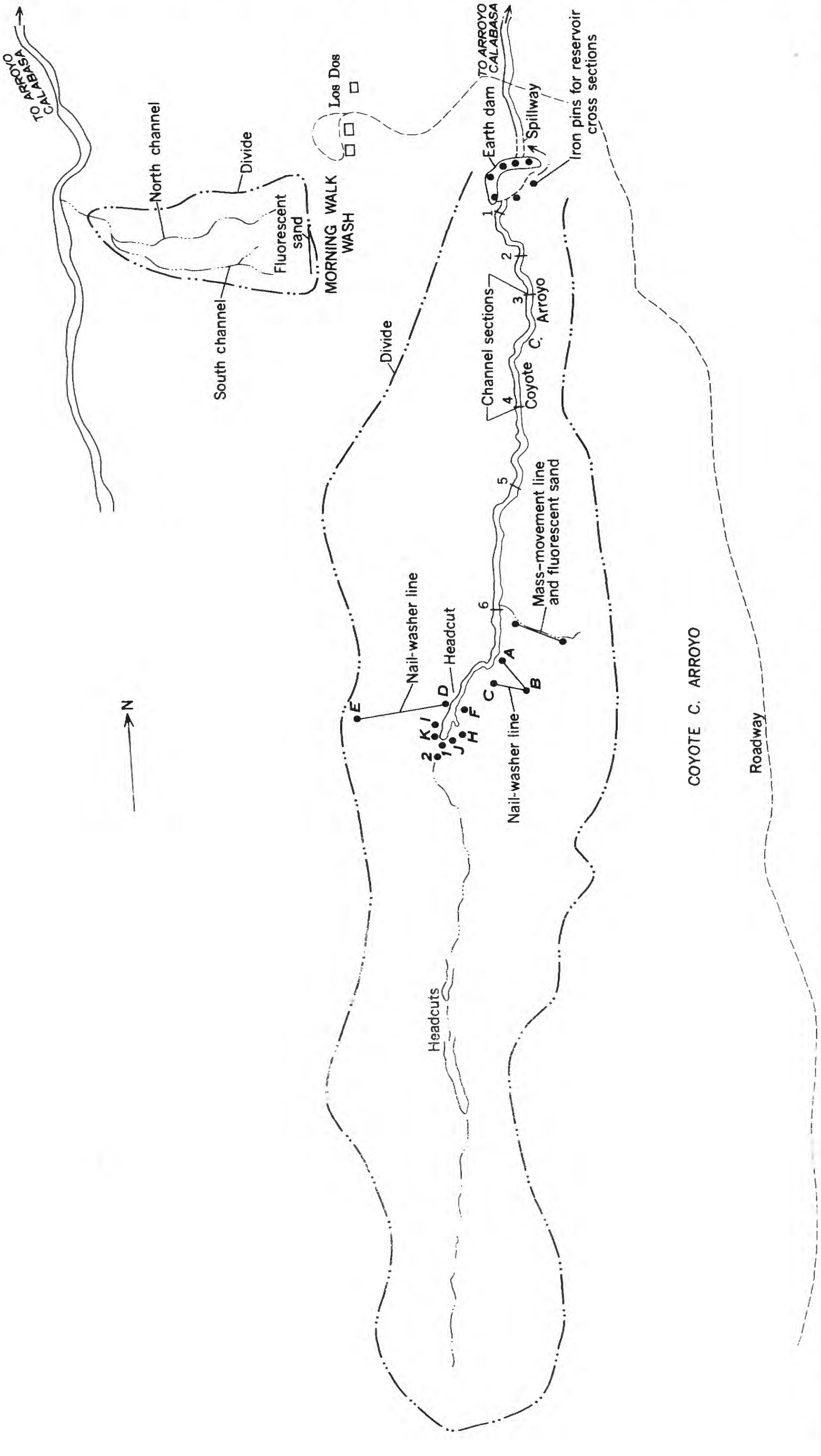


FIGURE 145.—Drainage basins of Coyote C. Arroyo and Morning Walk Wash; solid circles labelled in bold type are nail-and-washer observation points or iron pins for resurvey; channel cross-section locations are labeled 1–6.

A

B

C

D

E

F

FIGURE 146 (Above and left).—Photographs illustrating several of the individual study areas. *A*, Slopewash Tributary; the area shown is along the mass-movement line (see fig. 144 for location). *B*, Slopewash Tributary; the area shown is within the erosion plot. *C*, North Frijoles Reach, Arroyo de los Frijoles; the view is downstream from above the gaging station. *D*, Locust Tree Reach, Arroyo de los Frijoles; view upstream; visible in the foreground are rock groups from the painted rock experiments. *E*, Main Project Reach, Arroyo de los Frijoles; the view is downstream from above the gaging station. *F*, Main Project Reach, Arroyo de los Frijoles, looking upstream.

The riffle is a gravel bar or accumulation which is a topographic high, a feature which rises well above the mean bed elevation. The pool is a trough below mean bed elevation.

In the larger ephemeral streams of the area here studied, there is no such relief on the dry streambed. In fact the bed is remarkably flat across its width and closely resembles a gently inclined plane, for the longitudinal profile is quite straight.

Only in detailed mapping did we become aware of the fact that local concentrations of gravel on the sand bed correspond in principle to the riffle of the perennial river. These bars, as we call them, are so slightly elevated above mean channel bed elevation that they would not be recognizable as a topographic high. Rather, we have mapped them merely by inspection of surface texture. Because some gravel particles occur everywhere, designation of a bar is rather subjective, but generally it implies individual cobbles spaced within several diameters; whereas in areas not called bars the spacing of cobbles would be 20–50 diameters or more. Typical gravel concentrations are illustrated in figure 152*D*.

SPACING OF GRAVEL BARS

The position of gravel bars in the vicinity of the Main Project Reach as mapped each summer during the period 1958–63 is shown in figure 151. It seems apparent that the position of a gravel bar remains remarkably stable. This is true despite the fact that two or three flows of sufficient magnitude to move the material on the bars occurred between the successive mappings. For example, the largest flow measured during the entire period of study occurred between mappings in 1958 and 1959, and at that time scour to depths of 0.4–1.4 feet occurred. Thus all the material of the surface of the channel bed moved downstream, yet the bars were rebuilt in approximately the same places as before. However, with each annual mapping, a few bars are missing in the new map that were present in the old map, and also a few new bars appear.

Beginning in 1961, a more intensive effort was made to map gravel accumulations. It is this effort, rather than an actual increase, which, in figure 151, shows more extensive areas of gravel beginning in 1961.

In accordance with observations elsewhere the gravel bars are spaced on the average at a distance equal to five to seven times the channel width, and this ratio persists through all the years of record.

Measurements of gravel size and density on the surface of gravel bars were made at two different times separated by major flows. It was found that both the size distribution and density of particles greater than 1 inch in diameter remained almost the same.

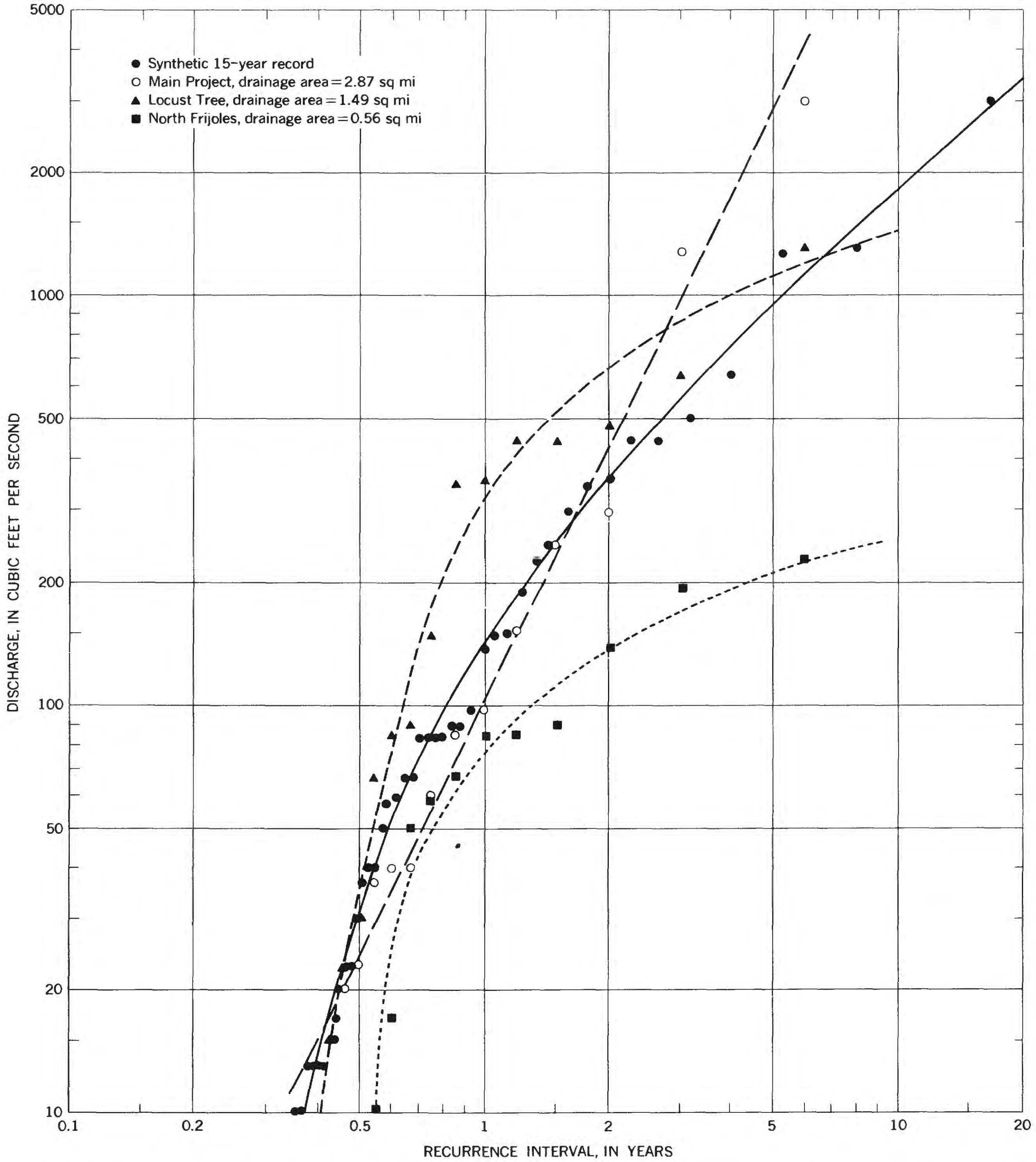


FIGURE 147.—Magnitude and frequency of flows, Arroyo de los Frijoles, 1958–62.

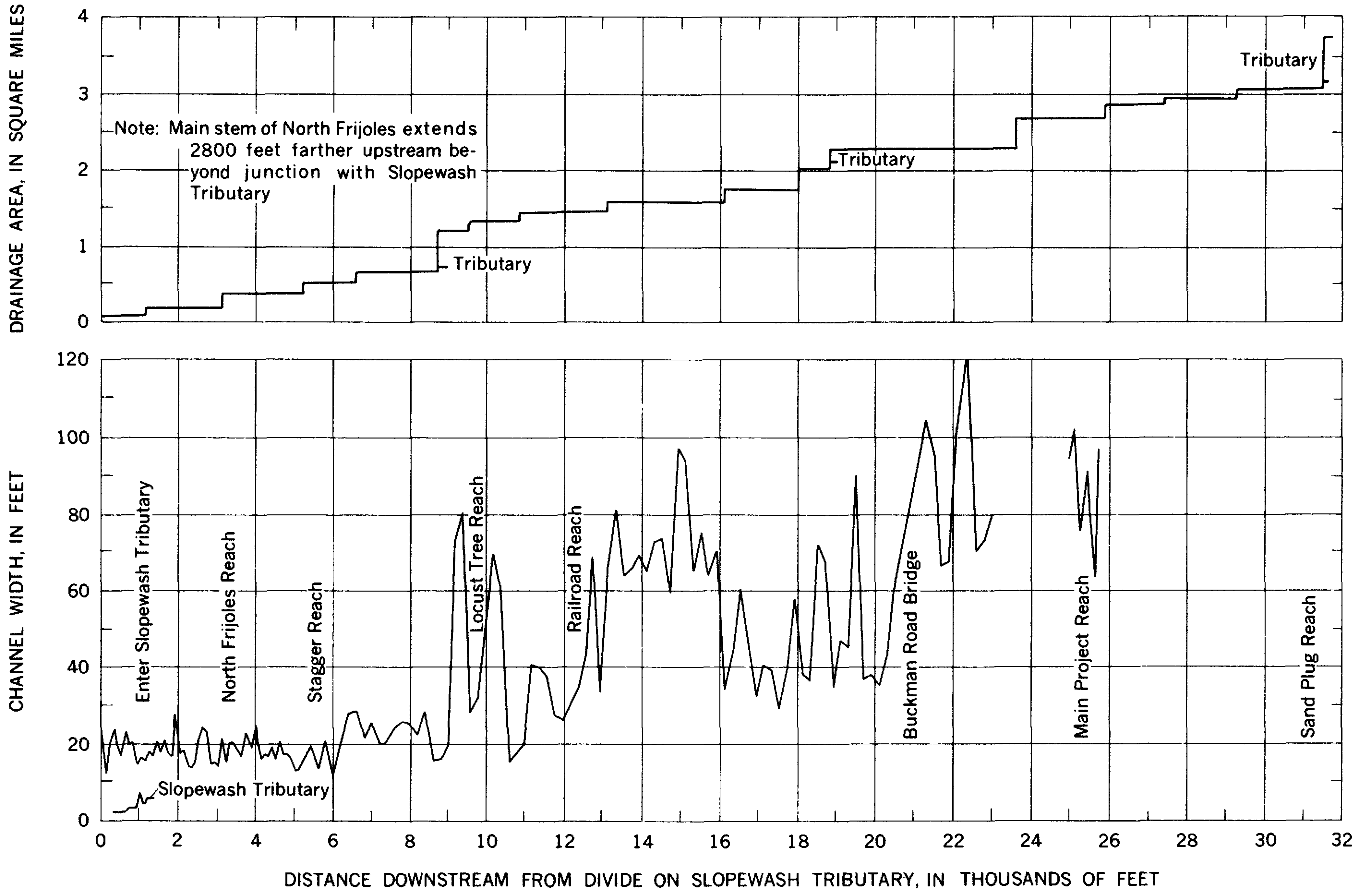


FIGURE 148.—Relation of channel width and drainage area to channel length, Arroyo de los Frijoles.

MOVEMENT OF COARSE PARTICLES

We had hypothesized that gravel bars owe their existence to the fact that particles in juxtaposition are less easily moved by flowing water than when widely separated. Marked cobbles arranged in groups of various spacings and collected after individual flows would provide a means of testing under field conditions whether this hypothesis would be sustained.

The following procedure was developed: Cobbles taken from the channel were completely painted. Each was given an indentification number equal to its weight in grams, and this number was painted on the cobble. The rocks were placed in the channel in groups, each group contained a chosen particle-size distribution and comparable groups differed in spacing of the rocks. After each flow the entire length of the channel was searched for painted rocks. Those found were recorded, collected, and replaced to await the next flow. This procedure was carried out after each significant stormflow during the summers of 1958–63, inclusive, and discontinued thereafter.

In these studies a group of particles consisted of 24 individual rocks arranged in a parallelogram. The distance or spacing between particles was one of three values, 2 feet, 1 foot, or 0.5 foot.

Except for the initial summer (1958) the individual groups included four particles in each of the following size (weight) classes:

Weight class (grams)	*Intermediate axis, approximate mean diameter (mm)*
300–500	65
500–900	85
900–1,700	105
1,700–3,300	125
3,300–6,500	160
6,500–13,000	230

Individual particles in the grid were arranged in a Latin Square pattern, in which each line of six particles includes one and only one of each of the size classes, and in each cross-tier, no rocks of the same size are in juxtaposition.

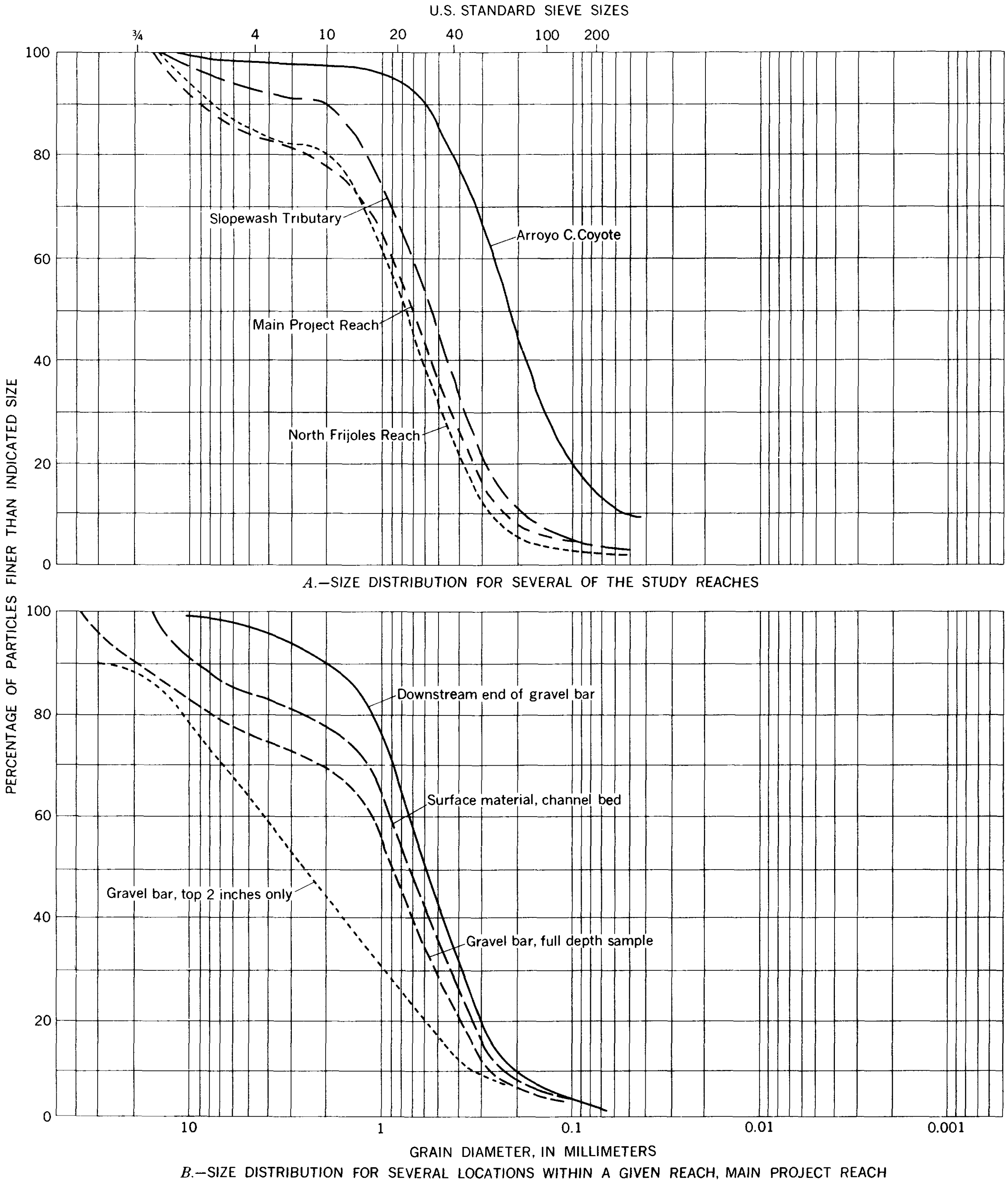


FIGURE 149.—Bed-material grain-size distribution, sieve analyses.

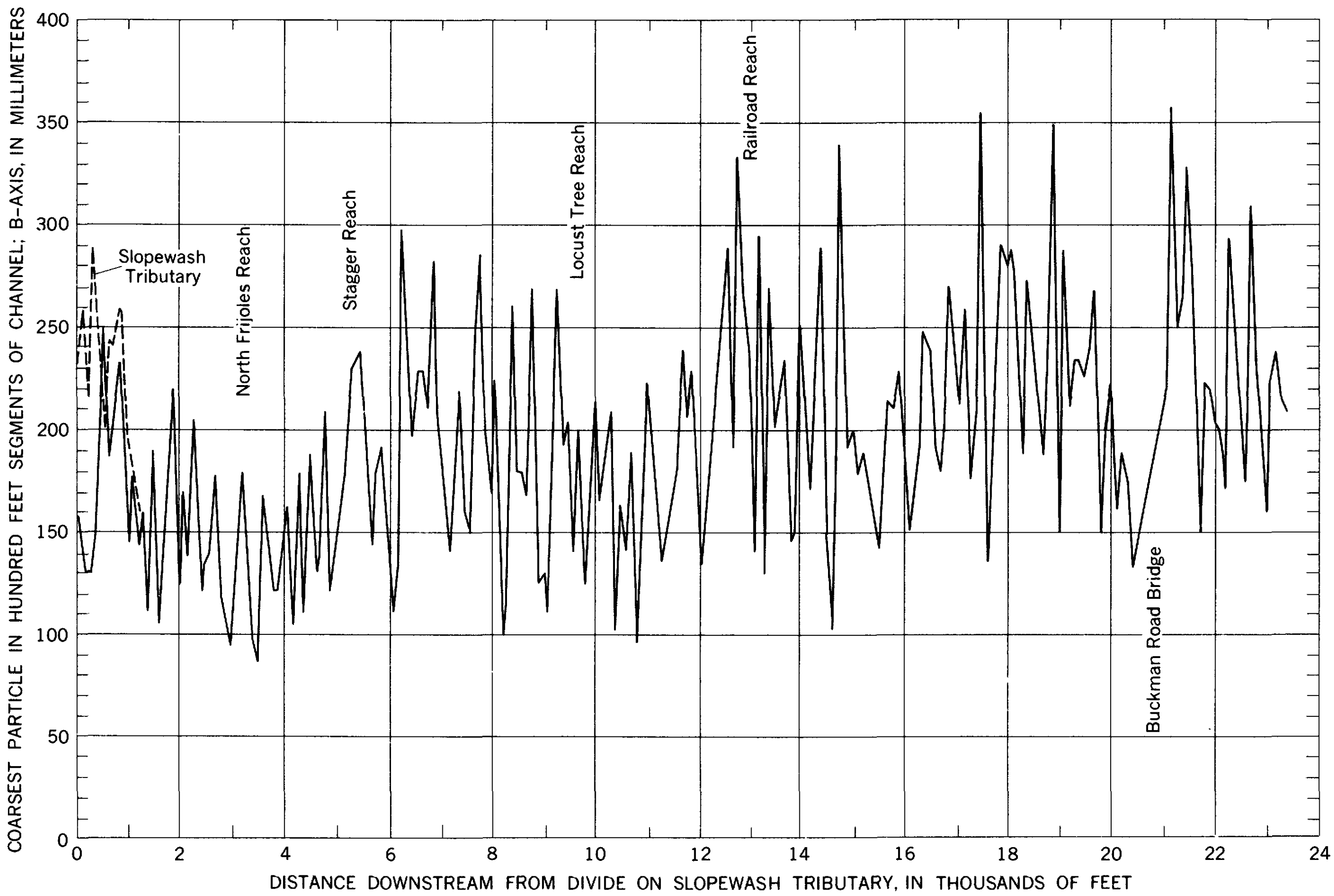


FIGURE 150.—Downstream distribution of coarsest particle in each 100-foot segment of channel.

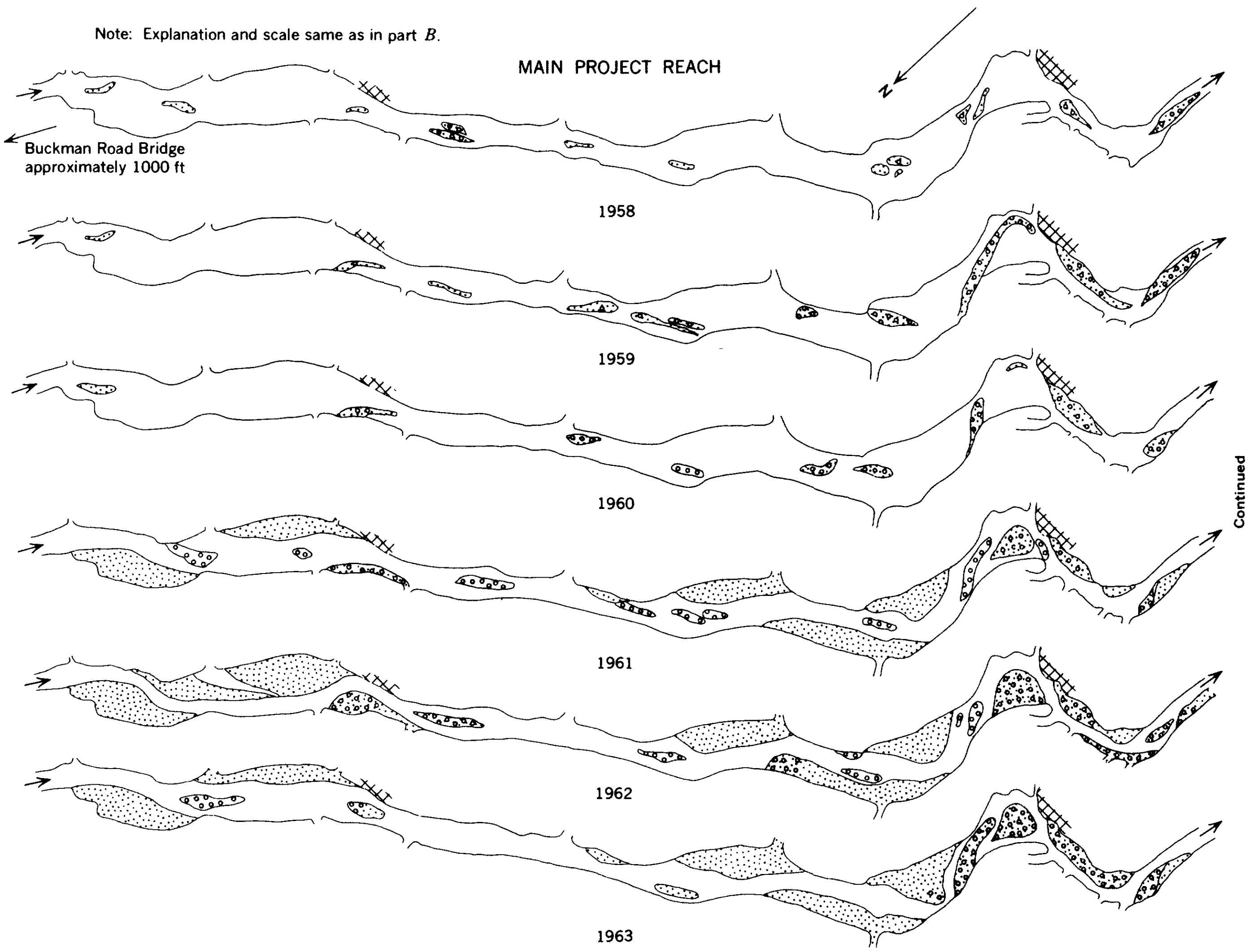
Also, for several flows, the experiment included some rock groups composed of only one weight class. In this arrangement, rocks were spaced on 1, 2, or 3 diameters rather than by the absolute distances of 0.5, 1.0, or 2.0 feet.

At the Main Project where the channel is straight, there were initially eight ranges of rock groups about 110 feet apart. The groups having 1-foot spacing lay along the centerline of the channel and the groups having ½-foot and 2-feet spacing on either side, alternating from one range to another. Arrangement of the four upstream ranges was the obverse of that for the four downstream ranges so as to eliminate bias in across-the-channel variation. The position of each particle was individually recorded together with its weight and dimensions of the long, intermediate, and short axes. In addition there were two lines of boulders (as much as 97,500 g) spaced 9 feet apart across the channel in this reach. At various times additional temporary ranges of particle groups have been installed at the Main Project Reach, but the eight ranges and two lines of large particles described above were maintained during the entire investigation. After each flow we measured the distance that individual particles moved, and in preparation for the next flow, reconstructed each particle group in accordance with the specifications described.

Procedure at other reaches was basically the same as for the Main Project Reach. At the Locust Tree Reach there were originally two ranges, three since 1960, each including groups having two different spacings, and also a line of large rocks spaced 6 feet apart. The channel is so narrow at the North Frijoles Reach that the groups having different spacings were located along the length of the channel rather than along a line perpendicular to it.

At the Railroad Reach there was a single line of angular basalt boulders weighing as much as 111,000 grams and spaced 4 feet apart. The Stagger Reach had two lines of basalt boulders weighing as much as 47,500 grams, and spaced 3 feet apart. Basalt is a lithology foreign to the drainage basin and was derived from highway and railroad fills.

Tracing the downstream movement of painted gravel particles during a flow involved certain difficulties. An



A.—SAND AND GRAVEL BARS FROM BELOW BUCKMAN ROAD BRIDGE TO HALF-MILE SECTION

FIGURE 151.—Spacing and composition of

initial problem was to find a paint that is weather resistant during long periods of immobility and is abrasion-resistant during transport. Oil-base paints proved unsatisfactory because they peeled excessively. Except for the first year, water-base masonry paint was used with satisfactory results.

Even if the paint remains intact and every particle found is identifiable, there are still losses due to burial of particles in the sand, entrapment in brushy areas, or transport outside the search area. The rocks from a given group may move downstream distances ranging from a few feet to 3 miles, depending on the magnitude of the flow. Because of their bright color, painted rocks are plainly visible in the sandy channel unless completely buried. Many particles are found partly buried (fig. 152) and the data on losses indicate that others become completely buried. Recoveries range from more than 90 percent in small flows to 2 percent for one exceptionally large flow. Apparently the losses have decreased since adoption of a water-base masonry paint, but even under optimum conditions losses of 10–30 percent during small flows and 30–50 percent during large flows are to be expected. The greatest losses occur in the smaller size classes.

Deep burial in the sandy channel seldom occurs in the area studied. Many holes 4 feet deep were drilled in the channel bed for installation of scour chains, and no coarse gravel was encountered. The composition of

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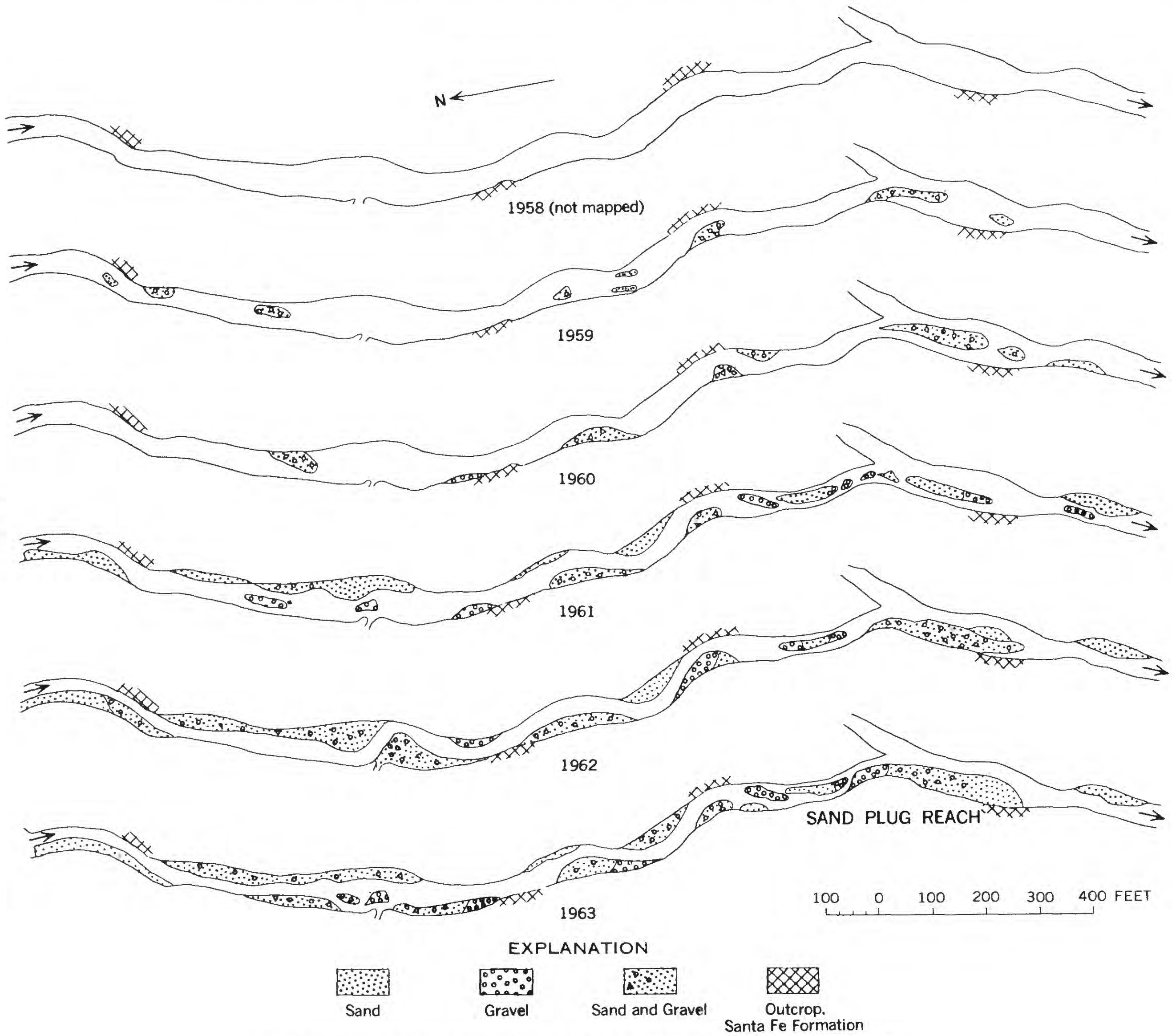


B.—SAND AND GRAVEL BARS FROM HALF-MILE SECTION TO SAND PLUG REACH

gravel bars, Arroyo de los Frijoles, 1958–63.

gravel bars lends support to the conclusion that coarse particles occur only at or near the channel surface. A typical bar (fig. 152*D*) is strewn with coarse gravel, and in a typical cross section it is apparent that this is only a surface veneer extending at most a few grain-diameters deep.

Even when the bed scoured more than a foot in a high flow and subsequently filled to the original elevation, large gravel particles did not become deeply buried and, for the most part, projected slightly above the refilled surface.

The explanation of this phenomenon appears to be the Bagnold-dispersive-stress (1956) caused by grain-to-grain impact during motion. The stress increases as the diameter squared and the large particles, subjected to highest stress, are forced to the bed surface where the dispersive stress is zero.

Subsequent to these observations, some streambeds in Maryland (annual precipitation 44 inches) were sampled to determine whether similar phenomena occur. It was found that gravel-bed streams in a subhumid region also tend to have a concentration of the largest particles at the surface of the channel bed (Leopold and others, 1964, p. 211).

For the purpose of segregating the influence of size and spacing on particle movement it is not necessary to consider the distance a given rock moved during a flow; that is, whether it was actually found downstream or

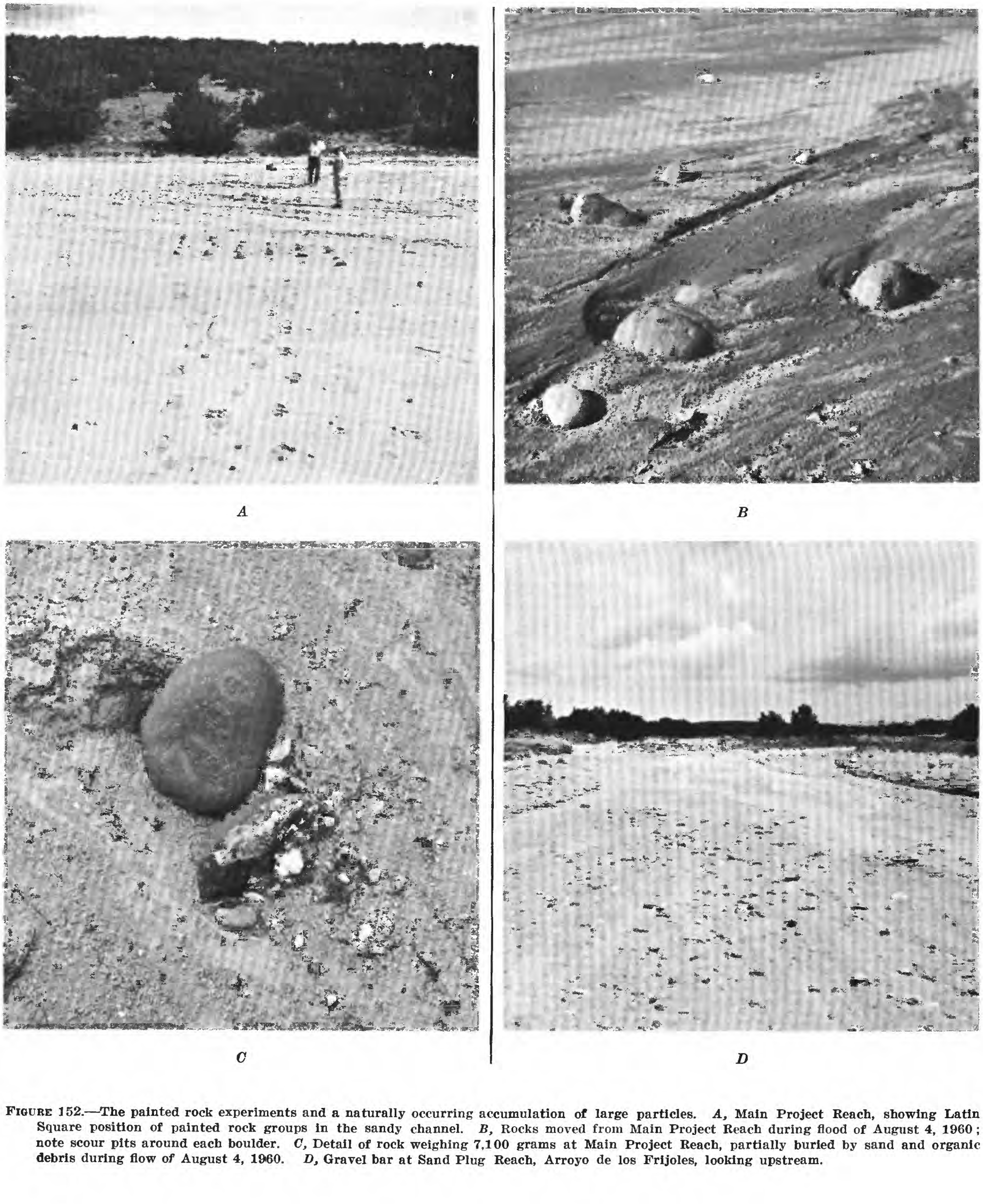


FIGURE 152.—The painted rock experiments and a naturally occurring accumulation of large particles. *A*, Main Project Reach, showing Latin Square position of painted rock groups in the sandy channel. *B*, Rocks moved from Main Project Reach during flood of August 4, 1960; note scour pits around each boulder. *C*, Detail of rock weighing 7,100 grams at Main Project Reach, partially buried by sand and organic debris during flow of August 4, 1960. *D*, Gravel bar at Sand Plug Reach, Arroyo de los Frijoles, looking upstream.

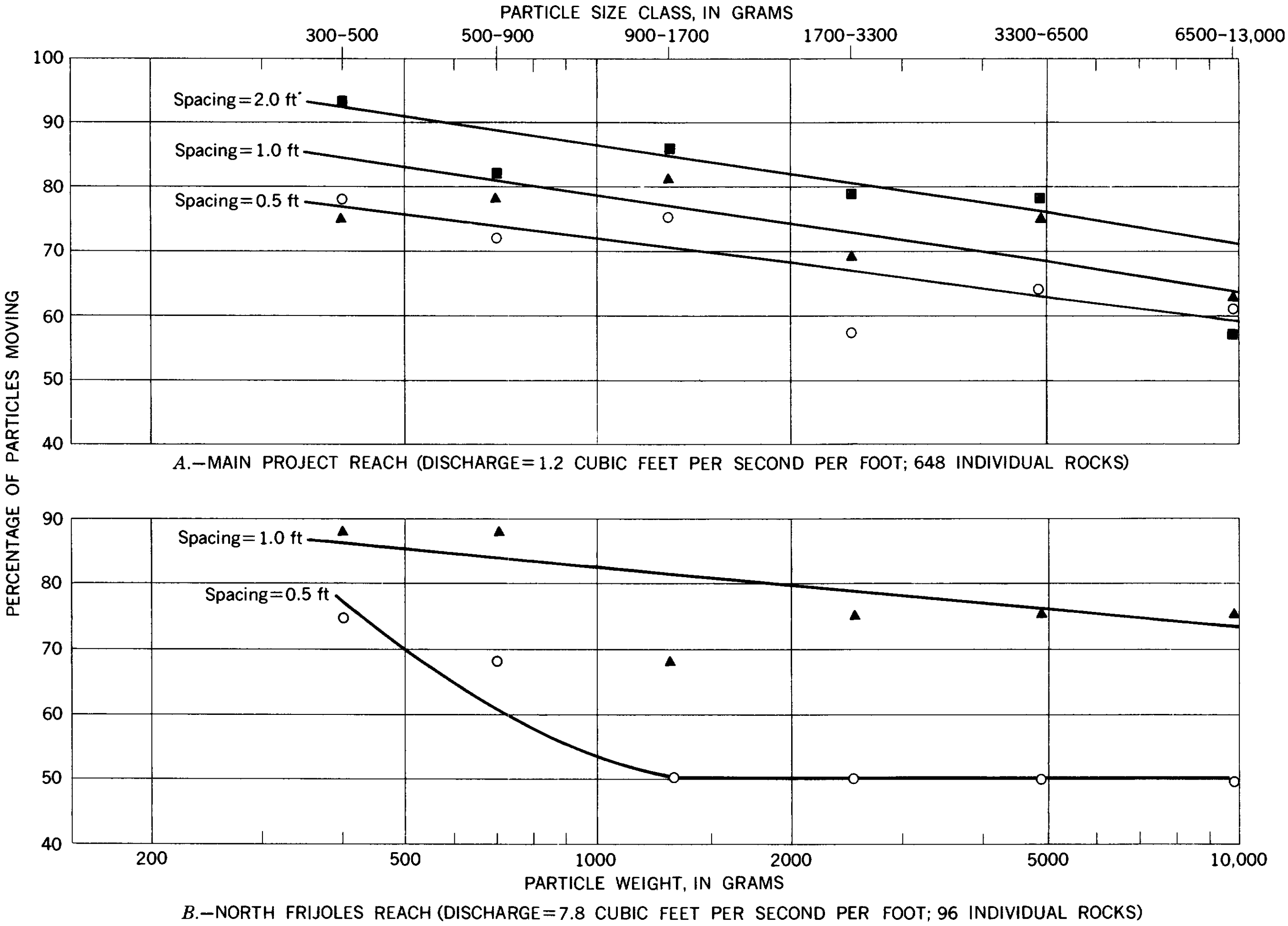


FIGURE 153.—The effect of spacing on percentage of rocks moving for a given discharge and particle size.

was simply missing. The particle had moved and how far it had moved was of no consequence. For each flow the percentage moved by size class and spacing was studied. In all, 14,000 observations were available for rock movements. The consistency of the data ranged from excellent to poor. A typical set of data are plotted on figure 153 to illustrate. From the set of graphs exemplified in this figure, further analysis was made in a manner explained in a separate paper by Langbein and Leopold. The pertinent results are presented in figure 154.

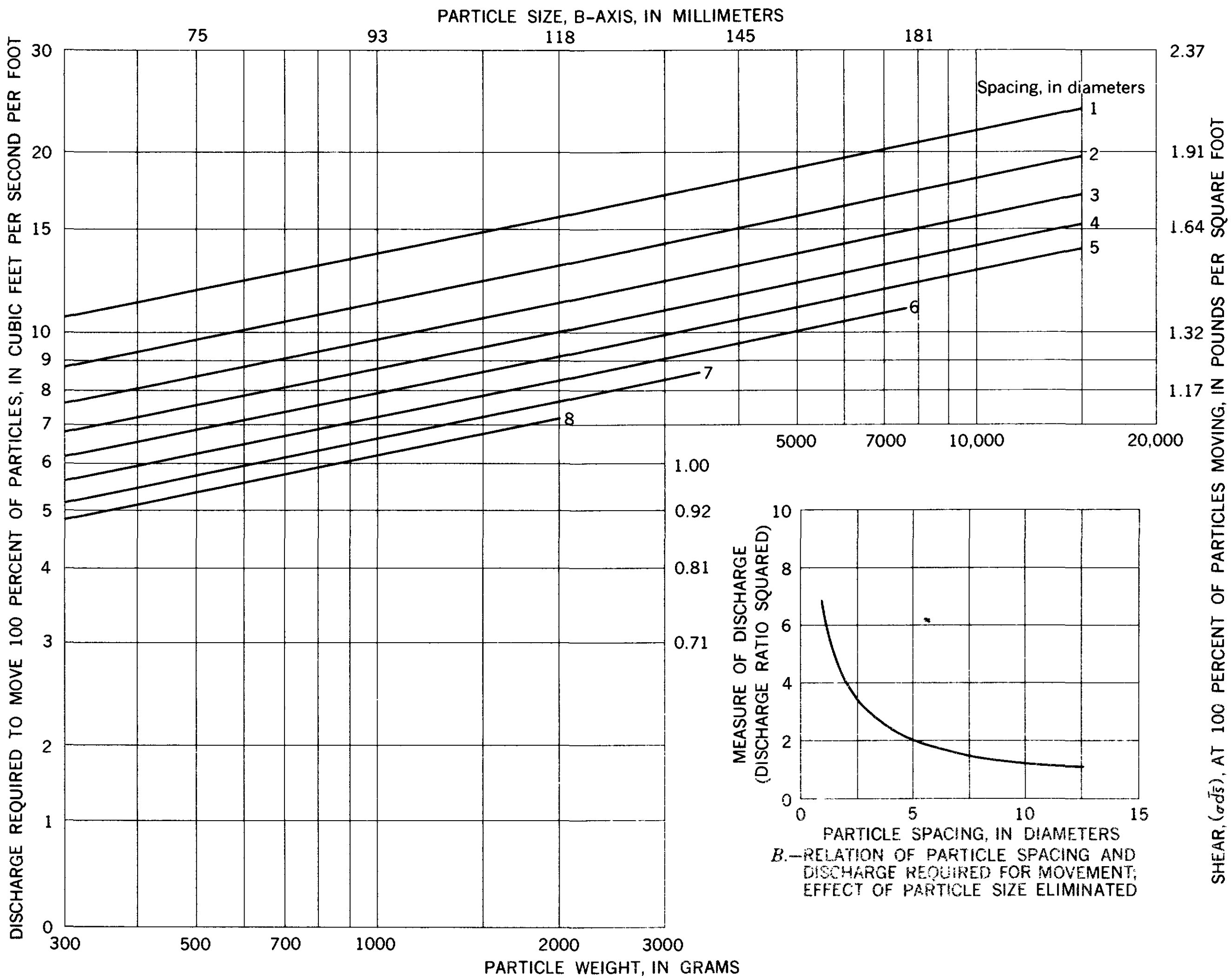
In summary, the results show that a larger flow is required to move particles which are close to one another than if they are spaced far apart. The influence of spacing decreases with increasing spacing and becomes negligible for spacings greater than about eight diameters. For example, a discharge of 11 cfs per ft would not move 500-gram particles if spaced at one diameter, but the same discharge would move 5,000-gram particles if spaced more than five diameters apart.

The effect of spacing on particle movement leads to the concept that a gravel bar is a kinematic wave caused by particle interaction, and is comparable in theory to concentrations of cars on a highway.

Owing in part to the phenomenon just described, the distance a coarse particle moves during a given flow is only slightly related to its size (fig. 155 and table 3). Particles lost are assumed to have moved distances comparable to those found. For some flows, all the particles recovered, regardless of size, were transported distances roughly equal. This is probably related to downstream decrease in discharge due to percolation into the channel. The relation of distance moved to maximum discharge during the flow is shown in figure 156. In general, the small particles do not travel materially farther than the large ones, and nearly half the flows include examples of larger particles moving farther than small ones. There is thus no neat progression of transport distances inverse to particle size.

SCOUR AND FILL

Scour and fill data from the Arroyo de los Frijoles are being collected by means of scour chains buried ver-



A.—RELATION BETWEEN DISCHARGE, SIZE, AND SPACING FOR 100 PERCENT OF PARTICLES MOVING

FIGURE 154.—Summary of data relating discharge, size, and spacing for painted rock experiments.

tically in the streambed with the top link at or slightly above the bed surface. After a flow the elevation of the streambed is resurveyed and the bed is dug until the chain is exposed. If scour has occurred, a part of the chain will be lying horizontally at some depth below the channel bed (fig. 157). The difference between the previous streambed elevation and the elevation of the horizontal chain is the depth of scour. The difference between the existing bed elevation and the elevation of the horizontal chain is the depth of fill. If no scour has occurred the depth of fill is the increase in bed elevation.

Scour chains, each 4 feet in length, were installed along a reach of nearly 6 miles, beginning in Slopewash Tributary and ending at Sand Plug Reach. The location of the chains usually followed the low-water channel. Over most of the study reach chains were placed at 1,000-foot intervals. In the Main Project Reach of 2,000 feet, chains were placed at 100-foot intervals. This spacing was believed sufficient to determine any downstream trend in the scour pattern in this arroyo. At seven of the chain sections, additional chains were installed across the width of the channel and provide an indication of any lateral variation in scour.

Scour-and-fill data are available for most of the 22 significant flows in the 7-year period, 1958–64. All data obtained during the scour-chain record are on file with the U.S. Geological Survey, Washington, D.C., 20242. However, since some chains were installed before others, an equal length of record does not exist for each chain location. In addition some chains, usually those in the uppermost or lowermost reaches, were not surveyed after each flow. These missing segments of data disallow a complete picture of scour and fill for individual storms,

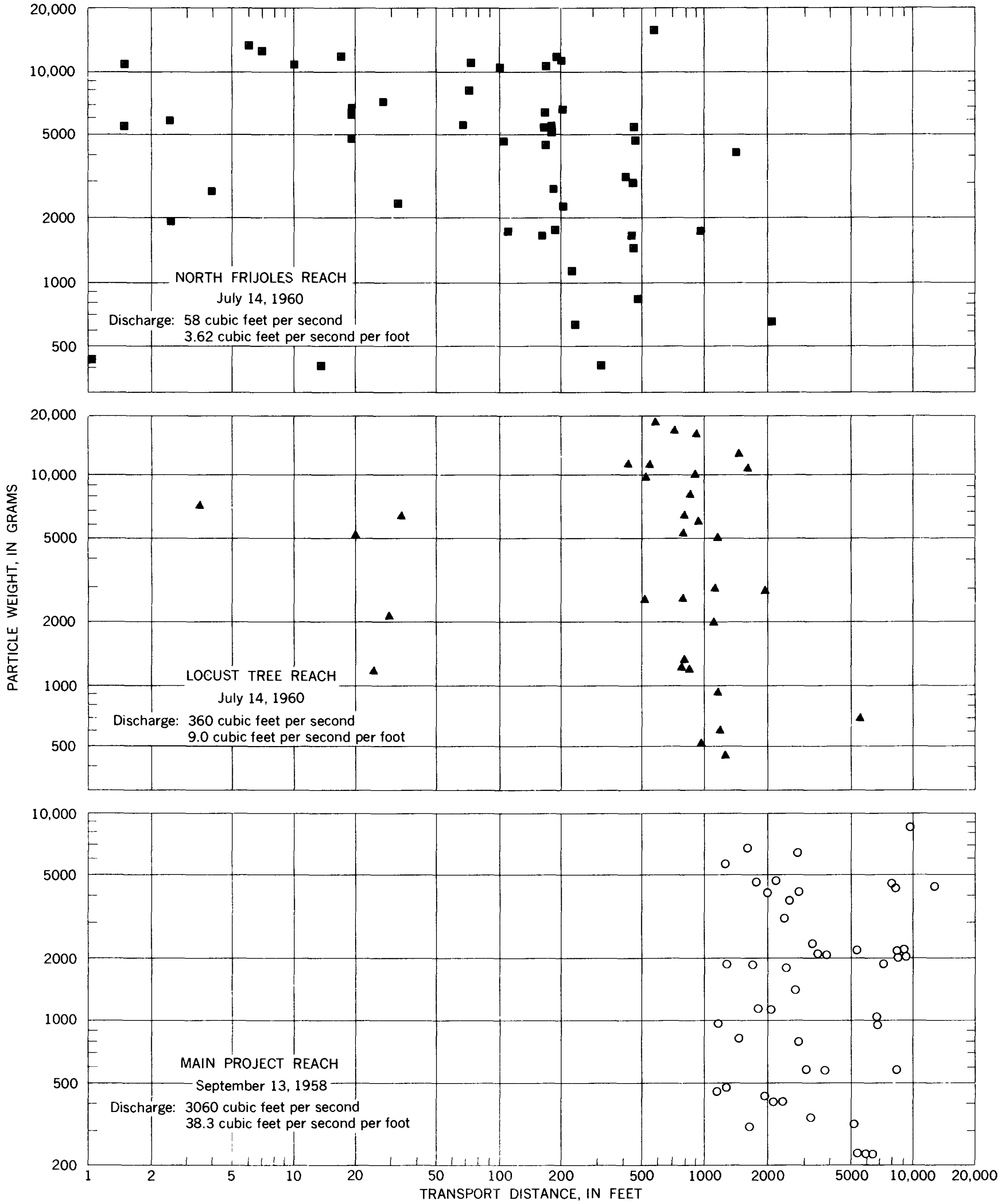


FIGURE 155.—Transport distance of coarse particles as a function of particle weight.

TABLE 3.—*Relation of transport distance to flow discharge*

[Leaders indicate that data are insufficient for an average or that category is inapplicable. Distance measurements centered in two columns represent data from adjacent size classes averaged together]

Location	Date	Discharge		Average transport distance, in feet, by size class of particle, in grams										
		Cfs	Cfs per ft	200–300	300–500	500–900	900–1,700	1,700–3,300	3,300–6,500	6,500–13,000	13,000–26,000	26,000–52,000	52,000–104,000	Average for all sizes
Main Project	9-13-58	3,060	38.3	5,880	2,336	3,862	3,500	4,537	4,815	...	...	...	...	4,028
	7-25-62 / 7-30-62	1,300 / 300	16.3 / 3.75	...	1,771		1,762		1,783		1,811	1,087	363	1,775
	9-18-61 / 9-19-61	60 / 250	.75 / 3.13	...	1,272		748		690		260	...	...	784
	8-04-60	152	1.90	...	495	630	605	172	136	99	...	...	...	456
	7-08-61	98	1.22	...	776	673	378	449	194	463	18	...	...	446
	8-12-61	80-90	1.06	...	489	380	130	51	83	141	2	...	...	186
	7-05-62	40	.50	...	277		126		200		...	...	...	145
	7-14-60	35	.44	...	126	103	76	121	38	24	0	0	0	93
	8-07-59	20-25	.28	...	3	11	...	...	...	0	0	0	0	7
	7-23-59	10-15	.16	...	15	8	7	0	0	0	0	0	0	11
Locust Tree	9-19-61	650	16.2	...	1,894		1,995		1,568		...	...	...	1,818
	7-08-61	498	12.5	...	925	1,952	471	841	1,592	496	...	...	...	1,123
	7-25-62 / 7-30-62	450 / 450	11.2 / 11.2	...	...	...	1,385		1,120		...	...	...	1,198
	7-14-60	360	9.0	...	...	2,198	796	1,116	720	806	757	...	...	1,051
	8-12-61	300-400	8.8	...	938		692		317		...	...	...	563
	7-05-62	150	3.75	...	...	...	266		84		...	...	...	234
	5-23-59	50-75	1.56	...	225	247	276	230	107	...	...	...	...	223
	8-17-59	20-25	.56	...	397	299	126	29	34	...	...	...	...	151
	9-06-58	10	.25	...	...	73	...	29	8	...	...	...	...	54
North Frijoles	9-19-61	230	14.4	...	789		674		547		972	...	...	670
	5-23-59	140	8.7	...	...	644	...	443	124	78	...	...	...	254
	8-12-61	85	5.32	...	550		316		142		170	...	...	332
	7-25-62	85	5.32	...	493		243		119		...	...	...	273
	7-14-60	67	4.18	...	108	659	336	242	269	78	...	...	...	216
	7-08-61	58	3.62	...	540	291	330	325	217	159	118	...	...	294
	8-24-59	50	3.12	...	117	229	218	110	79	48	71	...	...	125
	9-06-58	15-20	1.09	268	93	...	57	...	...	...	...	...	...	155
Stagger Reach	9-19-61	...	...	...	...	...	...	...	...	...	1,313	2,140	...	1,727
	7-14-60	...	...	...	...	...	...	...	...	...	458	304	...	400
	7-30-62	...	...	...	...	...	...	...	...	...	647	191	...	373
	8-12-61	...	...	...	...	...	...	...	...	...	49	199	...	109
	7-05-62	...	...	...	...	...	...	...	...	...	39	61	...	53
	7-25-62	...	...	...	...	...	...	...	...	...	45	35	...	38
	7-08-61	...	...	...	...	...	...	...	...	...	...	14	...	14
Railroad Reach	7-08-61	...	...	...	...	...	...	...	...	...	1,665	43	148	879
	7-14-60	...	...	...	...	...	...	...	...	...	381	260	...	340

but the net change in bed elevation since the time of the initial survey may still be obtained.

By 1959 the majority of the chains had been installed along the arroyo. Scour-and-fill data for a sample flow, for the year 1962, and for the period 1958–62 are shown in figure 158. The upper part of the figure shows the drainage area of Arroyo de los Frijoles and the general location of the chains by chain number. For the two individual flows, the lower dashed line represents the depth of scour. The upper dashed line represents the depth of fill. The heavy solid line represents the net change in bed elevation after scour and fill.

The nature of the flash flow is such that the entire length of the arroyo may not be flooded with each storm. The flow-producing rain may be so located that only lower reaches received runoff, or, for a smaller storm near the headwaters, a part or possibly the entire flow may be absorbed into the ground by percolation before is reaches a downstream section. A third possibility remains that a particular chain section may be left dry or has very little scour because it was not in the low-water path of flow. For a single storm, then there is a considerable variation in the recorded depth of scour from section to section. This variation is further exemplified in the Main Project Reach where the chains are placed at 100-foot intervals. In spite of individual variations a general consistency prevails among the data, that is, at most sections along the channel there is a scour and subsequent fill. All flows produce this same pattern; the magnitude of scour is primarily dependent upon hydraulic factors of individual flows, and these factors are related to the intensity and total amount of rainfall.

North Frijoles, Locust Tree, and Main Project reaches of the channel are the objects of special study and are also the reaches where flow rates are measured. It is within these reaches that the chain sections are located to determine cross-channel patterns of scour. The mean depth of scour at a section may be determined by averaging the values from the several chains at each of the sections. Mean values of scour for each recorded flow are tabulated in table 4. The data are plotted in figure 159. Despite considerable scatter among the data, the mean scour depth appears to be proportional to the square root of discharge per unit width of channel.

An increasing depth of scour downstream is not observed in any single profile (fig. 158).

Probably for similar reasons, the depth of scour is apparently independent of channel width. Channel widths have been illustrated on figure 148. No sys-

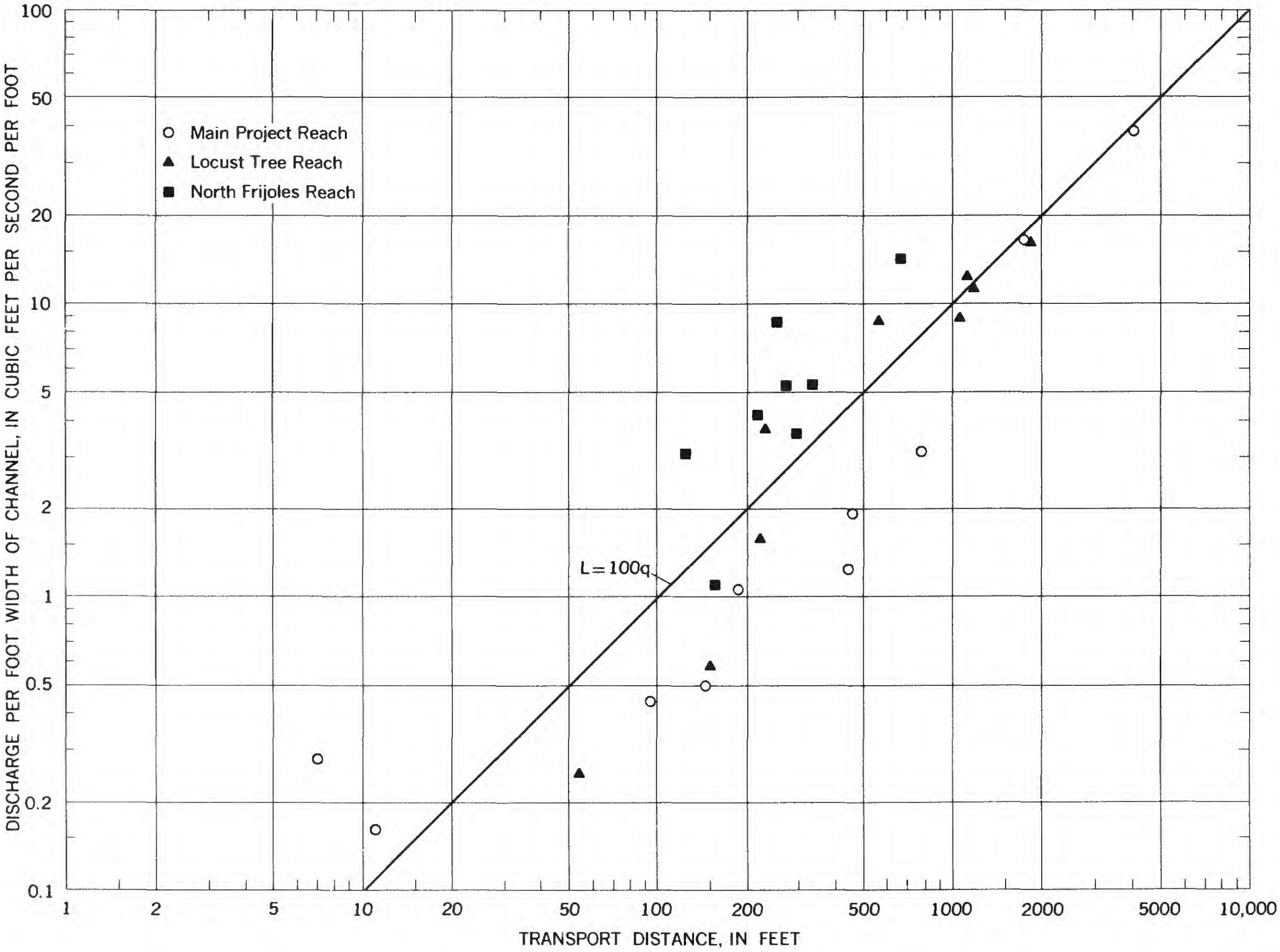


FIGURE 156.—Average transport distance of coarse particles as a function of discharge (sizes approximately 200–13,000 g).

tematic relation of local depth of scour to the corresponding channel width could be established.

The seven chain sections provided data to study lateral variations in scour across the width of the channel. One of these sections, chosen as representative of a typical reach, is illustrated on figure 160. This figure, illustrating a Main Project section near station 25,000 feet, indicates a net aggradation for the 6-year period. The whole width of the channel scours during nearly every flow, but the amount of scour and fill varies across the width.

The progressive effect of scour and fill over the length of the channel is illustrated in figure 161. Except for several isolated reaches, aggradation is occurring over the entire length of the channel. For the period of record, this aggradation amounts to an average of 0.04 ft per yr including those reaches which show a net scour.

Net scour in individual reaches can be partially explained either by natural or man-caused events. For examples, at a stationing of 32,000 feet (fig. 161) the large flow of 1958 cut through a fan-type deposit (literally a sandplug and hence the name for this reach) at the chain location and indicated a large net scour. This fan had earlier been deposited at the mouth of an entering tributary. At this sand fan most of the channel width was accumulating a net fill and now, 1964, an islandlike deposit over a foot high occupies a large part of the channel width. Channel-wide, a net aggradation does exist at that location, but because of the placement of the chain a net scour shows on the graph of figure 161.

Also, in some of the upstream reaches of the channel, excavation of sand by local contractors is responsible, at least in part, for the apparent net degradation at these sections.

The downstream profiles of the channel bed showing progressive accretions of sediment during aggradation probably represent as detailed an historical record of this process as has been compiled.

FIGURE 157.—Horizontal part of chain lying at depth of maximum scour, here about half a foot. Vertical part of chain disappears below man's hand.

The record demonstrates some nonuniformity along a channel 6 miles long, some short reaches not following the general trend. The reaches not participating in the aggradation do so consistently, but as in the Sand Plug Reach at the lower end of the studied length, the reason for its deviation relates to special and understandable local circumstances. Interestingly, the random pattern of storm occurrence does not lead to a random location of reaches of sediment accretion, for the increment of deposition is rather uniform from year to year.

The exaggeration of scale in figure 161 must be kept in mind, and the variations in yearly increments are really very small considering the channel length involved. If one short reach aggraded a tenth of a foot more than another a thousand feet away, the channel slope in the reach would be changed by only 0.0001 foot per foot. The variability along the channel due to the irregularities of depositional increment are of this order. Thus, despite random character of storms and the local loss of flow to channel percolation the mean slope of the bed is maintained over long reaches.

A more complete discussion of the records of scour is given by Emmett and Leopold (1964). For the present purpose, suffice it to say that scour is associated with dilation of the grain bed through the scour depth, but that individual particles may move intermittently and at a speed much less than that of the water. The volume of material scoured and moved is large. Because of its low mean speed downstream, that whole volume does not move entirely out of a long reach but, in effect, is shifted downstream only a limited distance.

TABLE 4.—*Mean depth of scour as a function of discharge*

North Frijoles Reach

Date of flow	Discharge (cfs)	Upper section: Discharge (cfs per ft)	Upper section: Scour (ft)	Lower section: Discharge (cfs per ft)	Lower section: Scour (ft)
9-6-58	17.5	0.87	0.018	1.46	0.050
9-13-58	194	9.7	.215	16.2	.977
5-23-59	140	7.0	.103	11.7	.460
8-24-59	50	2.50	.083	4.17	.000
7-14-60	67	3.50	.068	5.59	.135
11-16-60	9	.40	.023	.67	.315
7-08-61	58	2.90	.130	4.84	.268
9-19-61	230	11.50	.188	19.20	.598
7-05-62	7	----	----	.58	.040
7-30-62	90	4.50	.153	7.50	.175
7-20-63	10	.50	.180	.83	.128
9-21-63	5	.25	.293	.42	.448

Locust Tree Reach

Date of flow	Discharge (cfs)	Discharge (cfs per ft)	Scour (ft): Upper section	Scour (ft): Middle section	Scour (ft): Lower section
9-13-58	1320	34.0	0.820	----	----
5-23-59	62.5	1.69	.132	0.076	0.255
8-07-59	22.5	.56	.196	.060	.078
7-14-60	360	9.0	.260	.212	.205
7-08-61	498	12.47	.464	.406	----
8-12-61	350	8.75	.194	.368	.393
9-19-61	650	16.25	.280	.138	----
7-05-62	150	3.75	.274	----	----
7-30-62	450	11.2	.272	.334	.300
7-20-63	15	.38	.134	.076	.133
9-21-63	316	7.9	.314	.320	.305

Main Project Reach

Date of flow	Discharge (cfs)	Upper Reach: Discharge (cfs per ft)	Upper Reach: Scour (ft)	Lower Reach: Discharge (cfs per ft)	Lower Reach: Scour (ft)	Low-water chains: Discharge (cfs per ft)	Low-water chains: Scour (ft)
8-18-58	20	0.235	0.053	0.286	0.023	----	----
9-13-58	3060	36.0	.830	43.6	.557	----	----
5-23-59	4	.047	.050	.057	.008	0.050	0.025
7-23-59	12.5	.147	.000	.178	.240	.156	.043
8-07-59	22.5	.265	.033	.321	.022	.282	.057
7-14-60	35	.412	.036	.500	.033	.439	.048
8-04-60	152	1.79	.088	2.17	.425	1.90	.128
7-08-61	98	1.15	.124	1.40	.118	1.23	.145
9-19-61	250	2.94	.125	----	----	3.13	.316
7-25-62	1300	15.3	.511	18.6	.810	16.3	.273
7-20-63	5	.059	.024	.072	.010	.062	.000
9-21-63	391	4.6	.236	5.59	.175	4.9	.234

HILLSLOPE EROSION

EROSION PLOT ON SLOPEWASH TRIBUTARY

To measure the rate of hillslope erosion a grid system of erosion pins was installed in 1959 on one of the slopes in the drainage area of Slopewash Tributary. The general location of this grid system, or erosion plot, is shown in figure 144, and the locality is illustrated in figure 143. The erosion plot consists of 61 nails with washers spaced on 5-foot centers on an area 50×50 feet having a relief of 5 feet and furrowed by two shallow and narrow rills. These rills join midway through the grid system into a single larger rill.

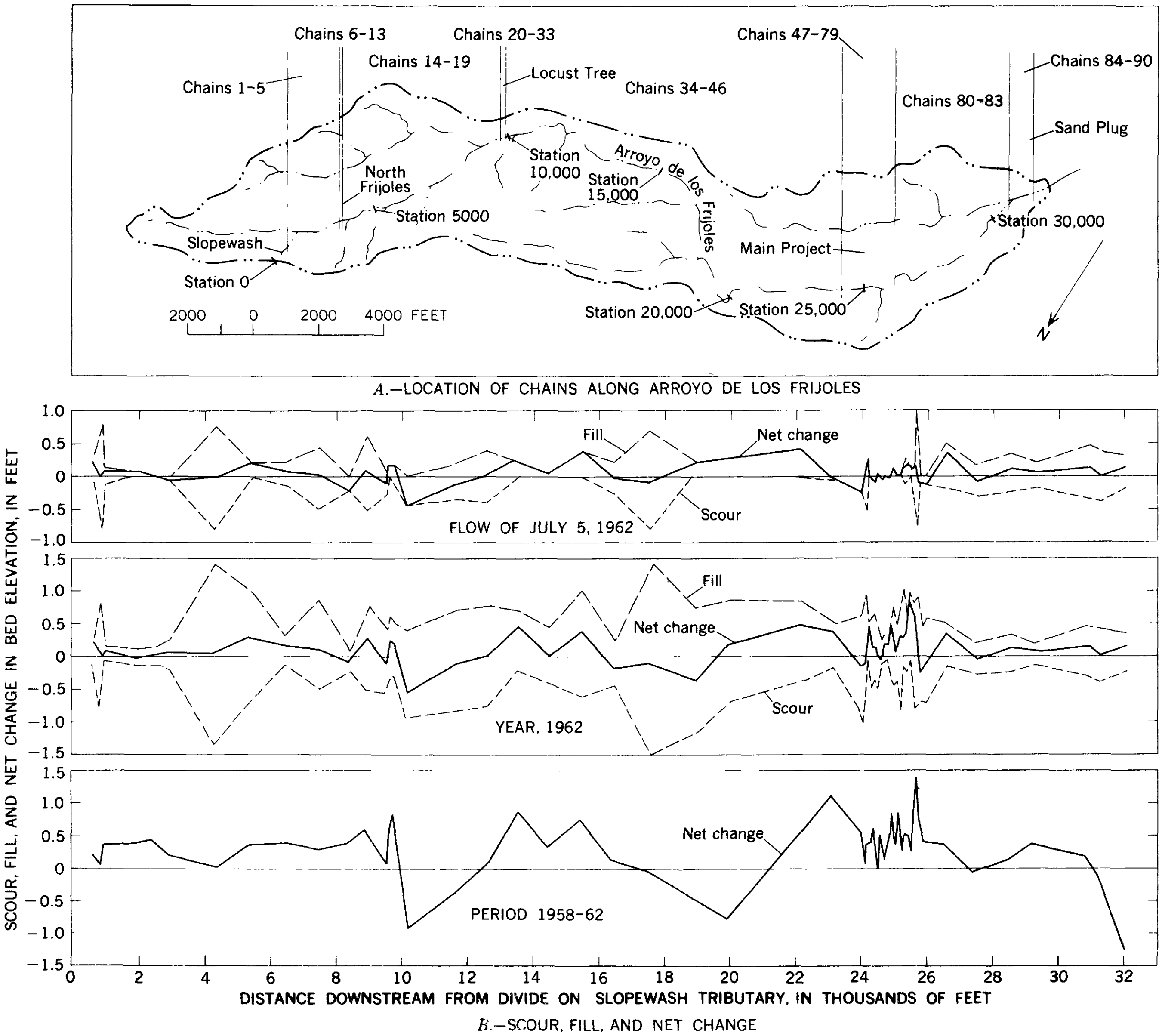


FIGURE 158.—Downstream pattern of scour, fill, and net change in bed elevation for a single-storm, a 1-year, and a 5-year period, 1958–62.

At the time of the installation, the nails (10-inch spikes) were slipped through a large washer and driven into the ground in a vertical position until the bottom of the washer was flush with the ground surface. Erosion undermines the washer, which then falls down a length of the pin. The pin protrudes above the washer at a distance equal to the erosion during the intervening period. While maximum erosion is marked by the washer, deposition may be recorded as the height of any material above the washer, a desirable feature in such places as a rill bottom where maximum and net erosion generally differ. Figure 162 shows typical erosion nails on the erosion plot and on transects. Elevations of all nail heads were measured and resurveys show that the nails remain stable and are not being heaved by frost action.

An attempt was made to map erosion values as topographic contours of erosion quantity, but because of the short length of record no systematic trend is apparent among individual values. At this time it appears that the pins on the steeper slopes adjacent to the rills show a slightly higher rate of erosion.

Pins in or near rills tend to show some deposition on the washer following scour. Depth of overland runoff

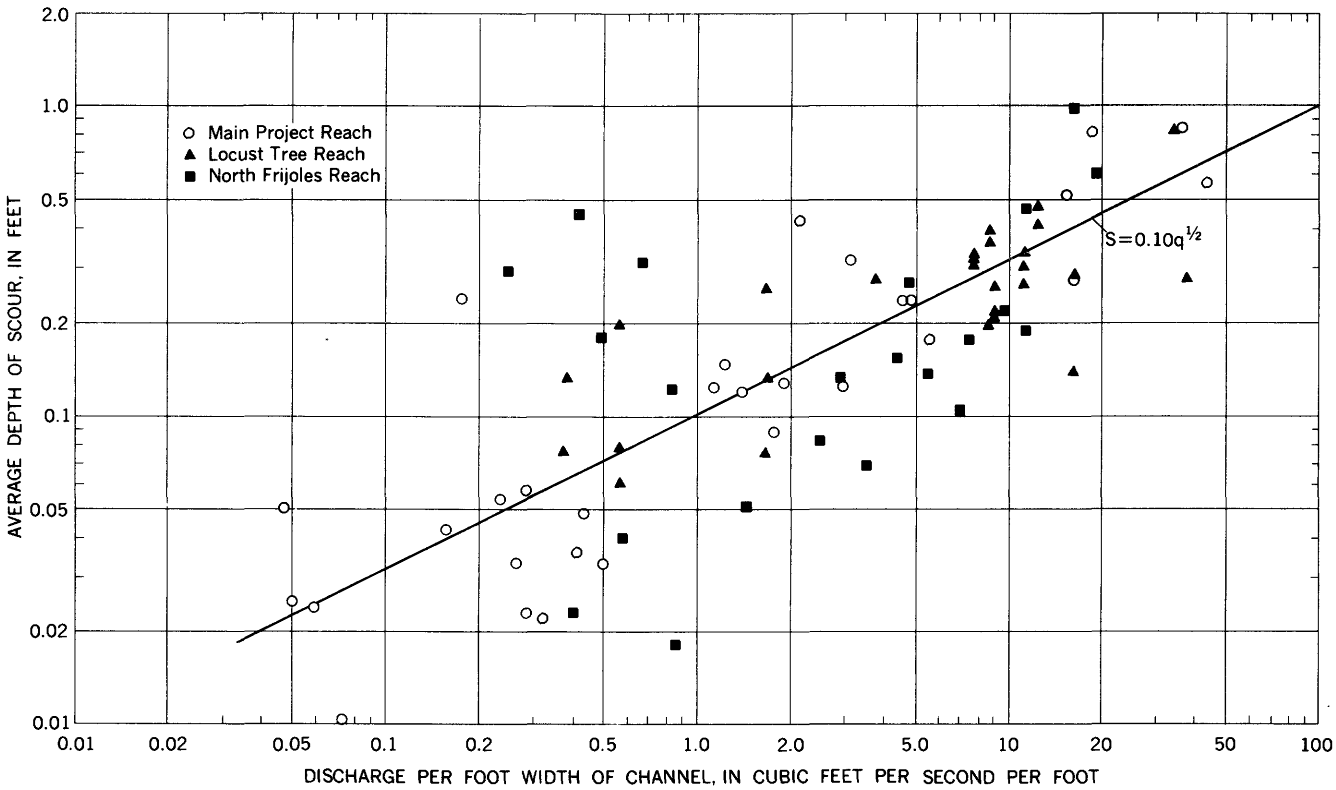


FIGURE 159.—Depth of scour as a function of discharge at chain sections; each point represents an average scour across the channel bed, based on 4–10 chains per cross-section.

is greater in such locations and it might be that erosion occurs during maximum overland flow depth and that deposition follows as the flow subsides. But deposition is the exception and not the general rule. The majority of the pins show very little or no filling on top of the washer.

Erosion data have been collected in the years 1961–64. Data in 1961 included only values of erosion and later, both erosion and deposition. The average erosion during the 5-year period, 1959–64, was 0.0117 ft per yr, and deposition on some of the pins averaged 0.0041 ft per yr—a net average rate of erosion of 0.0076 ft per yr.

Summary of data C contains data from the erosion-pin plot in Slopewash Tributary.

SLOPE-RETREAT PINS ON SLOPEWASH TRIBUTARY

Fifty-seven erosion pins are arranged on four lines transverse to the steep sides of Slopewash Tributary. These pins are the nail-with-washer just described, and are designated as "slope-retreat pins" on the location map of figure 144. An enlarged sketch elaborating details of these pins is shown in figure 163.

The pins are arranged in three groups, each group consisting of two lines spaced 2 feet apart. Each line, with pins spaced at 2-foot intervals, extends down the steep slopes to the channel bed and, for one pair of lines, cuts across the channel and up the steep slopes on the opposite side of the tributary. The slopes range in steepness from 21 to 38 degrees, and these generalized slope angles are marked on figure 163 for identification.

The pins were installed in 1959 and erosion measurements were made once a year in the period 1961–64. Net values of erosion for the period are shown below the pin numbers on figure 163.

For the 57 pins, the average rate of net erosion is 0.0142 ft per yr. This figure consists of an average rate of maximum erosion of 0.0281 ft per yr and an average deposition of 0.0139 ft per yr. Individual measurements varied from a net deposition to an erosion of more than 0.08 ft per yr. A summary of all data from the slope-retreat lines is included in summary of data D.

Perhaps more meaningful rates of erosion could be obtained by dividing the 57 pins into 3 categories. Category 1 includes pins 1–29 of the upper line, category 2 includes pins 30–45 of the upper line, and category 3 includes the 12 pins, 46–57, in the lower line. Categories 1 and 3 are similar in their physiographic locations, but the pins in category 2 differ in that here apparent erosion is being disguised by channel deposits on some of the pins near the channel edge and by an accumulation of sloughed material on some of the lower

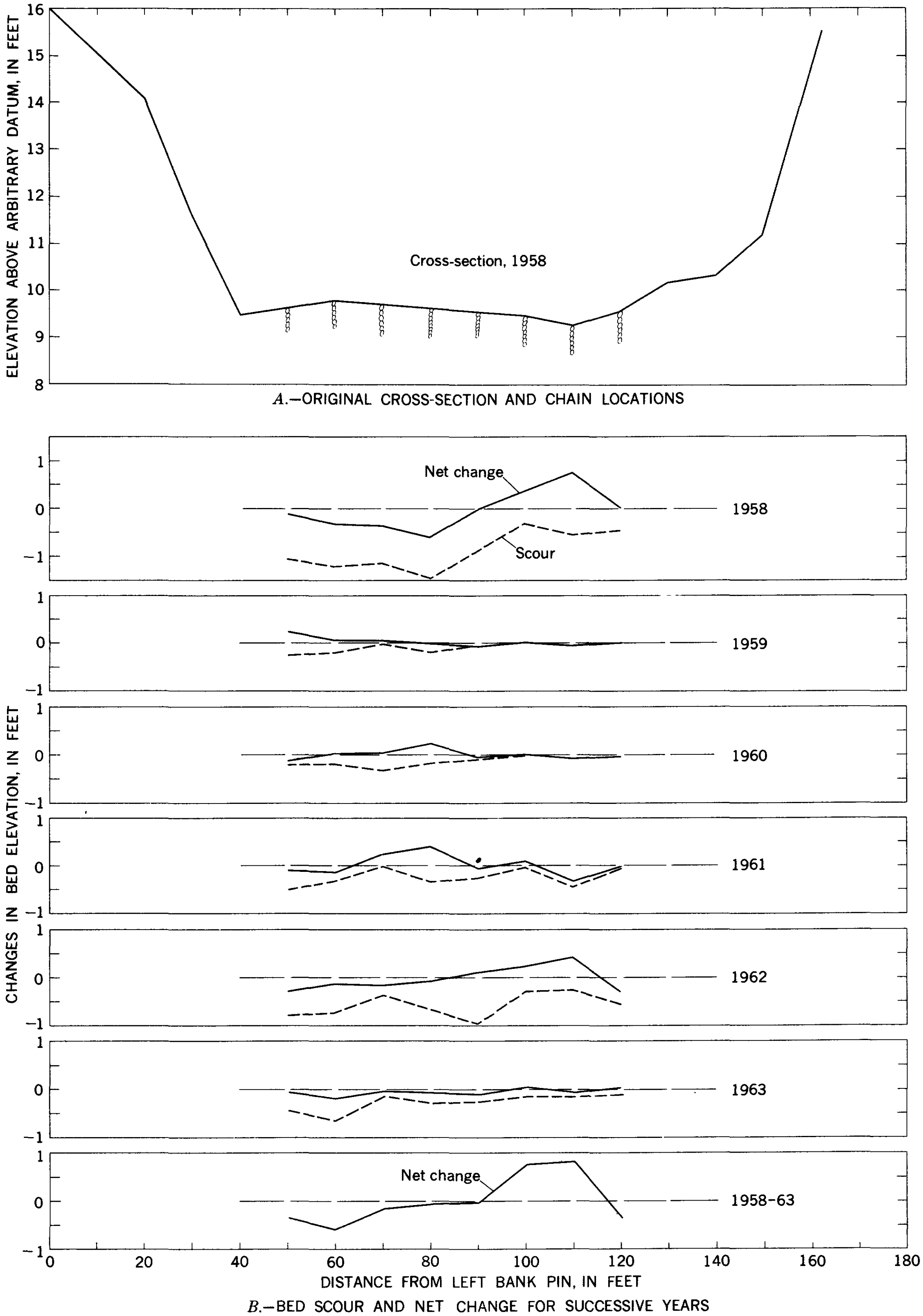


FIGURE 160.—Scour and net change in bed elevation, upper chain section, Main Project Reach.

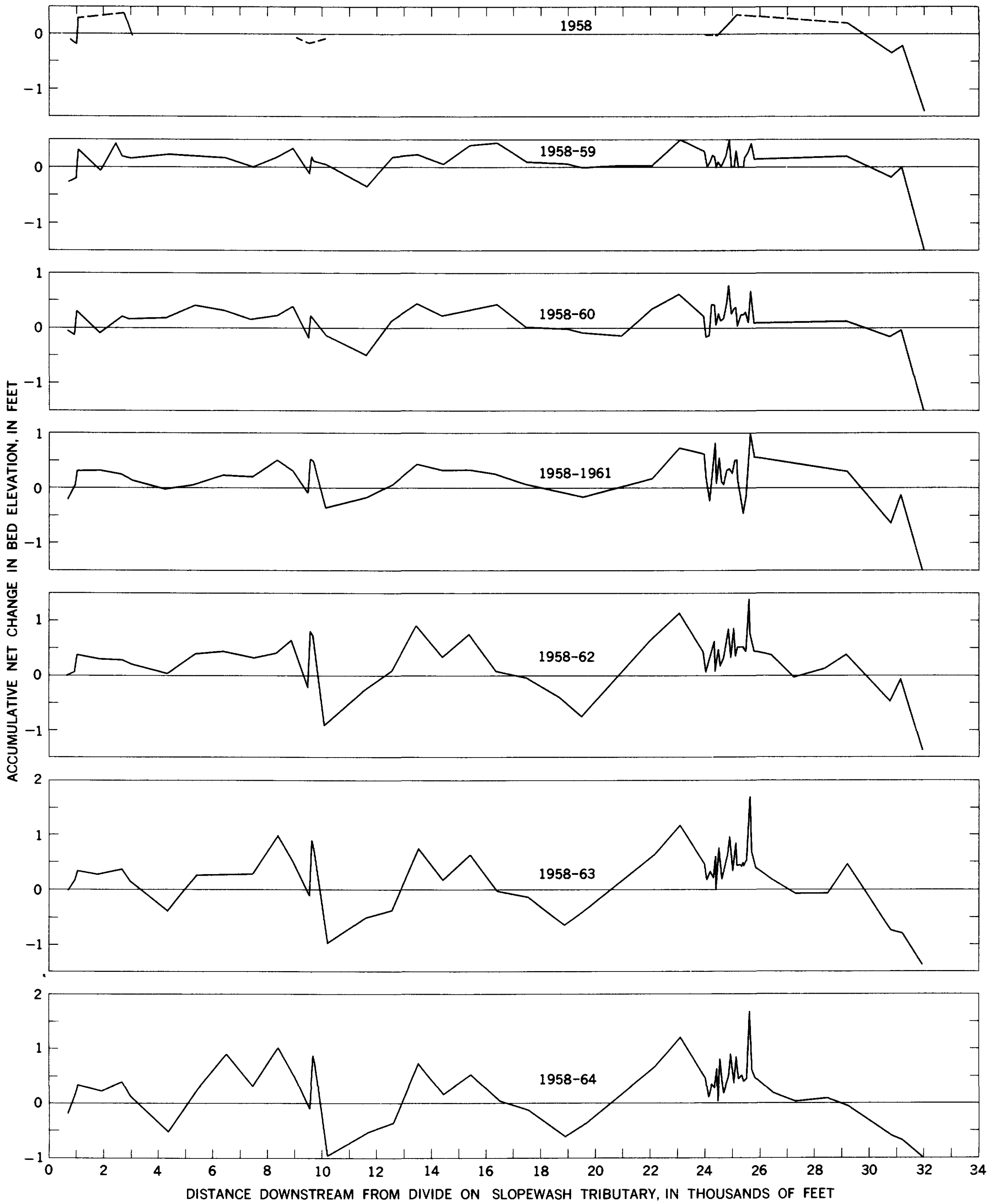
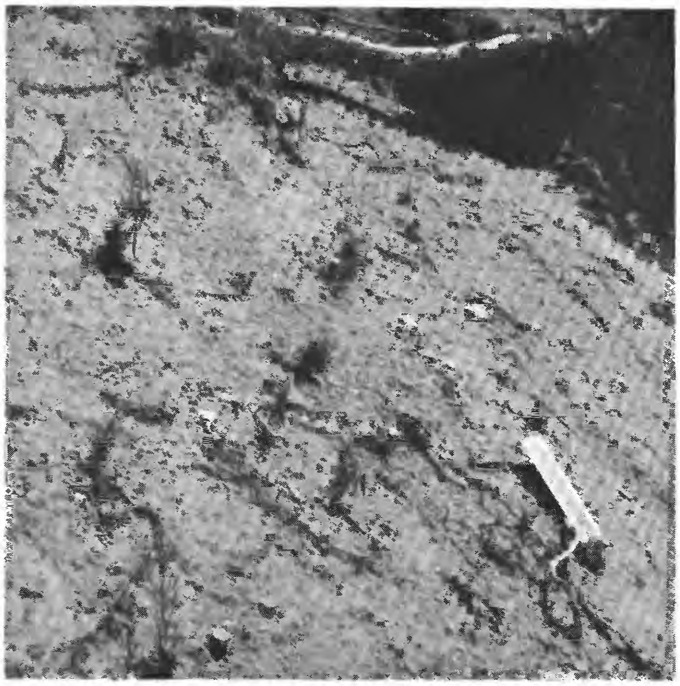


FIGURE 161.—Downstream pattern of accumulative net changes in bed elevation, Arroyo de los Frijoles.

A



B

FIGURE 162.—Erosion pins consisting of 10-inch spike and washer. *A*, Erosion pins in grid system, Slopewash Tributary (scale is a 6-inch ruler). *B*, Erosion pins on slope-retreat line, Slopewash Tributary.

pins on the sloping bank. Thus the 16 pins in this category actually show an average of a net deposition. Most likely this apparent deposition is only temporary, as a scour of the channel deposit will not only expose the lower nails again but will also allow the sloughed material to continue its downslope journey to the channel.

Rates of net erosion for pins in each of the three categories are: category 1, 0.0210 ft per yr; category 2, −0.0034 ft per yr (the minus represents net deposition); and category 3, 0.0183 ft per yr. More complete computations are included at the end of summary of data D.

Excepting those pins just mentioned in category 2, generally only those pins on the channel bed showed consistent deposition above the washer, and the fact that in most places these pins were completely buried indicates an aggrading channel. Undoubtedly much of the aggraded material is derived from the erosion of the steep slopes adjacent to the channel. However, the erosion rate on these slopes more than compensates for the volume accumulation of sediment on the channel bed. Implicit, then, is that much of the eroded fine-grained sediment is being carried further downstream.

Oddly, in the pin lines here discussed, the greatest rates of erosion were on the less steep slopes (upper left group on fig. 163), but in considering all observations, steep slopes generally show a greater rate of erosion than less steep slopes. No attempt is made at this time to ascribe to either of these two sets of measurements the percentage of total sediment which each produces. While the gentler slopes have a smaller erosion rate, their land area within the watershed is greater. Consequently, in terms of total volume of sediment, the gentler slopes may yield the greater amount.

Location and elevation of pins along lines CB and BA as well as the net 6-year erosion at each are indicated on the profiles of figure 164. The profiles provide an insight to the occasional contradictory data among pins. It appears that the greater steepness in local surface slope (that slope within 1–2 ft of the pin) is accompanied by the greater erosion. The greatest erosion is indicated by those pins on the very steep slopes just adjacent to, but not in, the channel bed. The pins on a locally flat slope, especially those just downhill of a steeper slope (see pins 2CB and 3CB, fig. 164) actually show a deposition occurring. This deposited material was undoubtedly derived in part from the greater erosion on the steeper slopes just uphill, for example, from pin 1CB. Pins on relatively unbroken slopes are in general agreement with each other and usually indicate about the average rate of erosion. Thirteen of the 17 pins showed a net erosion and 4 a deposition. If only those pins showing a net erosion were considered, the average rate of erosion would increase from the reported 0.0072 ft per yr to 0.017 ft per yr. The former value is in agreement with the value from the erosion plot and the latter with the value from the slope-retreat lines. Generally, the topography along the iron-pin lines is intermediate between that of the erosion plot and that of the slope-retreat lines.

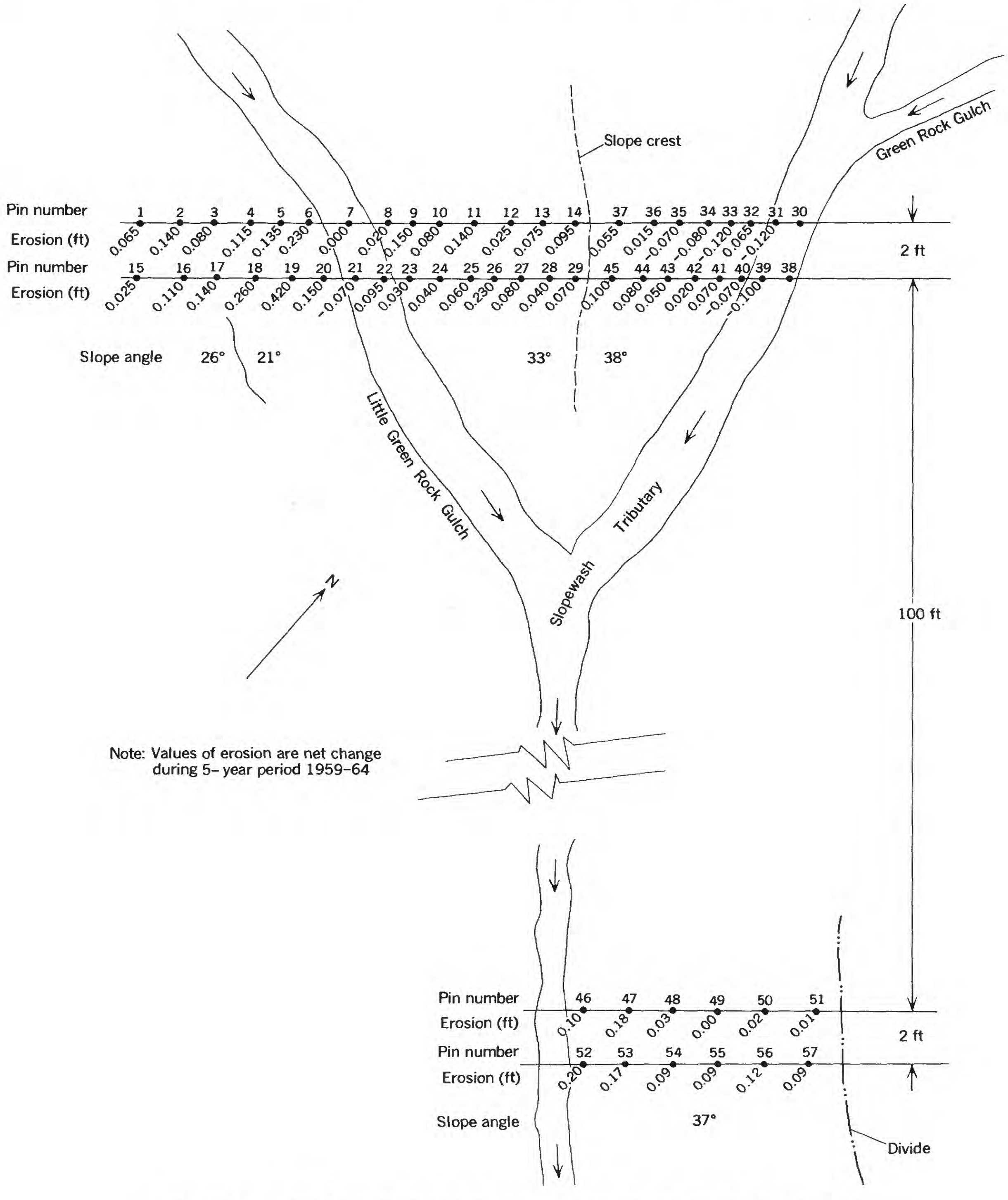


FIGURE 163.—Sketch map showing details of the slope-retreat pins, Slopewash Tributary.

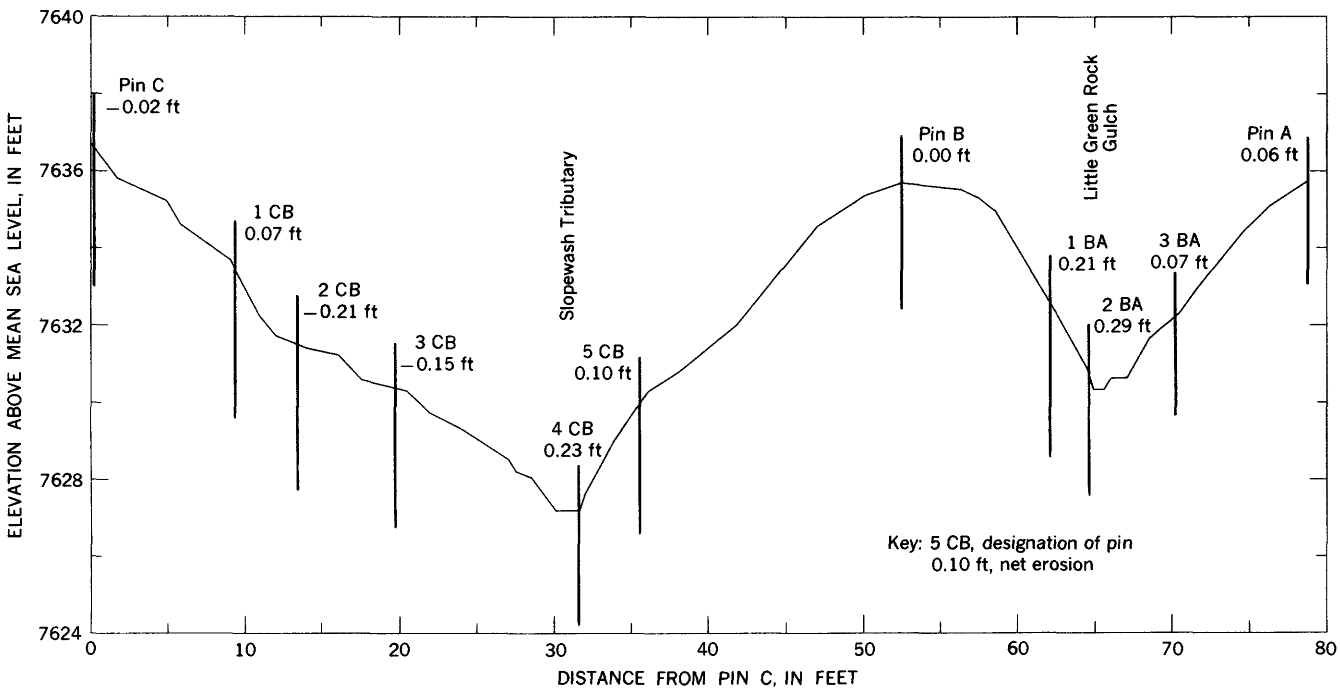


FIGURE 164.—Six-year (1958–64) net erosion on iron-pin line CBA, Slopewash Tributary drainage area.

OTHER MEASUREMENTS OF SLOPE EROSION ON SLOPEWASH TRIBUTARY

The second additional set of measurements for rates of erosion consists of eight iron pins located at the chain-sections below the junction on Slopewash Tributary (see fig. 144 for chain-section locations). These are 4-foot lengths of iron reinforcing rod, installed and observed as previously described. For each chain-section, a pin was located on each sloping bank and, for two of the sections, a pin was situated in the channel bed.

Installation was made in 1958 and data were collected in 1958–64, excepting 1961. The average rate of erosion for the bank pins is 0.0108 ft per yr and the bed pins indicate an average deposition of 0.0033 ft per yr. These rates are in agreement with the other observed rates for slope erosion and channel aggradation.

EROSION NAILS ON COYOTE C. ARROYO

On slopes leading into the headcut of Coyote C. Arroyo, a total of 65 erosion pins with washers are located on 3 lines, as shown in figure 145. The pins were installed in 1961 and have been remeasured yearly to 1964. Profiles were run on the pins to determine the slope, and also a resurvey of the pin elevations indicates no heaving due to either freeze-thaw or wet-dry actions. The average of the 65 pins indicates a yearly net erosion of 0.0237 foot. All the data for the pins are tabulated in summary of data F.

Rates of erosion for each of the three lines were consistent, ranging from 0.021 to 0.027 ft per yr. These values approximate the higher values for the slope-retreat pins in Slopewash Tributary, and it is believed that they exceed somewhat the average rate of erosion for the entire drainage of Coyote C. Arroyo, as is evidenced by a lower value for the grid system than for the slope-retreat lines in Slopewash Tributary.

Attempts to correlate individual rates of erosion with individual local ground slopes did not result in a neat regression of erosion rates with lessening slopes. To the observer on the ground, it appears rather instinctive that greater erosion is occurring on the steeper slopes; however, the disparity in the data is sufficient to mask attempts to illustrate graphically the relation of slope to rate of erosion.

TRACING OF FLUORESCENT SAND

A fluorescent sand (ASTM mesh size 40) was placed along three lines in two of the study areas to trace the movement of individual fine-grained sediment. One line was along the hillcrest of Morning Walk Wash (see fig. 139). The other two lines were in Coyote C. Arroyo, one along the nail line ED and the other along the mass-movement line (see fig. 145).

The sand was placed in 1961 and the initial position was marked. In 1962 the movement of this sand was determined by searching for grains at night with a black light. Despite a relatively large amount of erosion indicated by the erosion nails, the individual sand grains appeared remarkably stable. For the short distance of 5–10 feet individual grains moved in quantity. However, for distances greater than this very few grains could be found. Maximum distance at which we found a grain was about 50 feet.

The original concentration of the grains was not recorded and it is not known how many of the grains had actually moved but could not be found. The concentration of grains in the initial position was still large in 1962. However, it is believed that many grains, either by moving completely out of the searched area or by being covered, were not found.

In 1964 a second attempt was made to trace the movements of the fluorescent sand. The concentration at the original placement area had considerably lessened over that observed in 1962. Many grains were found within 50 feet of the original line and a few were found between 50 and 100 feet. Below 100 feet, but within several hundred feet, a few grains were found which fluoresced with the same characteristics as the placed grains, but comparison of these with grains from other observations indicated that they probably were native fluorescent minerals.

If any conclusion may be drawn from these experiments it would be that grains on the flat of a watershed divide are moved very slowly but that, once they are on the steeper slopes and within an area capable of overland flow, they are moved much more rapidly. This conclusion is supported by a 1-year set of data for erosion pins on a transect across a divide near the houses of Las Dos. These pins are referred in the project files as Corral Flat nail and washer line, but because of the short period of record are not elsewhere presented in this report. The 1-year of data show no erosion or deposition exceeding 0.005 foot, and the average for the line indicates little or no systematic movement of individual grains.

CHANNEL ENLARGEMENT IN SLOPEWASH TRIBUTARY

Although the slope retreat pins give an indication for the rate of channel enlargement, another set of measurements was designed specifically to provide rates of bank recession and channel aggradation-degradation. This set of measurements, designated as nail sections A–J (location shown on fig. 144, consists of 10 observation sections spaced approximately at 50-foot intervals along Slopewash Tributary. At each section a nail with washer was located on each sloping bank and one at the center of the channel bed. Rates of erosion and deposition were observed as previously described.

The sections were installed in 1959. Data have been collected yearly to 1964, excepting 1960. These data show that the average rate of bank erosion for the side pins is 0.0248 ft per yr. Deposition occurring at some of these pins averages 0.0058 ft per yr. The net bank recession is then equal to 0.0190 ft per yr. The channel bed pins indicate an eroded depth of 0.0694 ft per yr. This depth probably occurs as scour while surface runoff is flowing in the channel. Subsequent fill amounts to 0.1024 ft per yr. This leaves a net deposition of 0.0330 ft per yr, indicating an aggrading channel. This observation is consistent with other measurements indicating a channel aggradation. The channel aggradation is not confined to lower reaches of the channel but also extends upstream into the uppermost headwater rills. All nails in the channel on sections A–H show net deposition, and these vary in distance to watershed divide from 400 to 800 feet. Still, the amount of deposition in the small channels does not account for the volume eroded from upslope surfaces.

This excess of sediment is being supplied to the main streams and accounts for the aggradation observed there and reported in the section on scour and fill.

A summary of data for the nail sections are included in summary of data G.

SOIL CREEP OR MASS MOVEMENT

SLOPEWASH TRIBUTARY

To measure the magnitude of downslope soil movement occurring as soil creep, lines of mass-movement pins were installed in Slopewash Tributary and in Coyote C. basin (see figs. 144 and 145 for locations). The line in Slopewash Tributary is along the east fork some 100 feet above the junction of the tributaries. The line chosen crosses the meandering channel several times, and thus the pins are on the steep slopes (about 1:1) of the channel banks, alternately on one side and the other of the tributary. In figure 146 the photograph was taken with the camera at the north end of the line and the man is standing at the south end.

The two ends of the line are monumented and located in such a place that the monuments themselves are subject to no downhill movement. Iron rods, 4-feet long, were used to monument these end points. Generally at 5-foot spacings along the length of the line, ¼-inch galvanized iron pipes, 10 inches long, were driven vertically into the ground. At the time of installation they generally protruded about 0.1 foot above the ground surface. A transit was set up over the center of the monument on the north end of the line, oriented to the center of the monument at the south end of the line, and the distance of each pin away from the line of sight was recorded. Similar measurements are made on a resurvey except that the angle of the pin from the vertical and any increase in protrusion above the ground surface are also recorded.

Resurveys were made annually from 1961 to 1964. The average rate of downslope creep of the pin tops is 0.225 in. per yr. Considerable variations exist among individual measurements. However, all pins show net downhill movement for the 5-year period. Individual variations probably reflect local influences of the particular pin location; for examples, a twig, rock, local slope, or proximity to the channel.

All of the soil profile to the full depth of the pin is not moving as fast as the average rate reported. Most pins are rotating downhill, indicating that the top layers of soil creep at a faster rate than the lower layers. The average rotation of the pins is 1.4° per year. For seven of the pins the pin angles themselves explain all the observed downslope creep, the point of rotation being very nearly at, or slightly above, the bottom of the pin. For the other eight pins the center of rotation is a short distance below the bottom of the pin. For this latter set of pins it follows then that the entire soil profile, at least to the depth of these pins, must move downslope some distance. An average value of the downhill movement for the bottom of all pins is 0.003 in. per yr (a computed, not an observed value). This value, being so nearly equal to zero, indicates that only about the top 8 inches of soil are involved in mass-movement and that the soil nearest the surface has the greatest movement.

Since the pins are leaning downhill and some of the pin length protrudes above the ground surface, a more meaningful value of downhill creep would be that computed for the pin at the ground surface rather than at the pin top. These computations show the average rate of soil creep at the ground surface as 0.205 in. per yr, slightly less than the 0.225 in. per yr attributed to the tops.

Movement at the ground surface and at the pin base, along with the depth of inserted pin, allows computation of the volume of material moving. This value is 0.87 cu in. per in. of slope base per year, or 32 cu ft per mile of slope base per year.

The increasing protrusion above the ground surface observed at the mass-movement pins was also used to study erosion rates. The average rate of erosion for these pins is 0.025 ft per yr. Generally, these are the steepest slopes (approximately 45°) for which erosion values were obtained and they show the largest rate of erosion.

A summary of the downhill movement of the pin tops, rotation of the pins, and erosion at the pins are included in summary of data H.

COYOTE C. ARROYO

A mass-movement line of pins as just described was also installed along a tributary to Coyote C. Arroyo (location shown on fig. 145). The average downhill movement of the pin tops for the period 1961–64 was 0.267 in. per yr. During the period one pin showed an unexplained uphill movement.

The average downhill pin rotation during the period of observation was 1.7° per year. The relation of downhill movement to pin rotation is the same for these pins as for the pins in Slopewash Tributary.

The pins on this line showed greater erosion than those in Slopewash Tributary. Thus, computations for the rate of downhill movement at the ground surface used a value for the length of pin exposed equal to the original protrusion plus one-half of the erosion. Computations show the average rate of movement at the surface as 0.202 in. per yr, a figure remarkably close to that obtained in Slopewash Tributary. The volume rate is somewhat less than that in Slopewash owing to a smaller depth of soil movement, here 7.5 inches. The computed volume rate of mass-movement is 25.5 cu ft per mile of slope base per year.

A summary of data for the mass-movement line in Coyote C. Arroyo is included in summary of data I.

HEADCUT ENLARGEMENT

FENCE LINE HEADCUT

Fence Line Headcut is a tributary to the Arroyo de los Frijoles, entering on the left bank about 1,500 feet below the Main Project Reach. Figure 165 is a photograph of this headcut in 1964. In 1960 the headcut was staked with six iron pins, each 4 feet in length. The rate of enlargement of the headcut is determined by

FIGURE 165.—Fence Line Headcut.

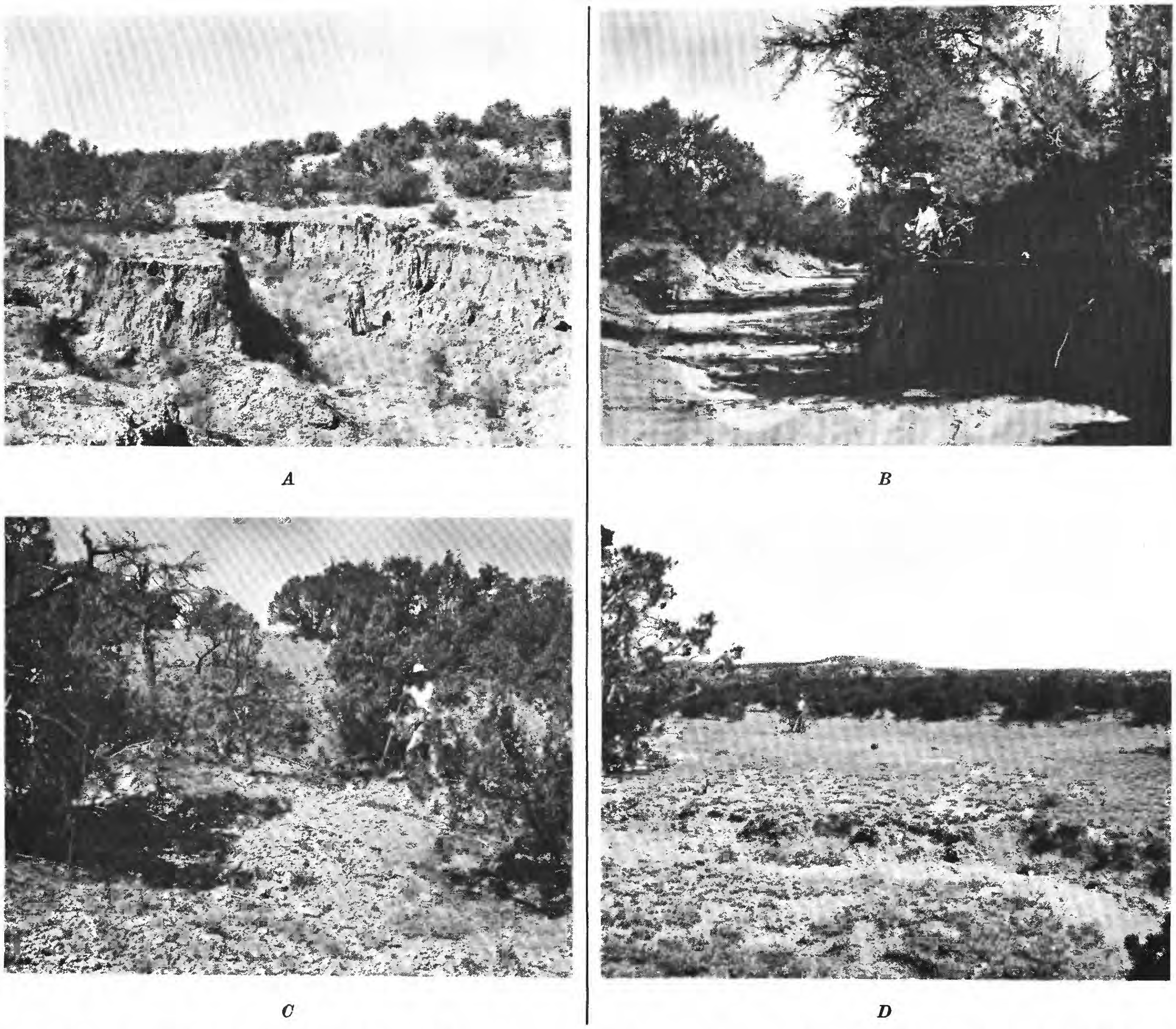


FIGURE 166.—Aspects of the drainage area of Coyote C. Arroyo. *A*, The largest headcut, cut in valley alluvium of Coyote C. Arroyo (also see map of fig. 167). *B*, Channel of Coyote C. Arroyo about 800 feet downstream from headcut pictured in *A*; man points with shovel to position where C^{14} sample was obtained to date the Coyote terrace deposits. *C*, View near the watershed divide of Coyote C. Arroyo; note the lag gravel typical of headwater areas not covered by colluvium. *D*, Typical view of the valley alluvium; coarse particles are found here only in watercourses, as in that in foreground.

measuring the distance from the iron pins to the vertical walls of the cut. Resurveys indicate that the headcut is slowly enlarging at all points of measurements, but that the greatest rate of enlargement is at the upstream end where the headcut is advancing nearly 1.5 ft per yr. Height of the vertical walls of the cut averages 6 feet.

The average volume of sediment discharged by this one gully is estimated at over 500 cu ft per yr, mostly from headward advancing.

COYOTE C. ARROYO HEADCUT

Coyote C. Arroyo is a discontinuous gully involving four headcuts. About 2,000 feet below the headwater divide is the largest of the headcuts, below which the gully is continuous to the master stream. The area around this largest headcut has been studied in detail and figure 166 includes photographs of the vicinity. Rate of headcut enlargement is being recorded by yearly planetable mapping and by measurements from iron pins driven at known distances from the vertical walls.

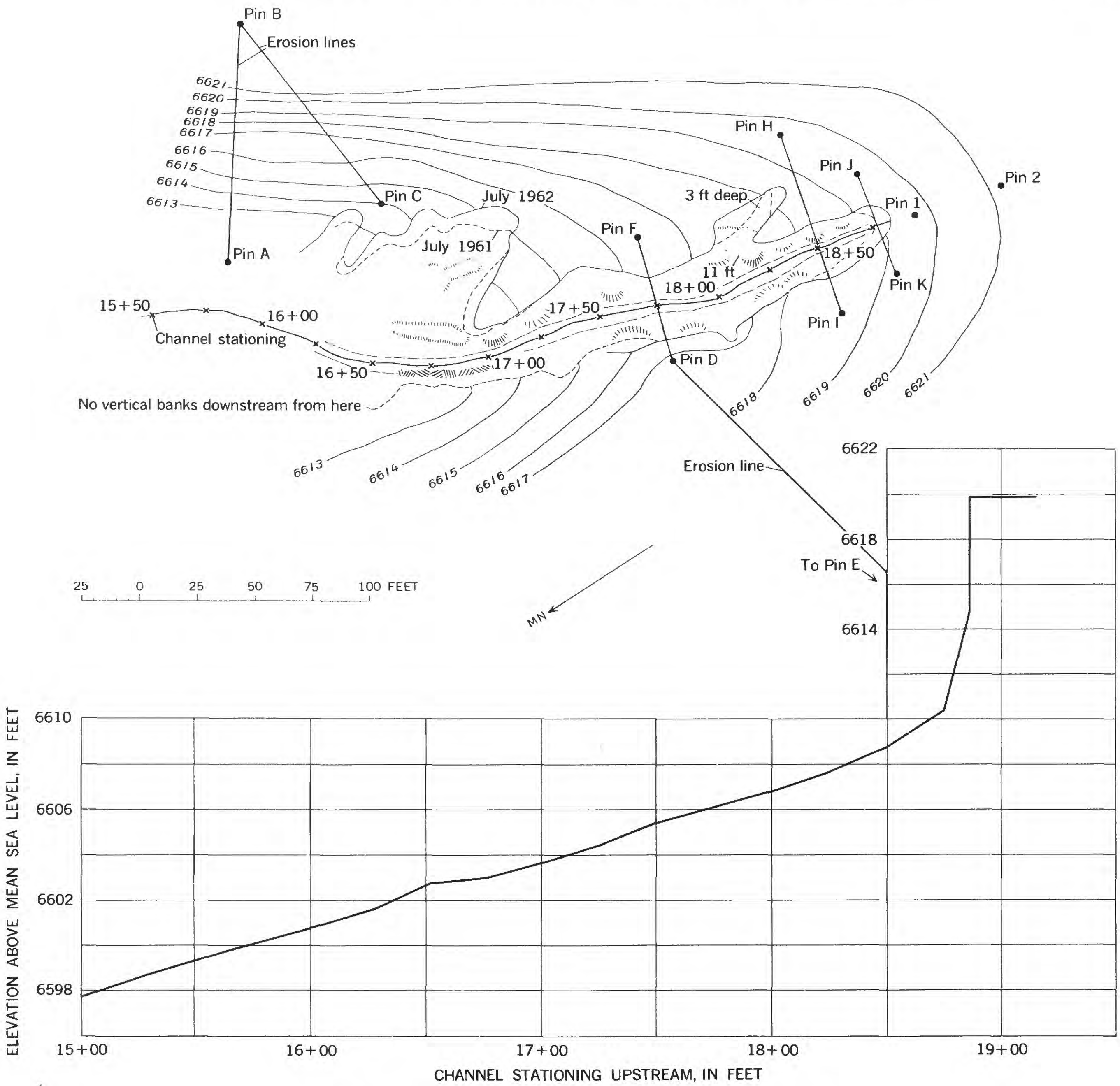


FIGURE 167.—Topographic map and profile of Coyote C. Arroyo headcut.

The planetable map of 1962 is shown in figure 167 and, as a dashed line, the outline of the headcut as it appeared the previous year. Most of the headcut has retreated some and the greatest amount of retreat is recorded in extremities which extend either up the primary direction of the channel or in the direction of tributary swales. Measurements from the pins to the cut bank indicate a lateral retreat of 0.4 ft per yr and a retreat at the most headward extreme of 2.6 ft per yr. Thus, while the map of figure 167 provides some insights about headcut retreat, mapping is not sufficiently accurate to delineate the relatively minute retreats which are occurring.

The initial 400 feet of channel profile is shown below the headcut map to provide an indication of channel slope and the sloughed material associated with the headcut. The average slope of the channel here is 0.03 ft per ft compared to 0.02 ft per ft in the channel 1,000 feet downstream. The volume of material contributed to the stream by the enlargement of this headcut has been computed to be 1,650 cu ft per yr for the period 1961–64.

MOVEMENT OF LARGE PARTICLES IN HEADWATER RILLS

SLOPEWASH TRIBUTARY

Two of the channels that have been studied in detail with respect to movement of individual rocks, Green Rock Gulch and Little Green Rock Gulch, are shown in figure 144. The former is also illustrated in figure 168. Starting at or near the mouth of these two channels individual rocks, each 3–6 inches in diameter, were completely painted. They were then replaced in the rills at measured distances from the mouth. This distance, in feet, was painted on each rock for identification and the total number of rocks at each distance was recorded. A total of 250 rocks was painted in Green Rock Gulch and placed at distances of 1–47 feet upstream of the mouth. Forty rocks were painted in Little Green Rock Gulch and placed from 21 to 36 feet upstream of the mouth.

The initial placement was in 1959 and resurveys were made annually. At the time of the resurveys the movements of the individual rocks were easily discernible because identification numbers on the painted rocks were no longer in consecutive order nor at the distance corresponding to their number.

Although the number of rocks moving has not been large, the recovery percentage is high. In 1964, 5 years after placement, 88 and 78 percent respectively of the rocks in the two gulches are still accounted for. Missing rocks are usually those that moved but later were obscured by either vegetation or a sand covering, that is, they were not buried in place. This is suggested by some of the rocks in the main study which were reported as missing in a given flow but were found after a subsequent flow.

FIGURE 168.—Green Rock Gulch, a tributary to Slopewash Tributary. Rocks wash into this minor rill from the lag gravel covering some of the hillslopes seen in the background.

The data have not been sufficient to describe a trend in movement. Both the upper and the lower halves of the reach on Green Rock Gulch show about 25 percent of their rocks moving or missing. Because of the large number of rocks not moving and the large variability in distance of those moving, the data are perhaps not yet meaningful. However, the longest distances recorded to date are of rocks originally placed in the lower 10 feet of channel and these have moved as much as 540 feet.

GUNSHOT ARROYO

Gunshot Arroyo is the first tributary entering Arroyo de los Frijoles below the sweeping S-curve half-mile downstream of the Main Project Reach. Measurements in Gunshot Arroyo include the tracing of large particle movements in the channel bed and on a steep sloping bank of the channel, the retreat of a knickpoint formed in the channel by an outcropping of semiresistant Santa Fe formation, channel enlargement, and degradation-aggradation studies.

In 1960 the initial survey and installations included the selection, painting, and replacing of rocks in the channel. The rocks, ranging in diameter from about 3 to 10 inches, were completely painted and numbered with the distance in feet corresponding to the initial position upstream of the junction with Arroyo de los Frijoles. The largest number is 880 and the watershed divide is located at station 1,150 feet. The rocks were placed at 10-foot intervals.

In 1962 a complete resurvey was made of the existing measurements and a longitudinal-profile survey was run from 150 feet below the mouth of the arroyo to and over the watershed divide. This profile is shown on figure 169. No vertical or cut banks were observed above station 620 feet and the channel disappeared above station 1,050 feet.

Superposed on the profile of figure 169 is a schematic illustration of the rock movements as recorded in 1962. Each rock position is identified as to moving, missing, or stationary. For those rocks which were found, the distance moved in feet is indicated by the number above the original position of the rock.

Most rocks below station 750 feet moved. Downstream from station 750 feet to station 450 feet, most of the moving rocks were found. Below station 450 feet a large percentage of the rocks were reported missing. The upper of the two mentioned subreaches has a gravel bed and the lower a sand bed. In the lower reaches of the channel most rocks that had moved were found partly buried in sand and, with few exceptions, those which had traversed the length of the tributary

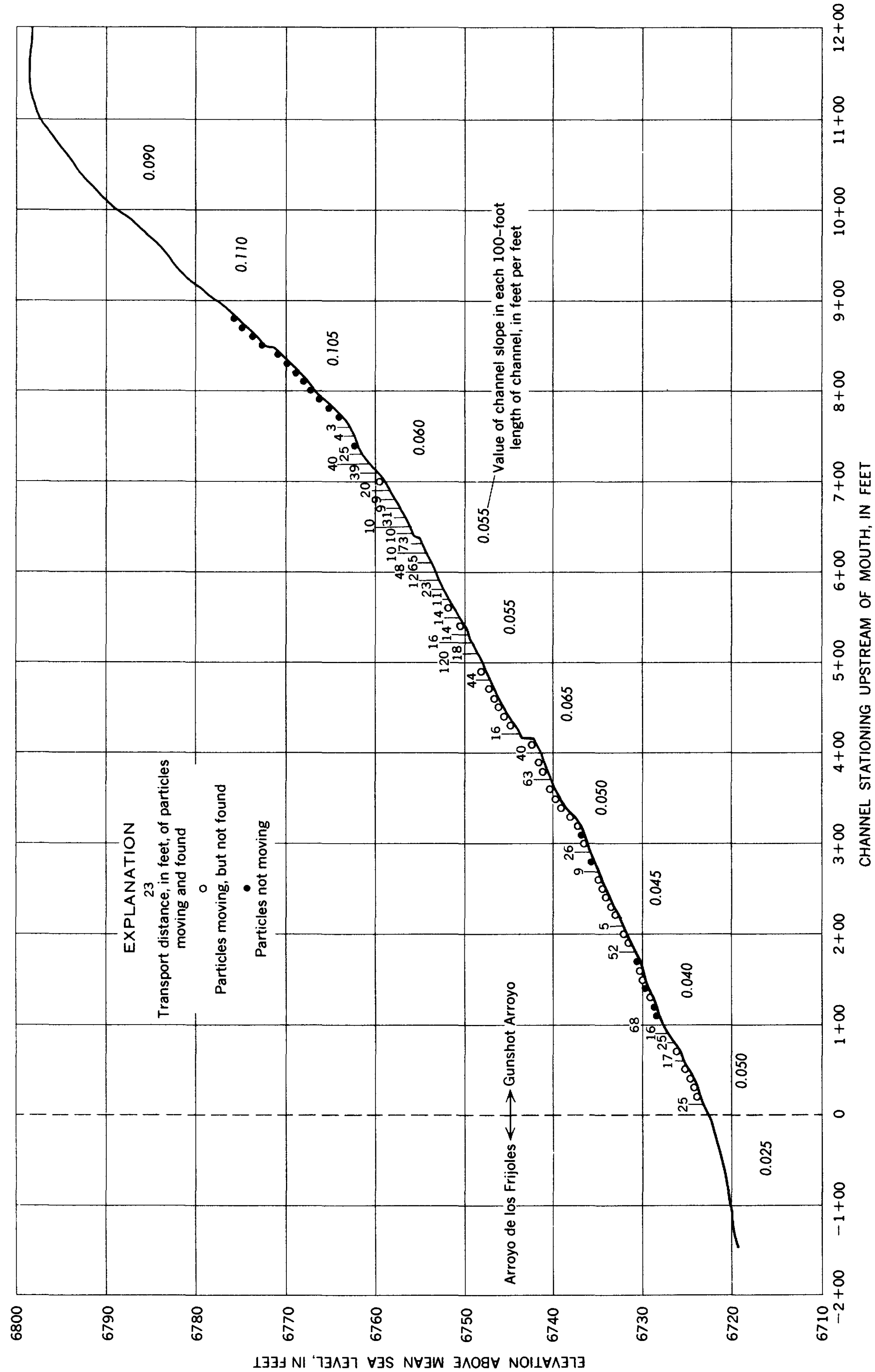


FIGURE 169.—Profile of Gunshot Arroyo illustrating movement of coarse particles, 1960–62. Average B- or intermediate-axis diameter of particles is 150 mm.

and into the channel of Arroyo de los Frijoles were not found. The rocks above station 750 feet were consistent in that none had moved despite the fact that these were on the steepest slopes.

At the time of the 1962 survey the rocks moving and found averaged a transport distance of 39 feet; the maximum distance recorded was 120 feet. If consideration were given to the missing rocks, which probably were transported entirely out of the tributary, these distances would be considerably increased. Of the rocks originally placed, 37 percent were missing and 22 percent had not moved.

After the 1962 survey the rocks found were returned to their original position, but the missing positions were not filled. Resurveys in 1963 and 1964 of these remaining rocks recovered only one rock reported missing in 1962. This adds credence to the probability that missing rocks were transported entirely out of the tributary.

In 1963 the number of total missing rocks increased to 82 per cent, and all but 2 of the 55 rocks remaining after the 1962 survey had moved. Of these 14 were found and averaged a transport distance of 218 feet and a maximum distance of 930 feet. The large increase in percentage of missing rocks is probably attributable to the storm which caused a 1,300 cfs flow at Main Project and which occurred between the surveys of 1962 and 1963. Most rocks remaining for the latter survey were from upstream positions and had longer distances to travel before being exposed to the greater chance of loss in the main channel. By 1964 the number of missing rocks had increased to 85 per cent.

Painted rocks on a typical steep slope (approximately 45°) at station 190 feet were resurveyed in 1962, 1963, and 1964. The rocks painted were native to the slope and generally ranged in intermediate-axis diameter from 1 to 3 inches. On an uncounted number of rocks painted in 1960, 175 remained in 1962 and 164 remained in 1964. Thus, in the last 2 years only 6 per cent have moved off the slope and have become lost in the channel. Between annual surveys an average of only 3 per cent of the rocks (excluding those missing) moved over one foot, but a gradual slumping was noticeable. In 1964, 118 rocks (72 per cent) had slumped downhill a measurable amount, and this slumping averaged 0.6 foot for the 4-year period. It appears that the effects of gravity, aided by such processes as freeze-thaw and wet-dry, have an appreciable influence on coarse particles on steep slopes.

The monumented knickpoint in the Santa Fe formation at station 417 feet averages about 1.3 feet in height, and between 1960 and 1964 no measurable amount of upstream retreat was recorded.

Scour chains placed in the arroyo bed at station 25 feet, 230 feet, and 468 feet indicate the channel is aggrading at a rate of 0.06 ft per yr for the 2-year period 1962–64. Although this is a short-term record, the value is in agreement with that of the main arroyo, 0.04 ft per yr.

MORNING WALK WASH

In 1961, painted rocks were placed at 10-foot intervals in the channel of Morning Walk Wash near Las Dos (fig. 139). The painted rocks ranged in diameter from 3 to 5 inches, the average rock size native to the gullies. A total of 166 such rocks were placed along the thalwegs of the two main channels and a smaller rill draining the hillslope.

A resurvey in 1962 indicated a very large percentage of the rocks had moved. Table 5 is a condensed presentation of the rock movements between 1961 and 1962. For example, in the north gully three times as many rocks had moved in the lower reaches than in the upper reaches and the rocks in the lower reaches tended to move greater distances. Many of the rocks were found in a fan deposit at the mouth of the channel.

As in Gunshot Arroyo the rocks found during the

TABLE 5.—*Summary of particle movement Morning Walk Wash, 1961–62*
[L, lower reach; U, upper reach]

Particles	South gully			South rill	North gully		
	L	U	Total or average		L	U	Total or average
Total originally placed	44	43	87	12	34	33	67
Percent moving, on basis of:							
Total found	41	40	40	25	77	12	45
Total found plus total missing	93	63	78	25	91	30	61
Percent not moving or not found	48	77	62	100	------	------	--------
Distance moved, in feet, on basis of total found:							
Average	177	339	258	211	------	------	--------
Maximum	473	723	--------	[1] 613	------	------	--------

[1] Lower reach.

survey were returned to their original position to await movement during subsequent flows, but the missing positions were not filled with new rocks. Thus data after 1962 became less meaningful except to determine the depletion rate of the originally placed rocks. Data for one of the painted rock experiments in headwater channels are included in summary of data J for 1961–64.

The condition of the paint on the rocks found indicates that the rocks are transported with only little abrasive action, that is, they are not broken up in place and removed as smaller particles, this despite the rolling and tumbling over other rocks in their trip downstream.

Two monumented cross sections of the channels were installed in 1961 and resurveyed yearly to 1964. During this period the upper section, 170 feet above channel mouth, showed no significant changes, while the lower section at the mouth showed about 0.2 foot of deposition in each channel bed. This value is consistent with other observations for channel aggradation.

SEDIMENTATION IN CHANNELS AND RESERVOIRS

About 1937, at the lower end of Coyote C. Arroyo some 1,900 feet downstream of the present position of the largest headcut, an earth dam was constructed across the arroyo. In 1961 the reservoir behind the dam was topographically mapped by planetable, and it was planned that resurveys would allow the determination of the amount of fill accumulating within the reservoir. Contours of equal deposition occurring during 1961–62, as well as original topography, are shown in figure 170.

Computations determining the volume amount of sediment collected in the reservoir during the period 1961–64 are shown in table 6. This amount totals 6,245 cu ft or 2,082 cu ft per yr. If the average rate of erosion shown by the erosion nails is assumed as a basin-wide average, the reservoir is shown to collect only about 5 percent of the total eroded sediment. However, the computation of this percentage may be of only academic interest because, as was remarked previously, values of the erosion rate computed from the pins installed in this basin are believed to be too large for the basin as a whole. Most of the sedimentation was in the year 1961–62.

The field-sketch map of figure 145 shows six channel cross sections at various distances up the arroyo. These cross sections were first surveyed in 1961; they have

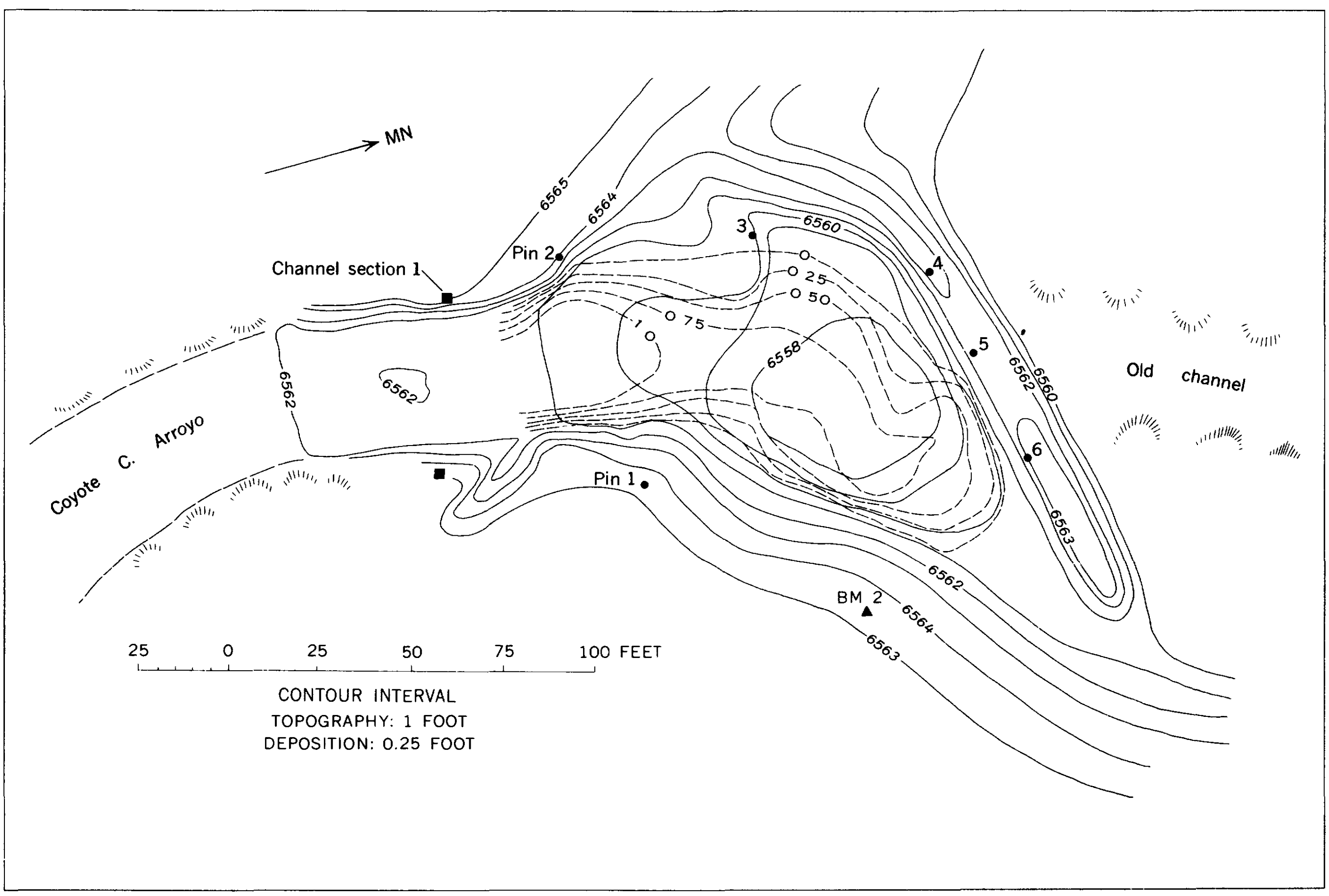


FIGURE 170.—Topography of dam and reservoir on Coyote C. Arroyo and contours of deposition, 1961–62.

TABLE 6.—*Observed sedimentation in reservoir behind dam on Coyote C. Arroyo, 1961–64*

Cross section	End pins	Decrease in area of cross section due to deposition (sq ft)			Effective width of section (ft)	Average depth of deposition (ft)			Effective area of reservoir (sq ft)	Amount of sedimentation [1] (cu ft)		
		1961–62	1961–63	1961–64		1961–62	1961–63	1961–64		1961–62	1961–63	1961–64
1	BM 2–6	10.0	10.0	10.4	30	0.33	0.33	0.35	1,000	330	330	350
2	BM 2–5	28.3	26.2	24.3	43	.54	.61	.56	825	445	505	460
3	BM 2–4	29.0	38.0	39.0	53	.55	.72	.74	900	500	650	665
4	1–5	30.5	50.5	55.5	55	.55	.92	1.01	913	505	840	920
5	1–4	34.0	68.0	73.0	60	.57	1.13	1.22	1,436	820	1,620	1,750
6	1–3	15.5	8.5	14.5	35	.44	.24	.42	1,850	815	445	775
7	1–2	51.5	44.5	39.5	40	1.29	1.11	.99	1,336	1,725	1,485	1,325
	Total									5,140	5,875	6,245
	Rate—cu ft per yr									5,140	2,938	2,082

[1] Amount of sediment contributed from basin (40.8 acres):

$$\frac{2082}{40.8\times 43,560}=0.0012 \text{ ft per yr}$$

been resurveyed yearly to 1964 and allow computation of deposition in the channel. Stationing and channel changes are summarized in table 7. The volume accumulations of sediment in the 1,435-foot reach included by the sections are also shown in the table. These data indicate that 3,192 cu ft per yr of sediment is deposited in this reach, which corresponds to channel aggradation of about 0.10 ft per yr. This value represents about 8 percent of the total eroded sediment indicated by the erosion pins.

The percentages of total eroded sediment accounted for by the surveys in the reservoir and in the lower reach of channel are not total reservoir and channel storage of sediment for the entire basin. Our studies have indicated that even headwater rills are aggrading, thus there is much more channel length in the basin available for sedimentation processes. Although the surveyed reservoir is the only man-built barrier, other natural reservoirs are also available. The discontinuous nature of the channels provides many alluvial fans and flats which may be considered as natural reservoirs; at least, sedimentation rather than erosion is occurring in these areas.

ANALYSIS OF SEDIMENT BUDGET

To account for sediment volumes contributed by erosion and to compile a balance sheet is not easy, because of the variance within the measurement data. With regard to what appears to be the main process contributing debris (sheet or surface erosion), the problem is how to average the rates observed by the nail and washer data at various localities and derive a figure applicable to the whole contributing area. To use the data on volumes contributed by headcuts presents little problem because there are only a few headcuts per square mile in the study area. Bank cutting and consequent channel enlargement is not an important source of sediment, as indicated by measured cross sections of channels. The data on mass-movement pins present a special problem because, lacking knowledge of certain details of the

TABLE 7.—*Observed rates of channel changes in Coyote C. Arroyo*

Section	Channel stationing (ft)	Change in channel shape (+, deposition; −, scour; (sq ft)			Length of reach (ft)	Volume of sediment [1] (cu ft)		
		1961–62	1961–63	1961–64		1961–62	1961–63	1961–64
1	30	+30.75	+29.00	+28.25	120	3,690	3,480	3,390
2	210	+8.75	+10.00	+11.00	165	1,445	2,100	2,310
3	365	+16.75	+14.10	+14.75	225	3,770	3,180	3,320
4	650	−2.70	−.50	.00	290	−785	−145	0
5	955	+.70	+.80	+1.10	395	265	315	435
6	1,435	−1.30	−.25	+.50	240	−310	−60	120
Total						8,075	8,870	9,575
Rate—cu ft per yr						8,075	4,435	3,192

[1] Amount of sediment contributed from basin (40.8 acres):

$$\frac{3192}{40.8\times 43,560}=0.0018 \text{ ft per yr}$$

process, the total area subject to effective sediment contribution from this source is difficult to estimate.

No great problem is presented by channel aggradation, for these measurements are far more complete than for other processes. Two important sources of possible error remain—the unmeasured volume of debris passing out of the basin as bedload or suspended load, and the trap efficiency of the reservoirs.

These difficulties face any investigator who is constructing a sediment budget. No perfect solution is available, but at least the assumptions made in the computations can be stated and the implications of the assumptions can be analysed. Although the quantities are only roughly approximate, a summary of debris inflow, outflow, and storage is attempted. Table 8 summarizes the average values of the measurement quantities. These values are arithmetic averages of individual readings taken over the period of measurement at the respective measurement points. Because comparison of mean and median values shows no great disparity, we used mean values exclusively in this report.

The main assumptions enter the computations in progressing from average-measurement data, table 8, to computations of average rates of erosion and deposition summarized in table 9.

The main source of data on sheet erosion is the pin-and-washer installations. More variance is noted between successive years than among the respective pins in the same year. Within a given group of nails the mean rate of erosion for the 3-year period was plotted by individual pins against the local ground surface slope at the pin, but no correlation was found. This lack of correlation is attributed to the fact that each group of nails applied to only a small range of slope values. Some influence of slope probably can be seen in the comparison of values of surface erosion in table 8. For example, the average land slope on the erosion plot of Slopewash Tributary is less than on the nail lines of Coyote C., and the corresponding net erosion rates are 0.008 and 0.024 ft per yr respectively.

But it appeared unjustifiable to correlate these net erosion values for different localities merely with slope because many other factors probably are also operative. The significance could not be tested statistically with only seven localities.

The average value of surface erosion for the whole basin (0.015 ft per yr; see table 9) represents our best judgment of the order of magnitude. This value is in agreement with the result obtained by equal weighting of number of pins and number of years of data, 0.0145.

Two values of volume eroded by headcut retreat are available. Approximately the average of these two was

TABLE 8.—*Data on measured rates of erosion and deposition*

[SWT, Slopewash Tributary]

Erosion	
Surface erosion:	
Erosion plot, SWT:	
Pins	61
Years	5
Net erosion—ft per yr	0.008
Slope-retreat pins, SWT:	
Pins	57
Years	5
Net erosion—ft per yr	0.014
Nail lines, Coyote C. Arroyo:	
Pins	65
Years	3
Net erosion—ft per yr	0.024
Nail sections, bank, SWT:	
Pins	20
Years	5
Net erosion—ft per yr	0.019
Mass-movement pins, SWT:	
Pins	15
Years	5
Net erosion—ft per yr	0.025
Iron pins, SWT:	
Pins	19
Years	6
Net erosion—ft per yr	0.007
Chain section pins, on banks, SWT:	
Pins	8
Years	6
Net erosion—ft per yr	0.011
Gully erosion:	
Coyote headcut:	
Years	3
Retreat (ft per yr):	
Laterally	0.4
Headward	2.6
Volume of material eroded—cu ft per yr	1,650
Fence line headcut:	
Years	4
Retreat (ft per yr):	
Laterally	0.15
Headward	1.5
Volume of material eroded—cu ft per yr	500
Mass movement (soil creep):	
Slopewash Tributary:	
Pins	15
Years	5
Downhill movement at ground surface—in. per yr	0.205
Volume of material moved—cu ft per mile of slope base per yr	32
Coyote C. Basin:	
Pins	12
Years	3
Downhill movement at ground surface—in. per yr	0.202
Volume of material moved—cu ft per mile of slope base per yr	25
Movement of individual rocks:	
Morning Walk Tributary:	
South gully and rill:	
Rocks	99
Years	3
Rocks moved—percent	75
Average distance moved—ft per yr	190

TABLE 8.—*Data on measured rates of erosion and deposition*—Continued

Erosion—Continued	
Movement of individual rocks—Continued	
Morning Walk Tributary—Continued	
North Gully:	
Rocks	67
Years	3
Rocks moved—percent	67
Average distance moved—ft per yr	96
Gunshot Arroyo:	
Rocks	88
Years	4
Rocks moved—percent	100
Average distance moved—ft per yr	93
Green Rock Gulch:	
Rocks	250
Years	5
Rocks moved—percent	23
Average distance moved—ft per yr	59
Little Green Rock Gulch:	
Rocks	40
Years	5
Rocks moved—percent	32
Average distance moved—ft per yr	1
Deposition	
Aggradation of channels:	
Slopewash Tributary:	
Nail section:	
Number of chains, pins or sections	10
Years	5
Average net aggradation—ft per yr	0.033
Pins at chain section:	
Number of chains, pins, or sections	2
Years	6
Average net aggradation—ft per yr	0.003
Arroyo Frijoles, mainstem: including North Branch:	
Number of chains, pins, or sections	90
Years	6
Average net aggradation—ft per yr	0.040
Coyote C. Arroyo:	
Number of chains, pins, or sections	6
Years	3
Average net aggradation—ft per yr	0.100
Gunshot Arroyo:	
Number of chains, pins, or sections	3
Years	2
Average net aggradation—ft per yr	0.060
Filling of small reservoirs:	
Coyote C. Arroyo Dam:	
Drainage area—sq mile	0.064
Years	3
Volume deposition—cu ft	6,245
Sediment collected—ton per sq mile per yr	1,633
Big Sweat Dam:	
Drainage area—sq mile	0.0060
Years	1.2
Volume deposition—cu ft	95.3
Sediment collected—ton per sq mile per yr	660

applied to the number of headcuts per square mile estimated from detailed knowledge of the area.

Mass-movement pins are installed on sloping gully walls which are steeper than the hillslopes in general. Though when the measurements were begun we had not expected downhill creep to be of significance in a semiarid climate, our observations and those of others (for summary see Leopold and others, 1964, p. 349–353) indicate that it is a process which cannot be disregarded. Mass wasting should deliver debris to the rills and channels in proportion to the rate of downhill creep and to the total length of channel in a given area. A drainage density was computed by using a Horton analysis of the number and lengths of channels. In a square mile the order of the largest channel including rills is seven. The number and lengths of various orders are as follows:

TABLE 9.—*Average rates of erosion and deposition*

Erosion	
Surface erosion:	
Average rate—ft. per yr	0.015
Percentage of total basin contributing	65
Erosion rate—tons per sq mi per yr	13,600
Gully erosion:	
Average volume per headcut—cu ft per yr	1,000
Headcuts per sq mi	4
Erosion rate—tons per sq mi per yr	200
Mass movement:	
Average downhill rate at ground surface—in. per yr	0.20
Length of channel affected—mi per sq mi	35.6
Average volume eroded—cu ft per sq mi per yr	1,960
Total volume—tons per sq mi per yr	98
Total erosion—tons per sq mi per yr	13,900
Deposition	
Aggradation of channels:	
Channel area—sq ft per sq mi	579×10^3
Average rate of deposition—ft per yr	0.05
Deposition—tons per sq mi per yr	1,440
Collected in dams—tons per sq mi per yr	1,663
Total deposition—tons per sq mi per yr	3,073

Order	Number	Length (miles)	Adjustment to channel segments: Length (mile)	Number	Number × length (miles)
7	1	1.2	0.50	1	0.5
6	3.5	.70	.48	4.5	2.2
5	11	.22	.11	14.5	1.6
4	45	.11	.06	56	3.3
3	140	.05	.027	185	5.0
2	400	.023	.013	540	7.0
1	1,200	.01	.01	1,600	16.0
Total					35.6

By this estimate there are about 35 miles of channel and rill in a square mile area, and because there are two banks of a channel, the length of channel boundary possibly subject to debris production by creep is some 70 miles. Using an average of 28 cu ft per mile of slope-base per year,

$$28\times70=1{,}960 \text{ cu ft per yr per sq mi,}$$

which at 100 lbs per cu ft is 98 tons per sq mi per yr.

Movement of individual rocks was not included as a separate item of contribution to sediment production.

Depositional data consisted of channel aggradation which was computed into tons per square mile as follows:

Order	Segment length (miles)	Width (ft)	Channel area (sq ft)
7	0.5	28	75,000
6	2.2	16	186,000
5	1.6	8	67,000
4	3.3	3.5	61,000
3	5.0	2.5	66,000
2	7.0	1.3	48,000
1	16.0	.9	76,000
Total			579,000

Then 579×10^3 sq ft of channel area aggrading at 0.05 ft per yr is 28,900 cu ft; at 100 pounds it equals 1,440 tons per sq mi per yr.

The collection of sediment behind the dam in Coyote C. Arroyo gave a figure of 1,633 tons per sq mi per yr. The production and trapping of sediment may be summarized as follows:

	Total sediment (tons per sq mi per yr)	*Sediment production (percent)*
Surface erosion	13,600	97.8
Gully erosion	200	1.4
Mass movement	98	.7
Total	13,900	100±
Deposition in channels	1,440	10
Trapped in reservoir	1,633	12
Total	3,073	22±

By far the largest contribution of sediment is by sheet erosion. Channel deposition is only about half of the total sediment trapped, the latter being only about one-quarter of that produced. It is recognized that if the budget were correct and the reservoir trap efficiency were 100 percent, the total of deposition in channels and trapped in the reservoir would equal sediment production. It is our opinion that the sediment moved as sheet erosion does not all get into the channel, but is temporarily stored in thin deposits widely dispersed over the colluvial area, and that furthermore, there is a very low trap efficiency to the reservoir.

Other measurements of sediment accumulation in western United States give values of 1,200 to 2,400 tons per sq mi per yr (Brown, 1945).

To our knowledge, of the published reports on sediment yield from semiarid drainage basins, by far the most excellent is that of Hadley and Schumm (1961), who measured, among other things, sediment accumulation in a large number of stock ponds and small reservoirs. These data were studied in relation to geologic formation, runoff, and various geomorphic characteristics of basins. Their data are far more comprehensive than ours insofar as sediment accumulation in reservoirs is concerned. The only unique feature of the present data is that we attempt to assess the relative importance of different processes of sediment production.

Despite their deficiencies, our data bear comparison with the more extensive values published by Hadley and Schumm, as in the following:

Sediment accumulation:	*Acre ft per sq mi per yr*	*Tons per sq mi pr yr* [1]
Coyote C. Arroyo (0.064 sq mi) accumulation in reservoir and channel	1.41	3,073
Average curve for all lithologies, for 0.06 sq mi area (Hadley and Schumm)	1.8	3,930

[1] Based on 100 lbs per cu ft.

For small basins the sediment accumulation observed by us in New Mexico is of the same order of magnitude as in basins of similar size in Wyoming underlain by shale or other lithologies high in silt content. Hadley and Schumm (fig. 30, p. 173) showed that for the Cheyenne Basin sediment accumulation was related to relief ratio (basin relief divided by basin length). The average relief ratio for our Coyote C. and Slopewash tributaries is 0.59. Entering this value in the Hadley-Schumm curve for all lithologies, the estimated value of sediment accumulation is 2.4 acre ft per sq mi per yr, and in the curve of those authors applicable to Fort Union formation only, the value is about 2.5. These values are slightly higher than the 1.41 observed in Coyote C. Arroyo but still of the right order of magnitude.

The finding of Hadley and Schumm (fig. 26, p. 163) that sediment accumulation per unit area of basin decreases rapidly with increasing drainage area is in keeping with our result that sheet erosion basin-wide estimated from erosion pins gives a value of sediment production about 4.5 times larger than can be accounted for in channel aggradation and reservoir accumulation. This feature is probably related in part to the same cause postulated by those authors: absorption of water in the dry channel beds below areas affected by local storms. But the fact remains that even in our detailed study of deposition, sediment spread thinly over colluvial areas does not show up in measurement data.

Another interesting comparison is with data on sediment production by dry sliding of debris on the steep slopes of southern California. Krammes (1960) measured debris in metal troughs laid on contour in burned and unburned areas in San Dimas Experimental Forest near Glendora. He found a sediment yield of 24.7 tons per acre per year (15,800 tons per sq mi per yr) after a brush fire, which compared with 2.69 (1,720 tons per sq mi per yr) before the fire had denuded the slopes. Of the total annual yield 89 percent of the debris was contributed during nonrain periods by dry sliding. The figure for prefire condition is about half the sediment yield observed by us in New Mexico, but the postfire figure is five times larger than our value.

Returning to the question posed earlier in this report, it appears that in semiarid areas of the type studied sheet erosion not only predominates as a sediment source but also seems quite capable of providing the sediment making up the bulk of alluvial fills during periods of aggradation. Indeed, the present channels are aggrading, and at 0.05 ft per yr the observed rate would eventuate in a fill as deep as the Coyote alluvium under the high terrace in 100–200 years. No doubt such a rate would not be sustained as an average for so long a period because in a century there would be some years, no doubt, during which net degradation would occur.

Nonetheless, the present processes and their rates appear quite capable of resulting in deposition of alluvial fills comparable to those of past periods which filled major valleys. The present is, then, a reasonable picture of conditions during which valley aggradation occurred in post-Pleistocene time.

The importance of sheet erosion makes it quite possible that aggradation can occur in tributaries, even in small channels only a few hundred feet from the watershed divide. Gully or rill erosion was probably insignificant or absent during the deposition of the principal alluvial fills in these valleys. Gully erosion assumes its important role during periods of valley trenching or arroyo cutting as was observed in the post-1880 period.

CLIMATOLOGICAL OBSERVATIONS DURING AGGRADATION

From the archeologic materials and a C^{14} date, it is computed that the upper part of the Tesuque formation accumulated in the Tesuque Valley, a few miles from our study area, at an average rate of 104–156 yr per ft (Miller and Wendorf, 1958, p. 190). During the period 1958–64 we observed an average rate of channel bed change that would result in aggradation at the rate of about 25 yr per ft. The present landscape is similar to that under conditions which probably prevailed in the same area, let us say, in the first centuries of the Christian era. But the land at present has hardly begun to recover from widespread devastation of the overgrazing in the late 19th century. The combination of a grazed range and the present climatic swing provides comparable rainfall-runoff conditions to those caused by a somewhat more unfavorable climate but uncomplicated by the effects of grazing animals.

What are the salient aspects of climate in relation to vegetation which create the difference between a period of aggradation and one of degradation in valleys? This question has merited the attention of many geomorphologists and has been answered tentatively in a variety of ways. Considerable evidence points to a coincidence of increasing aridity with degradation and increasing humidity with aggradation, but there are opposite views. Reaching a firm conclusion will have to await continuation of just the kinds of observations being here reported. Because we cannot hope to obtain a definitive answer to the question with 7 years of measurement, we are publishing our results principally to encourage others to join us in similar programs of simple measurement over a period of time in order that there will gradually become available concurrent data on rate of channel change, precipitation, and runoff.

The precipitation record for Santa Fe, N. Mex., is the longest in the United States. This record has been analysed in detail for its relation to the erosion problem (Leopold, 1951) and even then, 14 years ago, the difficulty of analysis lay not in the length of the precipitation record but in the lack of quantitative data on land erosion and channel changes. Our measurement data are not yet enough, but the nature of the problem can be more clearly seen than was possible without them, as will now be explained.

Leopold (1951) showed that the mean annual precipitation at Santa Fe did not significantly change between the first and second half of the century of record, but the frequency of daily rainfall amounts did change. In the present discussion we will review briefly that argument and bring the analysis up to date of the present writing, 1964.

Three graphs are presented in figure 171. Graph *A*, the annual march of yearly precipitation totals, is plotted without any averaging. Graphs *B* and *C* show that part of the annual amounts contributed in summer (July–Sept. incl.) months. The mean summer total of 6.06 inches consists mostly of thunderstorm rainfall which each season begins about July 15 after a relatively dry late spring and early summer. Thunderstorms are nearly daily occurrences in the nearby mountains from mid-July to early September. Graph *C* shows that part of the summer rainfall made up by rains totalling one inch or more in a day.

In the three parts of figure 171, trends in the 114 years are not easily discernible without the use of mov-

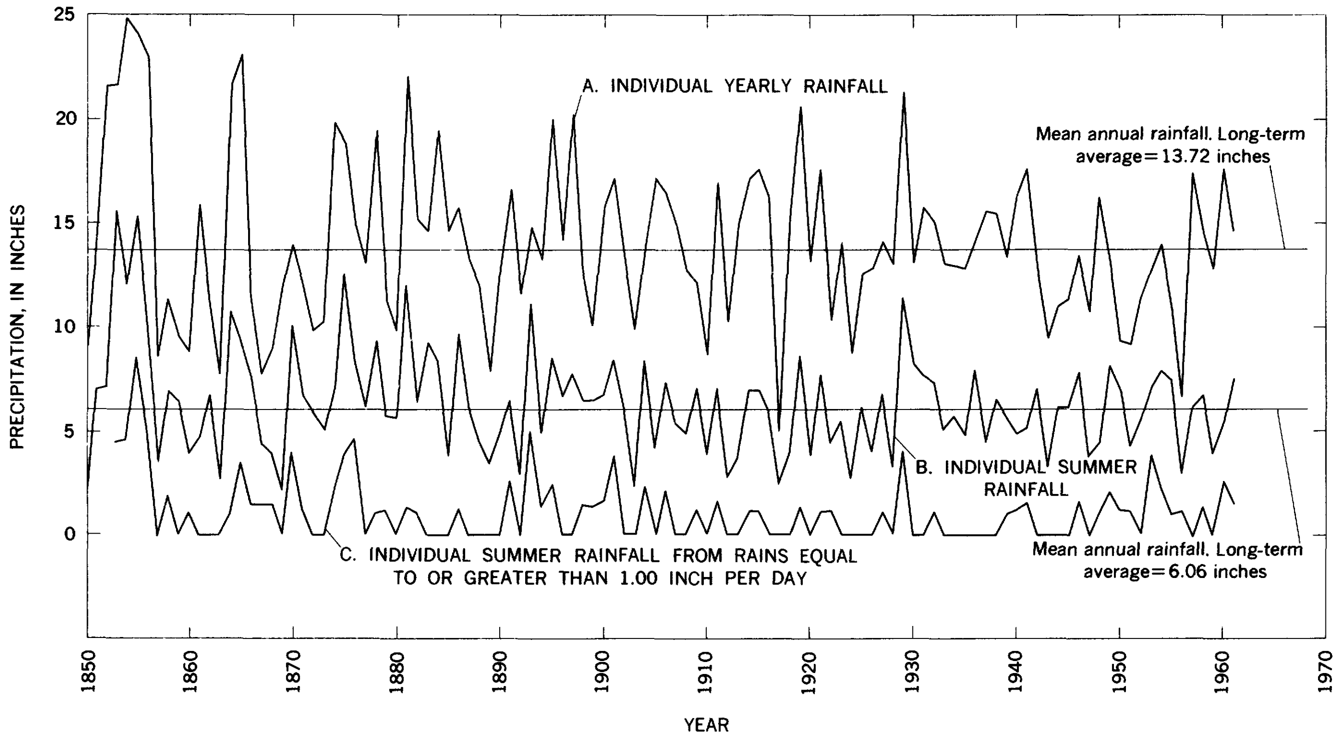


FIGURE 171.—Precipitation, Santa Fe, N. Mex.

ing averages. Inspection of the graphs reveals the dry period of the 1940's and early 1950's and the heavy summer rainfalls of the early 1850's.

Figures 172 and 173 break the precipitation record into its summer and nonsummer components, and then again into the number of rains of different categories of size of daily rainfalls. The secular change in number of nonsummer rains of less than 0.5 inch in a day so prominent in Leopold's analysis is obvious here, figure 173*B*. A more subdued but parallel trend is seen also

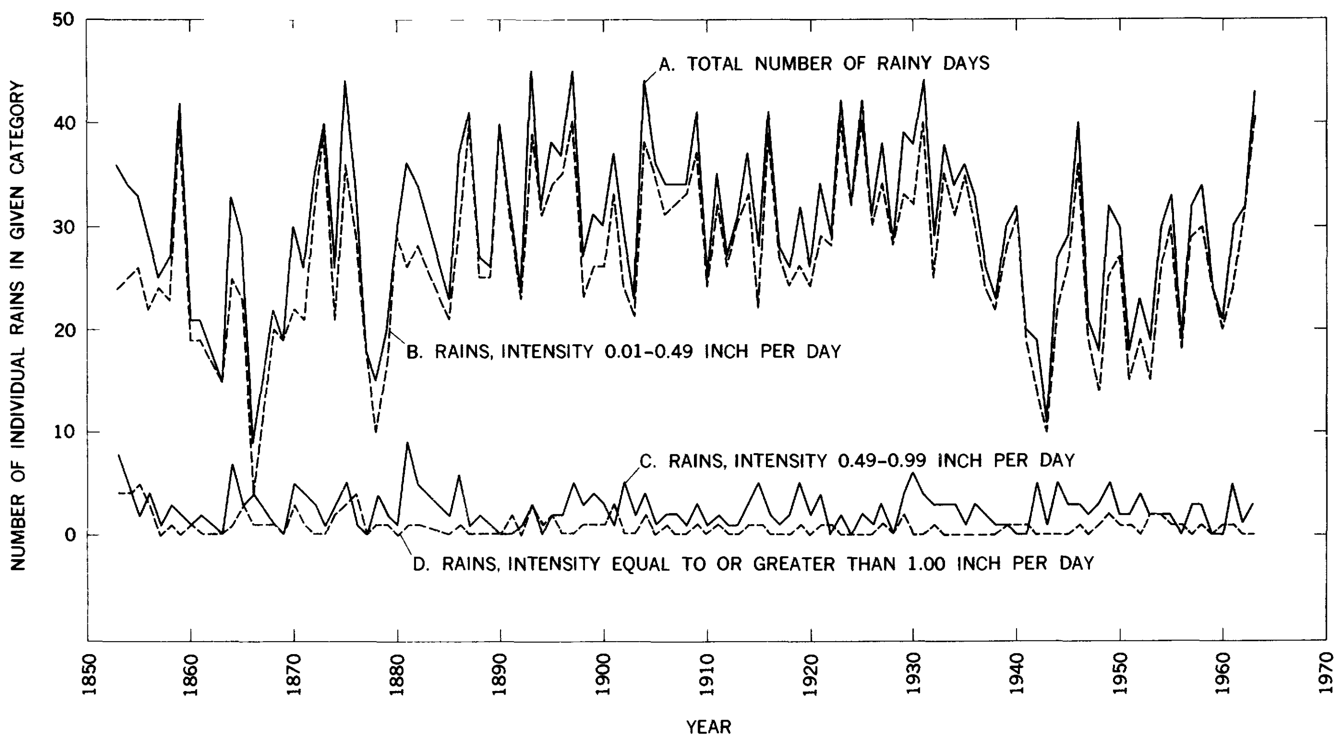


FIGURE 172.—Number of individual summer rains (July–Sept. incl.), Santa Fe, N. Mex.

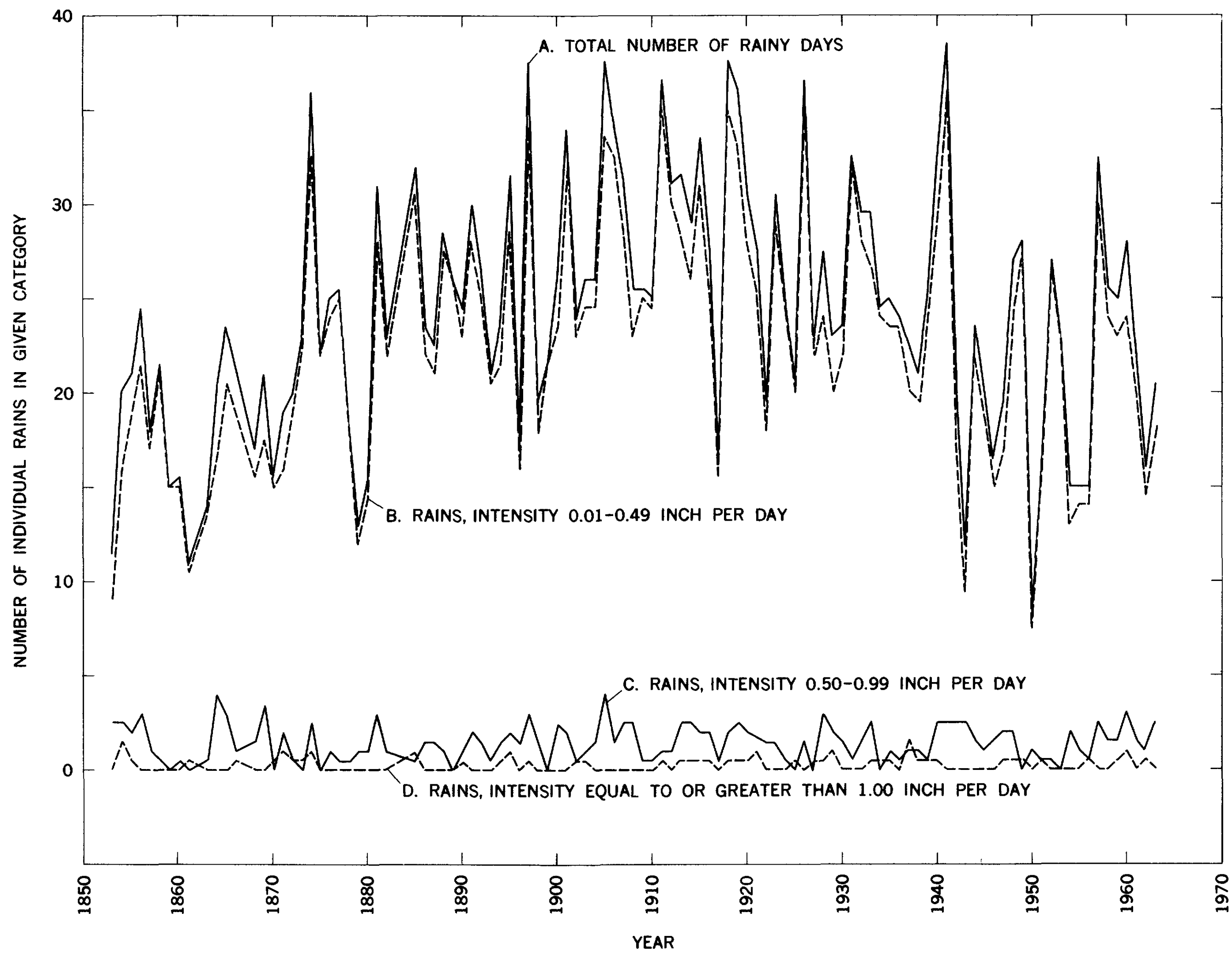


FIGURE 173.—Number of individual nonsummer rains, Santa Fe, N. Mex.

in the number of summer rains less than 0.5 inch per day. These secular changes leave the general impression that the last 25 years were more similar to the first 25 years of record than to the middle of the record period; that is, 1942–57 seems to resemble 1853–72.

This impression is strengthened by examination of figure 174 which shows the annual march of the average intensity of rain expressed as inches per day per rainy day, that is, the number of inches of rain in a year divided by the number of rainy days that year. The rains of the early and final part of the record were more intense than during the middle of the record.

Similar analysis led Leopold (1951) to argue that the period coincident with the advent of heaviest grazing, 1850–80, was characterized by a deficiency of the low-intensity rains which succor vegetation and by more than the average number of heavy rains which could act upon a weakened vegetal cover and promote erosion. This argument is a reasonable one, but to demonstrate its validity one needs concurrent and detailed data on erosion rates. Such concurrent data are now available for the 7-year period 1958–64, but this period includes years of both high and low intensity rainfall. The precipitation data are not clearly of the character that one could say unequivocally that erosion should be large or should be small. In short, the 7-year record is not long enough.

But the nature of the question ought to be clear from the data presented. Geomorphologists must make quantitative observations of erosion rates and channel changes over a long enough period to be clearly related to the concurrent precipitation record.

It is our hope that the presentation even of the short record now available will spur our colleagues to establish similar areas and continue simple measurements over a period of time so that those who follow us will have more to work with in analysis of this hydrologic and geomorphic problem.

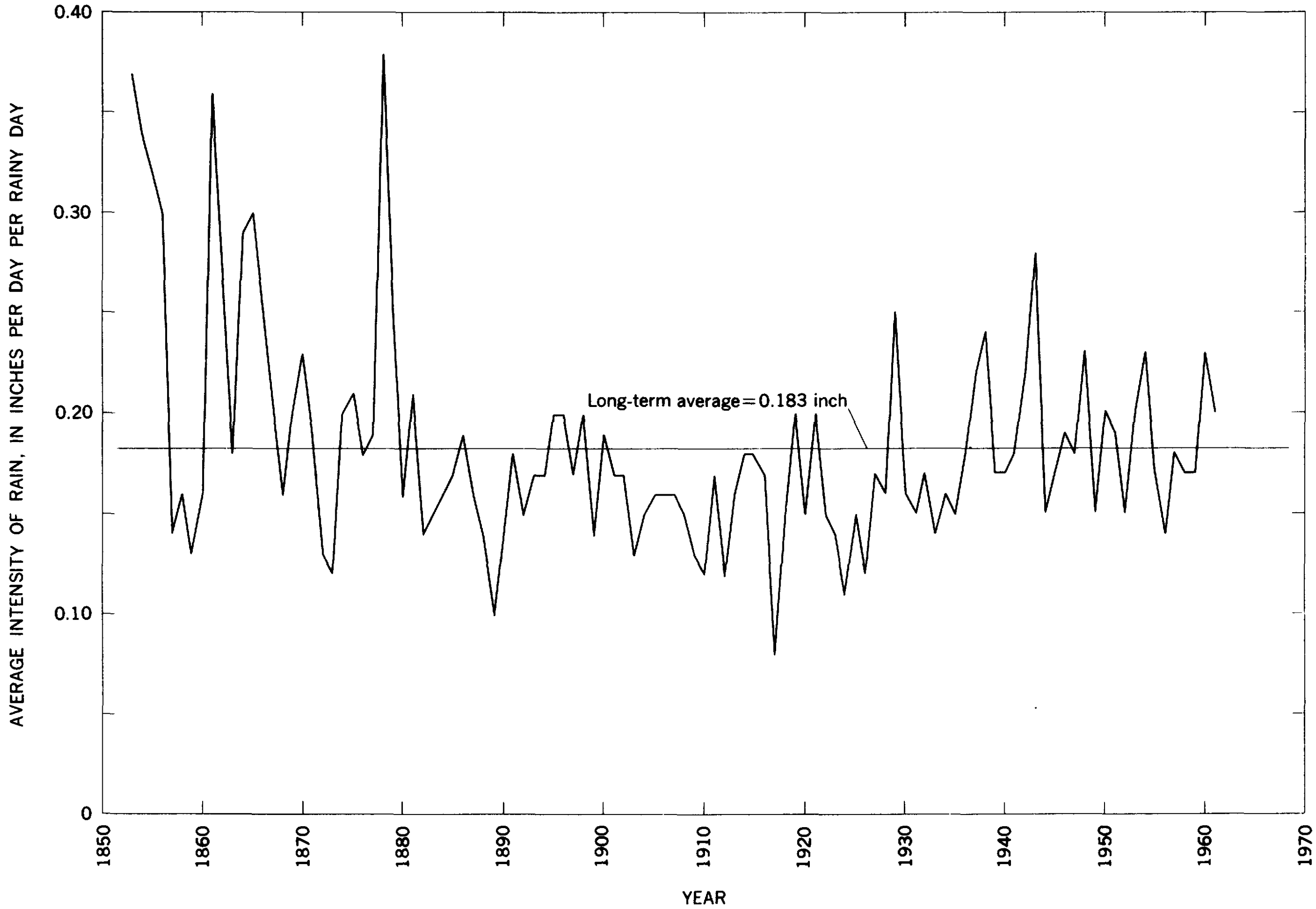


FIGURE 174.—Average annual intensity of rainfall, Santa Fe, N. Mex.

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SUMMARY OF DATA

A.—*Summary of nonrecorded rain-gage data, Arroyo de los Frijoles, 1959–63*

[Date of observation may be several days after storm date. Record should not be considered as annual precipitation. Tr., trace amount. Gage locations shown on fig. 143]

Date of observation	Precipitation, in inches, at rain-gage–											
	1	2	3	4	5	6	7	8	9	10	11	12
8-07-59	0.80	1.13	0.80	0.80	0.88	1.05	0.80	1.20	1.20	0.80	1.00	1.06
8-19-59	.25	.25	------	------	------	------	------	------	.20	------	------	.30
8-24-59	.50	.58	.50	.35	.32	.36	------	------	.30	------	.48	.65
10-30-59	1.00	------	1.45	1.40	------	1.40	1.38	------	------	1.32	1.30	1.26
6-10-60	.76	.70	.85	.80	.85	.80	.90	.90	1.05	.94	1.10	1.10
7-15-60	.50	.00	.80	.65	.35	Tr.	Tr.	Tr.	.00	.00	.00	1.02
8-05-60	.20	1.00	.80	------	.75	.50	.65	.45	.25	1.10	.35	.81
10-17-60	1.30	2.70	2.40	1.90	2.20	2.30	2.20	2.30	2.40	2.50	2.50	1.89
5-23-61	.00	.00	.00	.00	.00	.00	Tr.	.10	.30	.10	.20	------
6-16-61	.20	.20	.40	.30	.20	.20	.20	.20	.20	.30	.20	------
6-19-61	.00	.40	.00	.00	.00	.20	Tr.	.20	.10	.20	Tr.	.51
6-29-61	.10	.20	.40	.30	.50	.40	.50	.50	.30	.10	Tr.	.16
7-10-61	.60	.10	.80	.90	.40	.60	.60	.80	.90	.60	.60	.87
8-14-61	1.00	1.20	1.30	1.00	1.10	1.00	1.30	1.20	1.30	1.40	1.20	1.33
8-23-61	1.10	1.10	1.15	1.10	.90	1.00	.80	.80	.96	1.10	.85	1.13
9-19-61	1.20	.88	1.40	.95	.87	1.00	.82	1.00	.79	.89	.75	1.35
7-02-62	------	.20	.70	------	------	------	------	------	------	------	------	.90
7-09-62	.20	.50	.35	1.30	1.20	.20	.20	.30	.20	------	.40	1.09
7-27-62	------	2.00	.50	.50	.30	.80	.60	.70	1.00	1.10	.90	1.50
8-01-62	.40	.90	1.10	------	.60	.00	.50	.50	.20	.00	.00	.00
6-13-63	.79	------	1.20	.90	.20	.75	.80	.72	.71	.55	.50	.57
6-17-63	.20	.35	------	.40	.40	.60	.75	.75	.60	.55	.55	.35
7-10-63	Tr.	------	.02	Tr.	Tr.	.00	Tr.	Tr.	Tr.	Tr.	Tr.	.20
7-22-63	1.00	.00	.75	.50	.30	.35	.20	.10	.00	.00	.00	.07
8-27-63	.15	.20	.20	.40	.30	.30	.35	.40	.20	.25	.20	.40
9-23-63	1.30	1.30	1.40	1.10	1.00	1.10	1.30	1.30	1.20	1.30	1.10	1.67

B.—*Summary of recording rain-gage data, Arroyo de los Frijoles, 1959–62*

[Date of observation is within several days of major precipitation, but total precipitation includes also that between observations. Records should not be considered complete for use as annual precipitation. Gage located at Main Project Reach; see fig. 143]

Date of observation	*Precipitation (inches)*	*Date of observation*	*Precipitation (inches)*
8-07-59	1.06	7-08-61	.60
8-20-59	.26	7-28-61	.31
8-24-59	.80	8-13-61	1.33
8-26-59	.23	8-15-61	.10
10-02-59	.08	8-23-61	1.13
10-30-59	1.50	9-12-61	.70
11-13-59	.50	9-19-61	.80
12-17-59	.01	9-20-61	.10
		10-27-61	.70
1-21-60	.50	12-06-61	.10
2-29-60	.50		
5-18-60	.00	1-16-62	.30
6-10-60	1.10	3-09-62	.20
7-15-60	1.20	3-26-62	.20
8-05-60	.81	5-01-62	.10
8-23-60	.25	6-11-62	.10
10-07-60	.70	6-30-62	1.10
10-17-60	1.89	7-02-62	.00
12-12-60	.60	7-09-62	1.09
		7-23-62	.70
1-12-61	.10	7-26-62	1.50
4-03-61	1.30	7-30-62	.00
4-18-61	.38	8-02-62	.00
6-16-61	.20	8-28-62	.20
6-19-61	.60	9-17-62	.50
6-29-61	.30	11-26-62	.30

C.—*Summary of data, erosion-pin plot in Slopewash Tributary, 1959–64*

[Minus values in the net change columns represent deposition rather than erosion]

Pin	1959–61	1959–62		1959–63		1959–64		Net change 1959–64	
	Erosion (ft)	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Total (ft)	Yearly average (ft per yr)
1	0.02	0.00	0.01	0.04	0.04	0.015	0.020	−0.005	−0.001
2	.01	.03	.00	.03	.03	.025	.005	.020	.004
3	.01	.00	.01	.02	.02	.010	.005	.005	.001
4	.04	.05	.01	.05	.00	.040	.000	.040	.008
5	.03	.06	.00	.05	.00	.045	.000	.045	.009
6	.02	.04	.03	.04	.01	.040	.005	.035	.007
7	.02	.04	.00	.04	.04	.010	.025	−.015	−.003
8	.02	.03	.00	.04	.01	.030	.000	.030	.006
9	.02	.03	.03	.035	.04	.010	.040	.030	.006
10	.02	.03	.00	.025	.00	.045	.000	.045	.009
11	.04	.13	.11	.11	.11	.020	.025	−.005	−.001
12	.01	.00	.00	.015	.00	.020	.000	.020	.004
13	.03	.05	.02	.045	.03	.020	.005	.015	.003
14	.02	.03	.00	.03	.02	.025	.000	.025	.005
15	.03	.05	.00	.05	.00	.125	.000	.125	.025
16	.01	.03	.00	.02	.01	.035	.000	.035	.007
17	.01	.02	.00	.02	.00	.020	.005	.015	.003
18	.02	.02	.00	.02	.01	.015	.000	.015	.003
19	.02	.03	.00	.03	.00	.030	.005	.025	.005
20	.02	.04	.02	.03	.01	.025	.005	.020	.004
21	.03	.05	.00	.05	.00	.050	.005	.045	.009
22	.03	.05	.00	.05	.01	.055	.000	.055	.011
23	.02	.06	.00	.075	.00	.115	.000	.115	.023
24	.02	.03	.04	.03	.03	.020	.000	.020	.004
25	.03	.04	.03	.04	.00	.145	.000	.145	.029
26	.05	.06	.00	.09	.00	.130	.000	.130	.026
27	.01	.02	.00	.02	.00	.025	.005	.020	.004
28	.01	.02	.00	.02	.00	.030	.005	.025	.005
29	.01	.03	.00	.03	.00	.045	.005	.040	.008
30	.02	.03	.00	.03	.00	.050	.000	.050	.010
31	.01	.03	.01	.04	.01	.035	.000	.035	.007
32	.02	.00	.01	.02	.02	.035	.000	.035	.007
33	.01	.00	.04	.00	.07	----	----	----	----
34	.02	.04	.02	.035	.035	.025	.000	.025	.005
35	.02	.03	.00	.02	.01	.015	.000	.015	.003
36	.01	.01	.00	.02	.00	.025	.000	.025	.005
37	.01	.02	.00	.02	.00	.035	.000	.035	.007
38	.01	.02	.00	.02	.00	.040	.000	.040	.008
39	.02	.04	.00	.04	.00	.065	.000	.065	.013
40	.03	.05	.05	.05	.03	.040	.005	.035	.007
41	.02	.00	.02	.03	.03	.030	.035	−.005	−.001
42	.02	.04	.00	.06	.01	.075	.005	.070	.014
43	.03	.02	.00	.03	.00	.050	.000	.050	.010
44	.04	.07	.00	.08	.00	.080	.000	.080	.018
45	.01	.02	.02	.02	.02	.015	.020	−.005	−.001
46	.01	.03	.00	.02	.00	.025	.000	.025	.005
47	.01	.03	.00	.03	.00	.030	.000	.030	.006
48	.07	.10	.07	.11	.07	.065	.005	.060	.012
49	.04	.05	.00	.05	.01	.055	.005	.050	.010
50	.03	.05	.00	.05	.00	.055	.000	.050	.010
51	.03	.04	.00	.035	.00	.035	.005	.030	.006
52	.03	.03	.03	.04	.01	.030	.000	.030	.006
53	.02	.07	.00	.10	.00	.175	.000	.175	.035
54	.01	.02	.00	.02	.00	.025	.005	.020	.004
55	.01	.02	.00	.02	.00	.025	.000	.025	.005
56	.02	.03	.00	.03	.01	.040	.000	.040	.008
57	.04	.07	.07	.06	.03	.055	.005	.050	.010
58	.02	.04	.00	.03	.01	.020	.005	.015	.003
59	.01	.04	.00	.03	.00	.035	.005	.030	.006
60	.01	.00	.00	.02	.06	.010	.035	−.025	−.005
61	.02	.03	.02	.035	.00	.035	.000	.035	.007

Summary

Average erosion, 0.0117 ft per yr.
Average deposition, 0.0041 ft per yr.
Net average erosion, 0.0076 ft per yr.

D.—*Summary of data, slope-retreat pins in Slopewash Tributary, 1959–64*

[Minus values in the net change columns represent deposition rather than erosion]

Pin	1959–61		1961–62		1962–63		1963–64		1959–64		Net change 1959–64	
	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Erosion (ft)	Deposition (ft)	Total (ft)	Yearly average (ft per yr)
1	0.01	0.00	0.03	0.00	0.01	0.01	0.025	0.000	0.075	0.010	0.065	0.013
2	.06	.00	.04	.00	.02	.01	.03	.000	.150	.010	.140	.028
3	.05	.00	.03	.00	.01	.03	.035	.015	.125	.045	.080	.016
4	.04	.00	.06	.00	.01	.01	.015	.000	.125	.010	.115	.023
5	.07	.00	.04	.00	.02	.01	.015	.000	.145	.010	.135	.027
6	.17	.00	.03	.00	.02	.02	.030	.000	.250	.020	.230	.046
7	.01	.16	.21	.17	.03		.080	.000	.330	.330	.000	.000
8	.01	.00	.03	.00	.00	.06	.070	.030	.110	.090	.020	.004
9	.02	.00	.02	.00	.09	.01	.030	.000	.160	.010	.150	.030
10	.03	.00	.01	.00	.04	.01	.015	.000	.095	.010	.080	.016
11	.03	.00	.01	.00	.06		.040	.000	.140	.000	.140	.028
12	.02	.03	.08	.07	.03	.02	.015	.000	.145	.120	.025	.005
13	.01	.00	.02	.00	.06	.02	.005	.000	.095	.020	.075	.015
14	.04	.00	.02	.00	.03		.005	.000	.095	.000	.095	.019
15	.00	.00	.02	.00	.025	.025	.020	.015	.065	.040	.025	.005
16	.04	.00	.02	.00	.015		.035	.000	.110	.000	.110	.022
17	.04	.00	.03	.00	.035		.035	.000	.140	.000	.140	.028
18	.15	.00	.11	.00	.03	.03	.040	.040	.330	.070	.260	.052
19	.29	.00	.13	.00	.02	.02	.020	.020	.460	.040	.420	.084
20	.08	.00	.07	.00	.04	.04	.025	.025	.215	.065	.150	.030
21	.00	.18	.22	.10	.03	.03	.030	.040	.280	.350	−.070	−.014
22	.03	.00	.03	.00	.03	.04	.050	.005	.140	.045	.095	.019
23	.02	.04	.06	.02	.04	.04	.030	.020	.150	.120	.030	.006
24	.01	.03	-----	-----	.04	.05	.070	.000	.120	.080	.040	.008
25	.02	.00	.02	.00	.05	.05	.020	.000	.110	.050	.060	.012
26	.04	.00	.01	.03	.175	-----	.035	.000	.260	.030	.230	.046
27	.03	.00	.02	.00	.05	.05	.035	.005	.135	.055	.080	.016
28	.02	.00	.02	.00	.04	-----	.000	.040	.080	.040	.040	.008
29	.03	.00	.01	.01	.02	-----	.020	.000	.080	.010	.070	.014
30	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
31	.02	.00	-----	-----	.01	.07	.055	.135	.085	.205	−.120	−.024
32	.02	.00	-----	-----	.01	.09	.080	.085	.110	.175	.065	−.013
33	.03	.00	.01	.04	.02	.07	.075	.145	.135	.255	−.120	−.024
34	.04	.00	.00	.09	.01	.02	.025	.045	.075	.155	−.080	−.016
35	.01	.00	.00	.01	.00	.02	.030	.080	.040	.110	−.070	−.014
36	.02	.00	.00	.02	.02	.03	.030	.005	.070	.055	.015	.003
37	.02	.00	.01	.00	.03	.02	.015	.000	.075	.020	.055	.011
38	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
39	.03	.00	-----	-----	.02	.13	.090	.110	.140	.240	−.100	−.020
40	.03	.00	-----	-----	.04	.11	.050	.080	.120	.190	−.070	−.014
41	.02	.00	.00	.01	.03	.00	.030	.000	.080	.010	.070	.014
42	.01	.00	.02	.05	.02	.03	.050	.000	.100	.080	.020	.004
43	.00	.00	.03	.06	.01	.01	.080	.000	.120	.070	.050	.010
44	.01	.00	.06	.04	.01	.00	.040	.000	.120	.040	.080	.016
45	.01	.00	.05	.00	.02	.01	.030	.000	.110	.010	.100	.020
46	-----	-----	-----	-----	.19	.04	.050	.000	.140	.040	.100	.020
47	-----	-----	.11	.00	.00	.04	.110	.000	.220	.040	.180	.036
48	-----	-----	.05	.00	.00	.03	.010	.000	.060	.030	.030	.006
49	-----	-----	.03	.00	.01	.00	.000	.040	.040	.040	.000	.000
50	-----	-----	.04	.00	.00	.02	.020	.020	.060	.040	.020	.004
51	-----	-----	.02	.00	.02	.02	.000	.010	.040	.030	.010	.002
52	-----	-----	.03	.00	.08	.00	.090	.000	.200	.000	.200	.040
53	-----	-----	.03	.00	.07	.00	.070	.000	.170	.000	.170	.034
54	-----	-----	.10	.05	.01	.00	.030	.000	.140	.050	.090	.018
55	-----	-----	.02	.01	.01	.00	.070	.000	.100	.010	.090	.018
56	-----	-----	.10	.04	.00	.15	.210	.000	.310	.190	.120	.024
57	-----	-----	.09	.04	.00	.02	.060	.000	.150	.060	.090	.018

Summary of erosion rates, in foot per year

Pins	*Erosion*	*Deposition*	*Net erosion*
1–29	0.0326	0.0116	0.0210
30–45	.0197	.0231	.0034
46–57	0.0272	0.0089	0.0183
1–57	.0281	.0139	.0142