As one approaches Santa Fe from the west, it appears that the Sangre de Cristo Mountains are abutted by a single relatively broad remnant of an erosion surface cut on poorly consolidated sand and gravel of the Santa Fe formation of Miocene and Pliocene age. From the top of any of the lava-capped mesas near the Rio Grande, one obtains a splendid view of this surface which slopes gently upward to the east toward the mountains. Actually, the plain, which from afar appears smooth, consists of several erosion surfaces differing but little in elevation. Furthermore, close inspection shows that the relief is in fact greater than it appeared from a more distant view. Rolling hills, dissected by gullies and rills and interlaced with sandy, flat-floored washes, are nearly everywhere at hand. The general appearance of streams in the area studied can be visualized by inspection of the photographs in figures 2 and 3. (For definition of stream order see p. 16.) The network of drainage channels ramifies upstream into increasing numbers of successively smaller gullies and rills extending almost to the divides.

As elsewhere in arid regions, these channels present a variety of forms. They range from tiny rills biting back into mesa escarpments to deep trenches or flume-like arroyos incised in otherwise flat alluvial valleys. Despite these striking differences in appearance, they all have certain common characteristics besides the ephemeral nature of their flow. First, vegetation in or along the channel is so sparse that it exerts almost no influence on the form of the channel. Second, because large amounts of fine debris are readily available for transportation both in interstream areas and in the channel itself, the sediment concentration during flows greatly exceeds that of streams in more humid areas. Third, downcutting appears to proceed slowly after the initial development of gullying in a given reach. In a developing arroyo system, channels quickly achieve maximum depth and thenceforth little change in depth occurs despite a considerable thickness of easily removed material.

An arroyo in the Southwest discharges water only when a moderately heavy rain falls on the drainage basin. This is typically a summer phenomenon since flow-producing rain falls only from thunderstorms. Winter rains are of too low intensity to provide surface runoff and for this reason arroyos practically never flow in winter.

Summer thunderstorms in New Mexico typically produce rain over 5 to 50 square miles, but the larger coverage ordinarily results from movement of the storm. The storm itself covers, on the average, about 10 square miles. Depth-area curves of thunderstorm rainfall in New Mexico published by Leopold (1942) show that usually not more than 3 to 4 inches of rain falls over 3 square miles and the amount decreases to 1 inch over 50 to 100 square miles. It was our experience that flash flow in arroyos seldom occurs if the rainfall at the
FIGURE 4.—Passage of a small bore in the rising stage of an ephemeral flow in an arroyo channel, Rio Puerco, a tributary to the Rio Grande. Location is 8 miles north of Puerco Station, N. Mex., September 19, 1941. Soil Conservation Service photographs.

from the vertical walls and lying crumbled but uneroded in the channel. This debris is picked up and washed away by subsequent flows and is undoubtedly an important source of debris load.

Flash floods in arroyos, therefore, appear to do but insignificant amounts of bank cutting as a direct result of impingement of flow on the banks. Wetting of the banks, however, results in subsequent collapse of arcuate slabs of alluvium which tumble into the channel to become important additions to the load of later floods.
Collapse of gully walls is greatly facilitated by piping or tunnels which develop in the gully walls and lead waters from the adjoining surface to the channel by an underground route (see fig. 5). It was our observation that only a small proportion of total flow in a gully reaches the gully channel by direct overpour of the vertical banks. Piping tunnels and tributary gullies and rills deliver the bulk of the discharge.

The manner in which relatively large pebbles or cobbles move during flash flows is particularly worthy of comment. The bed material in the ephemeral streams studied in the Santa Fe area characteristically is composed of a matrix of moderately well sorted coarse sand, but it includes a certain number of cobbles, rocks, and even some small boulders. The cross section of flowing water during flash floods is wide and shallow, but the velocity of the water is high. Despite the small depth of flow, the large cobbles are effectively moved by rolling. Mudballs move in a similar fashion, rotating about the longest axis. Even cobbles which are irregular in shape and subangular roll along the stream bed for long distances without stopping. Cobbles were observed to roll spasmodically but rapidly even when the water was no deeper than half the diameter of the rolling object. At this depth the water seems to splash up on the upstream side of the cobbles and plunge over its top, so providing a torque. It is indeed common to see particles, small and large, sticking well out of the general water surface and rolling rapidly downstream with only temporary interruptions.

**PROBLEMS OF MEASUREMENT**

Attempts to obtain precise measurements of arroyo floods are fraught with many difficulties and inherent dangers. It was necessary to adopt unorthodox methods that yield data which are admittedly crude. Nevertheless, the data themselves are unique, and they appear to be adequate for the kinds of analyses undertaken.

Three factors militate against good measurements of the rising stage of arroyo floods. First, the stage rises to peak so quickly that one can seldom be present during the few minutes of rise even when he is trying to. Second, peak stage is dangerous for a person wading in the flood because of high velocity and the occurrence of surges or bores. Finally, peak flow of consequence occurs generally near the storm center where lightning is a deterrent to wading operations. Hence, most of the hydraulic data presented here were obtained during the falling stage of the individual floods. All measurements were made by wading; velocities were measured with a Price current meter.

When rocks as much as half a foot in diameter batter one's feet and meter in a current flowing 6 feet per second, and when the sand is constantly undermined from under one's heels, short-cut methods inevitably are adopted. For reasons which follow, our discharge measurements of arroyo flow must be considered rough approximations. Instead of using 20 to 30 measuring points or “verticals” across the channel, only 10 to 15 were used. The duration of current-meter observation at each point was reduced from 40 to 20 seconds, and the meter was set at 0.6 depth in most cases. It is standard procedure to make adjustments for variation in water level during the measurement, but stage could be measured only crudely. We traversed back and forth along the tag-line without interruption during the falling flood. Each traverse of the 10 or 15 sections across the channel was considered a measurement of discharge, and the mean stage during the traverse was assumed to apply to that measurement.

Suspended-sediment samples were collected with the DH 48 hand-sampler or, in a few cases, by dipping a bottle without the aid of a hand-sampler. The samples were collected near the midpoint in time of discharge measurements. Usually two samples, each depth-integrated, were collected at two points in the channel cross section. The concentration of sediment was determined separately in the laboratory. The average of the two concentrations was considered to be representative of the flow during the discharge measurement.
and figure 15 which pictures Arroyo de los Frijoles at a place where its size is typical of an 8th order stream. Channels of order 5 and order 10 can be seen in figures 2 and 3, respectively.

Because maximum stream length is a function of drainage-basin area, it is not unexpected that the relation of drainage area to stream order is also a straight line on semilogarithmic paper, as can be seen in figure 16. The smallest unbranched tributaries, which are rills about 8 inches wide and 1 to 4 inches deep, drain on the average about .00006 square miles or .04 acre. In the 670-square-mile basin of Rio Galisteo there are roughly 190,000 such first-order tributaries, as estimated from figure 13.

EQUATIONS RELATING TO HYDRAULIC AND PHYSIOGRAPHIC FACTORS

From the previous work of Horton or from our data plotted in figures 13 and 16, it is apparent that stream order, $O$, bears a relation to number of streams, $N$, in the form

$$O = k \log N$$

and a similar relation to stream length, $l$, slope, $s$, and drainage area, $A_d$,

$$O \propto \log l$$

$$O \propto \log s$$

$$O \propto \log A_d$$
relation of channel slope to channel width is generally in line with that of the larger ephemeral channels.

The solid triangles apply to similar unbranched rills occurring in steeper tributaries in the same area which drained the unconsolidated gravels of a pediment remnant somewhat nearer the mountains than the Arroyo Caliente. The difference in stream slope between Arroyo Caliente and Fifth of July Wash can probably be attributed to the difference in size of the gravel characterizing the two small basins.

To determine whether this relation between slope and width would be maintained even by the very smallest rills, measurements were made of the smallest natural rills which could be found in the area. The values of slope and width of these miniature features are represented by the black circles in the far upper left part of figure 18. They fall in a position so nearly representing an extension of the line in the diagram that it may be inferred that the slope-width relation in the area studied applies as far upstream as the smallest observable rill.

In the same area are many places where modern highways have required deep road cuts through the same material as that constituting the drainage basins under study. On the steep road cuts little or no vegetation has become established, and numerous steep parallel rills of an average depth of 0.2 feet have developed. The width and slope of these road-cut rills were measured. The slope had changed but little from that determined by the blade of the highway grader. The rills on road cuts are shown by open triangles on figure 18. These points are no more scattered from the mean line than any other data. It appears then, that if the degrees of freedom are reduced, in this instance by a prescribed slope, the width of the rill will be formed in accordance with the slope-width relations for natural streams having a larger number of degrees of freedom. This is interpreted as further evidence that channels cut by water carrying sediment tend to maintain a quasi-equilibrium even as far upstream as the most remote ephemeral rills.

THE DISCONTINUOUS GULLY

Beginning late in the 19th century the alluvial valleys of the West experienced an epicycle of erosion characterized by the development of valley trenches or arroyos (see fig. 25). These arroyos range in size from insignificant rills to canyons 600 feet wide, 50 feet deep, and 150 miles long. The notorious Rio Puerco (del Oriente) in New Mexico has the latter dimensions. Some gullies are narrow enough to step across but are deep enough to lose a giraffe in. As Gregg (1844, p. 184) said more than a century ago,

\[ \text{Figure 25.—A typical large continuous arroyo trenching an alluvial valley in New Mexico: Rio Puerco (del este) near Manelito, looking downstream.} \]

The sides are usually perpendicular—indeed, often shelving at the base, and therefore utterly impassable . . . Though, to a stranger, the appearance would indicate the very head of a ravine, I would sometimes be compelled to follow its meandering course for miles without being able to double its “breaks.”

It is characteristic of the large arroyos that depth remains quite uniform through very long reaches. This uniformity of depth means that the gradient of the channel bed had attained a slope almost parallel to the original valley floor. There is also another distinctive type of gully that is characterized by a vertical head-cut, a rapidly decreasing depth downstream, and a fan at the lower end. Such channels generally occur in groups arranged irregularly along the length of the drainageway, and because of this characteristic are called discontinuous gullies.

Bryan (1928) has presented evidence that when the Rio Puerco was first reached by the reconnaissance teams of the Army of the West in 1846, the valley floor was already being dissected by discontinuous gullies. Some of them were evidently large, for in August 1846, Lt. Simpson had to cut down the gully wall of the Rio Puerco in order to get his brass cannon across. Yet, at the same time, there were long reaches in the Puerco valley so smooth that the native grass was cut for hay, and water was diverted from the channel by felling a cottonwood tree to form a dam.

Discontinuous gullies have long presented a problem to the erosion-control engineer. In the first place, the mechanics of gully formation is very poorly understood. Although it is generally presumed that discontinuous gullies, at least in places, can coalesce and form a continuous channel, it is not known whether the nature