Erosion and Deposition in the Loess-Mantled Great Plains, Medicine Creek Drainage Basin, Nebraska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 352-H

Prepared as part of a program of the Department of the Interior for development of the Missouri River basin and part of the soil and moisture program

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By JAMES C. BRICE

EROSION AND SEDIMENTATION IN A SEMIARID ENVIRONMENT

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EROSION AND DEPOSITION IN THE LOESS-MANTLED GREAT PLAINS MEDICINE CREEK DRAINAGE BASIN, NEBRASKA

By JAMES C. BRICE

ABSTRACT

The Medicine Creek basin is representative of the loess-mantled Great Plains in climate, surface materials, and relief forms, but its relief, degree of dissection, and rate of erosion are higher than average. In operation, if not in rate, processes of erosion and deposition in the basin are considered to be representative of loess-mantled regions in a semiarid or subhumid climate.

About 12,000 years ago, the valley fill of the Peorian Loess was incised and the drainage system was ramified to approximately its present extent. During the subsequent episode of deposition (about 1,000–5,000 yr ago), the deposits of the Stockville terrace accumulated and the valley sides were graded. The formation of the Stockville terrace was followed by a minor episode of deposition, another of valley incision, and finally the accumulation of the late Recent alluvium, which has been intermittently incised during the past 500 years.

The property of the drainage system that is most useful in accounting for the areal distribution of gullies is called adjusted channel frequency, in the derivation of which the drainage basin area is adjusted by subtracting the area of upland. The slope of the exponential curves, relating mean channel length to channel order, changes at the lower channel orders because of drainage transformations, in late Recent time, that affected only channels of low order.

Gullies in the basin are widened, lengthened, and deepened mainly by scarp erosion. They are classified on the basis of topographic location as valley-bottom, valley-side, and valley-head gullies. Trenching of a valley reach to bedrock takes place not only by coalescence of discontinuous gullies but also by the successive upstream migration of several channel scarps. Many large valley-bottom gullies have evidently originated on locally steepened valley reaches, but the ratio of local slope to drainage area that is critical for the initiation of a gulley is not sharply defined. Valley-bottom gullies advance mainly because of plunge-pool action, but this mechanism is less important in the advance of valley-side and valley-head gullies. The areal frequency distribution of valley-head and valley-side gullies is correlated with two geomorphic properties: percentage of area in upland and adjusted frequency of first-order channels.

Hydraulic geometry of the channels is expressed by the slope of curves relating width, depth, and velocity to discharges equaled or exceeded 1, 2, and 25 percent of the time. At the gaging stations on Dry, Mitchell, and Brushy Creeks, the flow is categorized as ephemeral; at the others, as perennial. In a downstream direction, an increase in discharge of ephemeral streams is accommodated by relatively large changes in depth and velocity, but the increase in discharge of perennial streams is accommodated by a relatively large change in width. Curves relating suspended-sediment load to water discharge for the perennial streams are characterized by a break in slope at water discharges above normal but below the bankfull stage.

In general, the concentration of measured suspended sediment is higher in wet years than in dry, and the ephemeral streams have higher concentrations than the perennial streams. Differences in runoff and sediment discharge among five subbasins are attributed mainly to differences in relief ratio, adjusted frequency of first-order channels, and percentage of area in upland.

Active valley-head and valley-side gullies, and all but a few of the active valley-bottom gullies, are attributed to land use since settlement rather than to climatic change. Restoration of native vegetation to the heads of valleys, together with conservation measures on the upland, would be effective in the control and prevention of valley-head gullies, which are the most numerous in the basin.

INTRODUCTION

The purpose of this report is to give an integrated account of the geologic and hydrologic factors that are pertinent to erosion and deposition in a part of the loess-mantled Great Plains and to evaluate the major factors involved in gully erosion, channel deposition, and the discharge of water and sediment through channels. Climatic change as a cause of modern erosion is evaluated in the light of ecologic, stratigraphic, and archeologic evidence from terrace deposits of late Pleistocene and Recent age. Processes of scarp erosion are analyzed, gullies are classified, and the areal distribution of gullies is correlated with morphologic properties of the basin. Generalizations are made as to the hydraulic geometry of the channels and the relations between discharge and suspended-sediment load. Differences in runoff and sediment discharge among five subbasins are attributed mainly to differences in specific morphologic properties among the subbasins.

The Medicine Creek basin was selected by several cooperating agencies (U.S. Bur. of Reclamation, U.S. Agr. Research Service, and the Univ. of Nebraska) as a suitable area in which to investigate erosion and runoff. Collection of data, which was begun in 1951 and ended in 1958, was directed toward an evaluation of soil and water conservation practices and also toward an understanding of the processes and causes of rapid erosion in this region, which is the major subject of the present report.

The regional setting of the Medicine Creek basin, which is in the loess-mantled part of the Great Plains, is shown in figure 175. The processes of erosion and deposition in the basin are characteristic of loess-mantled regions in a semiarid or subhumid climate, and they apply specifically to an area of about 115,000 square miles that is within the Missouri River basin and is mantled with 8 feet or more of loess. Most of this area is within the Great Plains, although part is in the Interior Plains. The Medicine Creek basin is dissected to a much greater degree than many parts of the Great Plains, and the local relief is greater than average. Nevertheless, nearly all the relief forms typical of the Great Plains occur within the basin, including areas of nearly flat upland and sharply dissected areas of narrow divides and flat-bottomed valleys. Gullies of all types and sizes occur, and the frequency of gullies ranges from high in some places to low in others.

Medicine Creek, which is a tributary to the Republican River, has a drainage area of about 690 square miles that lies between the Platte and the Republican Rivers. Major subbasins and general geographical features are shown in figure 176. Remnants of the upland surface reach a maximum altitude of about 3,150 feet in the northern part of the basin and descend gradually to an altitude of about 2,400 feet at the bluffs of the Republican River. The maximum local relief, about 200 feet, is in the northern part of the basin. In general, the upland is more sharply dissected in the northern part, and the divides tend to be flat but narrow; in the central and southern parts, the divides are broader and slope gently toward the valleys. The general aspect of the relief in the southern part of the basin is shown in figure 177, which is an oblique aerial view southwest from a point above Medicine

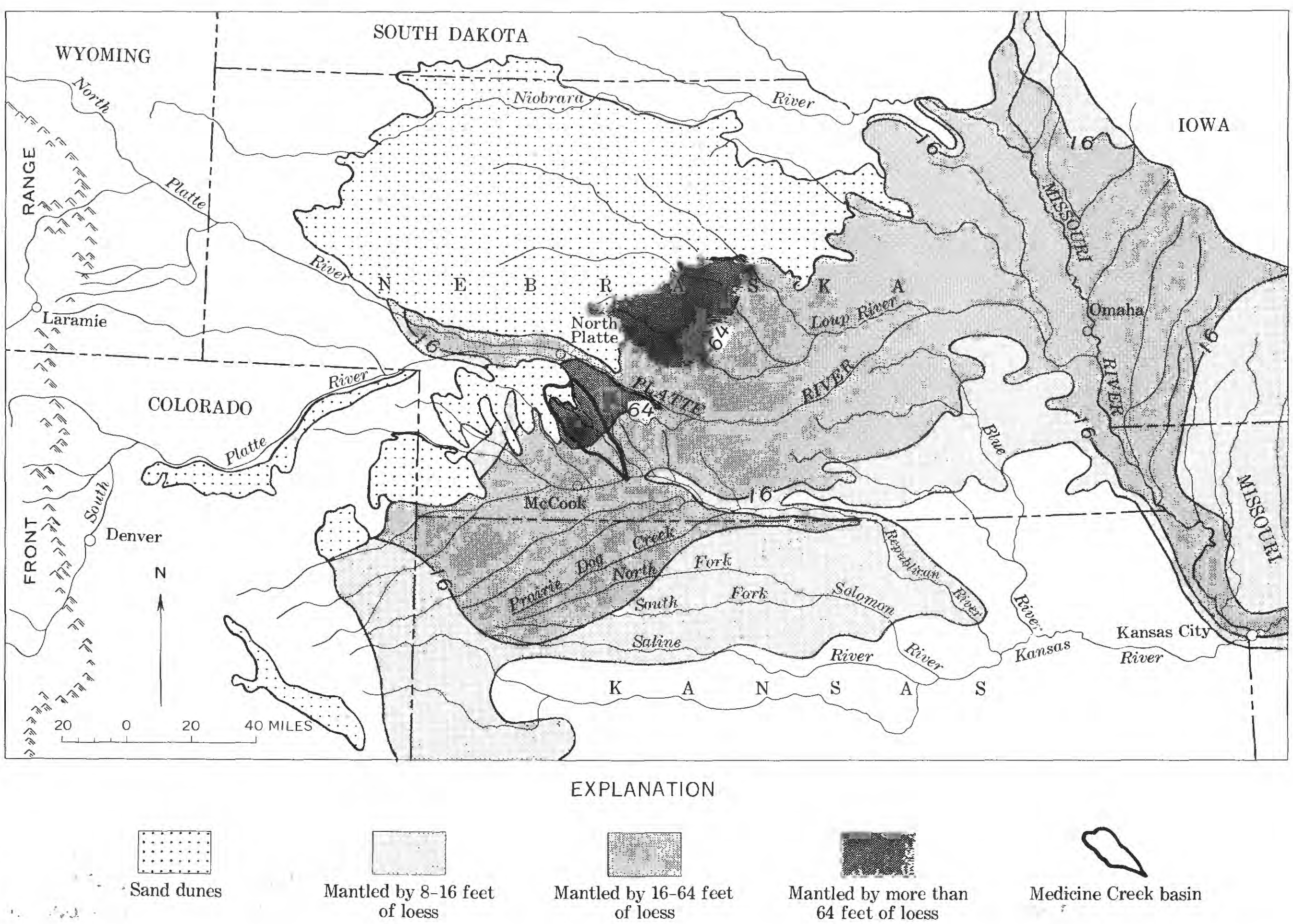


FIGURE 175.—Map showing the regional physiographic setting of Medicine Creek basin. Distribution and thickness of loess generalized from Thorpe and others (1952).

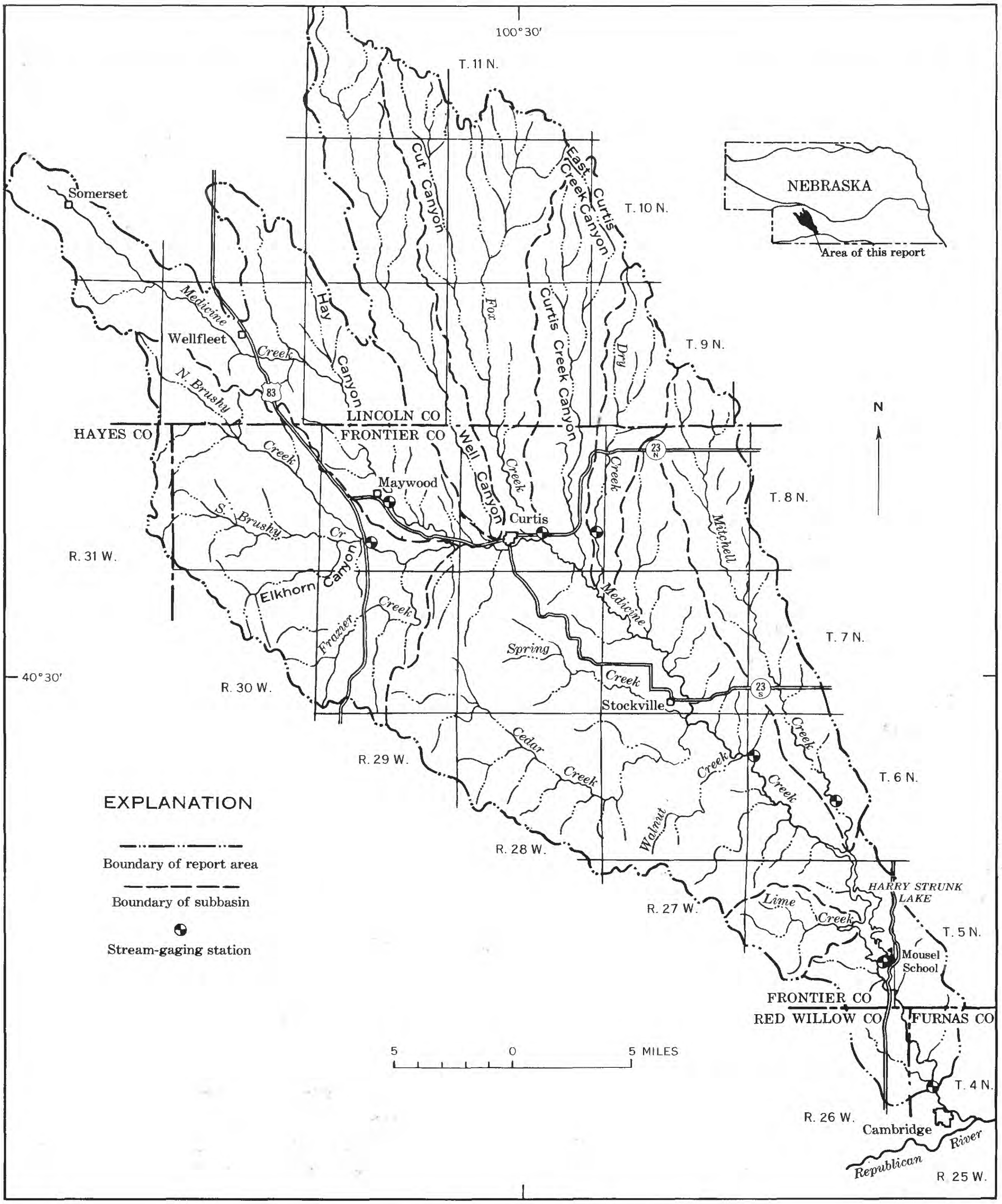


FIGURE 176.—Location map of Medicine Creek basin.

FIGURE 177.—Oblique aerial photograph of typical relief in southern part of Medicine Creek basin. Medicine Creek at lower left. Photograph by River Basin Surveys, Smithsonian Institution, 1948.

Creek and about 7 miles north of the town of Cambridge.

Fieldwork for geomorphic purposes was begun in the summer of 1953 and continued during the summers of 1954–56. Special hand-level and stadia-rod equipment was devised to permit the measurement of slopes without an assistant. Field studies, as well as office work, were facilitated by excellent topographic map and aerial photographic coverage of the entire basin. On the 1:24,000-scale topographic maps, prepared by photogrammetric methods and published by the Geological Survey in 1957–58, even minor topographic features are accurately represented. The Munsell color system was used for field description of loess and soil.

Data contributed by the cooperating agencies have been used in the preparation of this report. The detailed surveys necessary to measure rates of channel erosion on Dry Creek were made by the Bureau of Reclamation, who also contributed data on precipitation. Land use was tabulated by the Agricultural Research Service and the Soil Conservation Service. Runoff and suspended sediment were measured by the Geological Survey.

Many persons contributed to this report, which was prepared under the successive supervision of P. C. Benedict, regional engineer, and D. M. Culbertson, district engineer, U.S. Geological Survey. The section on native vegetation was read by E. J. Dyksterhuis, range conservationist for the Soil Conservation Service. Fossil snails were identified and information on snail ecology was given by W. J. Wayne of the Indiana Geological Survey. One carbon-14 age determination was made by Meyer Rubin, geochemist of the U.S. Geological Survey, and another by J. L. Kulp of Columbia University.

CLIMATE

By CLOYD H. SCOTT

The climate of the Medicine Creek basin is typical of the interior of continents of the middle latitudes with rather light rainfall, hot summers, cold winters, large variations in precipitation and temperature from year to year, and frequent changes in weather from day to day.

The mean annual temperature at Curtis, near the center of the basin, is about 52°F. Maximum and minimum temperatures above 100° and below 0°F occur occasionally. The coldest month is January when the average temperature is about 27°F, and the warmest month is July when the average temperature is about 78°. The monthly mean temperature at the U.S. Weather Bureau Station at Curtis for the years 1931–55 is shown in figure 178.

Much of the precipitation occurs during April through September, generally as thunderstorms. On the average, more than half the total annual precipitation occurs from May through August. Precipitation varies widely from the average (fig. 178); 7 months had no precipitation at least once during the period 1931–55, and some months had no precipitation several times during that period. Maximum amounts exceeded the averages by about two to seven times.

The annual precipitation also varies widely from year to year (fig. 179). The minimum annual amount of slightly less than 11 inches was recorded in 1934, and the maximum of about 38.2 inches was recorded in 1915. The 66-year average (1895–60) was about 21.5 inches, but the 25-year average (1931–55) was only 19.1 inches.

The 5-year moving averages (figs. 179 and 180) show the general trends of precipitation at Curtis and McCook from 1895 to 1960. The annual totals are highly variable from one year to another, but the 5-year moving averages show a somewhat cyclic trend. Even though the high- and low-precipitation years tend to be grouped somewhat, about half of the years have above-average precipitation amounts. However, during 1951–58 at Curtis, 5 years had precipitation below average; 4 of the years had more than 6 inches below average.

The 5-year moving average for Curtis indicates a long-term trend toward decreasing annual precipitation. The consistency of the precipitation data at Curtis was checked by plotting a double-mass curve of data at Curtis and at McCook. A pattern composed of data for McCook, Cambridge, and North Platte was first used; but the data for North Platte and Cambridge were inconsistent with the

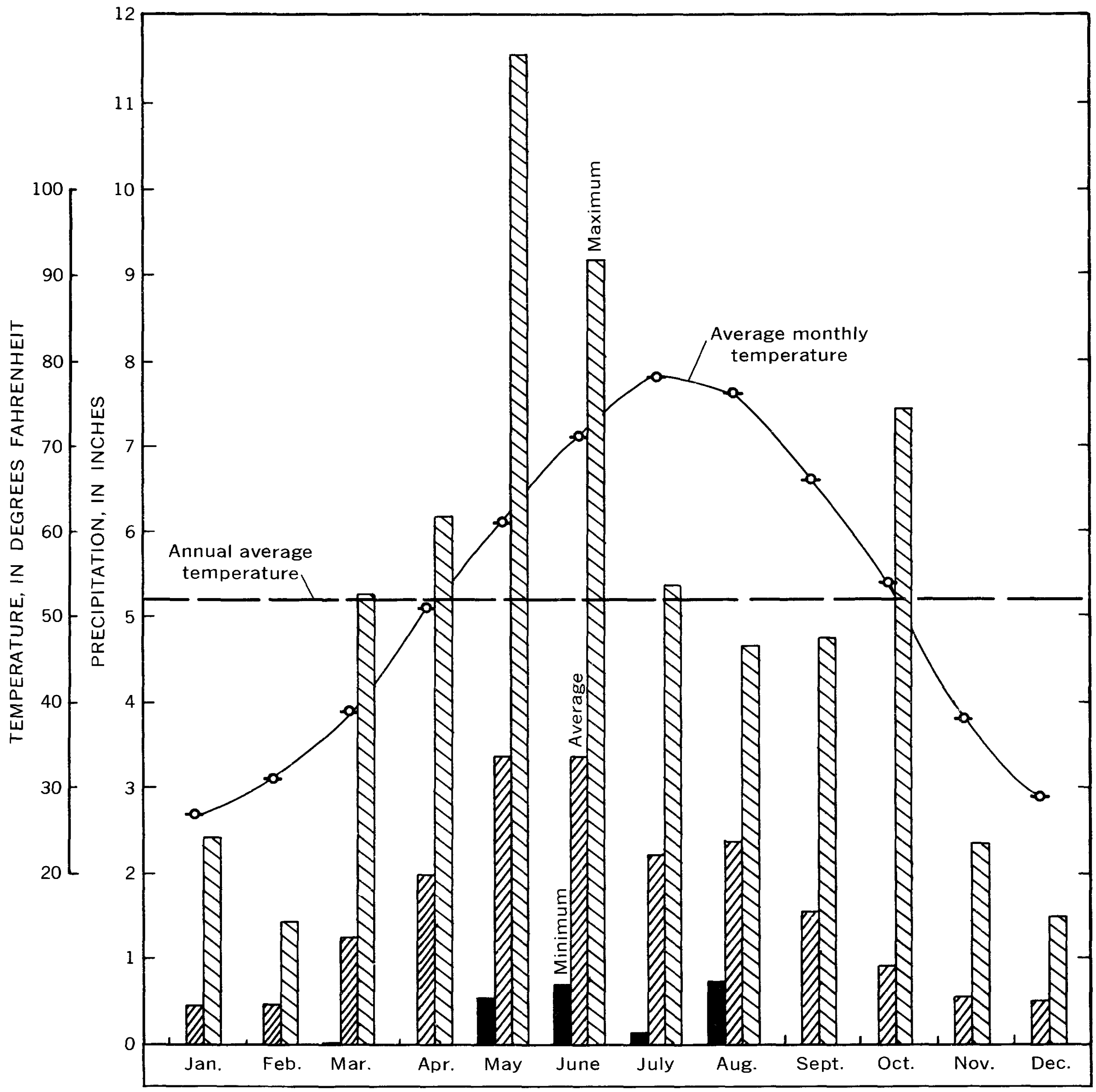


FIGURE 178.—Average monthly temperature and maximum, average, and minimum monthly precipitation at Curtis, Nebr., 1931–55

pattern, whereas the data for McCook seemed to be consistent. The double-mass curve showed a trend toward more precipitation at Curtis beginning about 1908 but returned to about the original slope in 1914. There is no record that the gage was moved in 1908, although the location was changed in 1914 (U.S. Weather Bureau, 1955a).

The pattern of the 5-year moving average for Curtis (fig. 179) is generally similar to the pattern for McCook (fig. 180) except that the precipitation for the period 1908–18 was higher at Curtis than at McCook and for the period 1940–52 was lower at Curtis than at McCook. The apparent secular decrease in annual precipitation at Curtis is probably a result of uneven areal distribution and is not considered to be representative of the region. As shown by the double-mass curve, the data at Curtis may have been somewhat biased for the years 1908–14.

Precipitation at Curtis averaged about 18.77 inches for the years 1951–58, or somewhat below the 66-year average of about 21.5 inches. Extremes of annual precipitation for this period ranged from 31.61 inches in 1951 to 12.36 inches in 1952. The occurrence of a high and a low in consecutive years is not unusual owing to the large variations in rain-

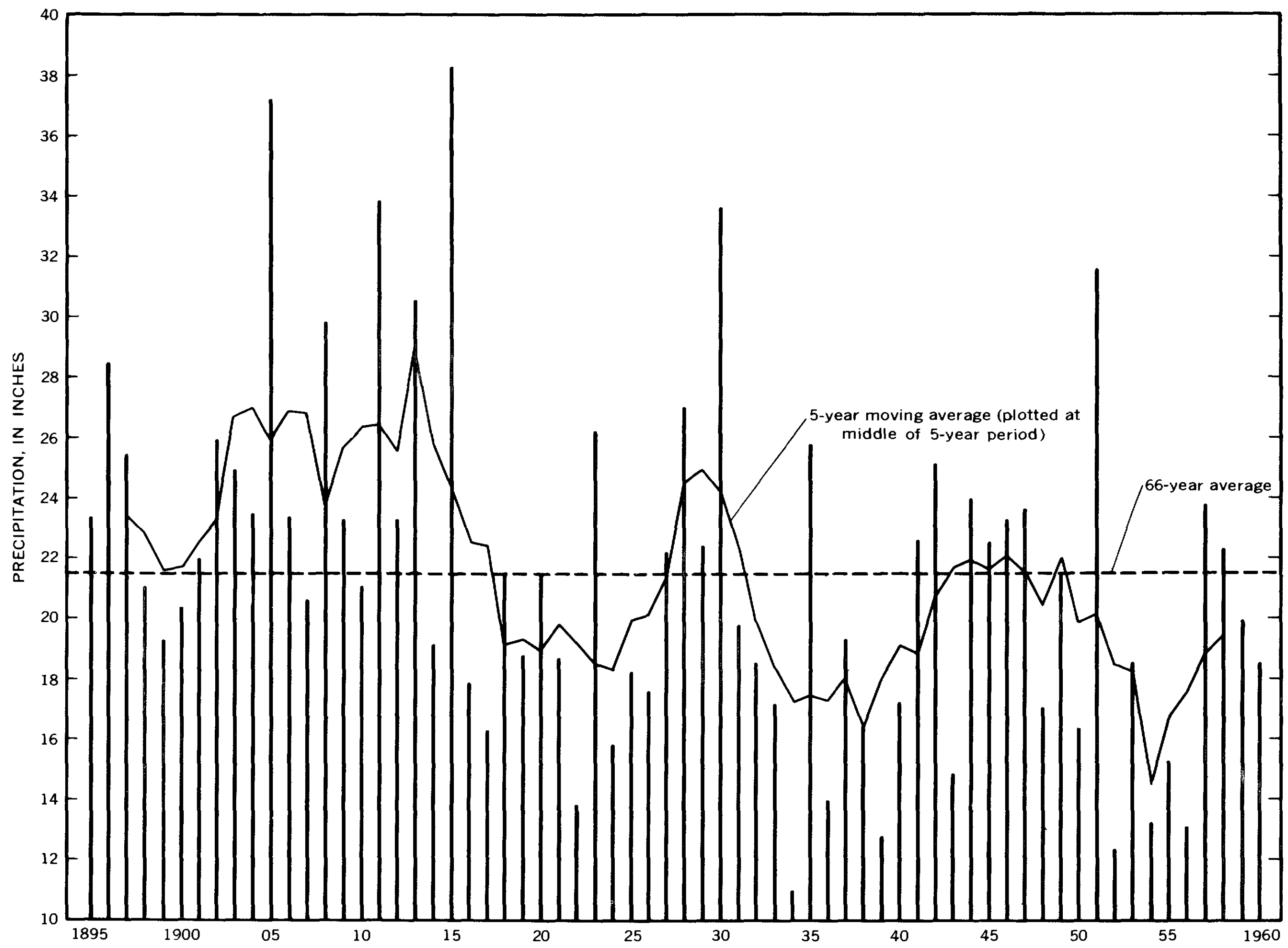


FIGURE 179.—Annual precipitation at Curtis, Nebr., 1895–1960.

fall over much of the central part of the continent. At Curtis, only 2 of 6 years since 1895 that had in excess of 30 inches of precipitation, were followed by years that had more than the long-term average amount. An extreme occurred in 1915–16 when the difference between precipitation amounts exceeded 20 inches.

Although averages and extremes give some indication of precipitation, a more meaningful description of rainfall can be obtained through the use of rainfall intensity-duration-frequency curves. Such curves (fig. 181) were developed for Curtis for return periods of 2 and 5 years based on the annual series of 1-, 6-, and 24-hour amounts. The California method of plotting positions, $T_r = n/m$, was used; a log normal distribution was assumed. T_r is the return period in years of item having order number m in a decreasing series, and n is the period of record in years.

An empirical factor of 1.13 (U.S. Weather Bureau, 1957) was used to convert the clock-hour amounts of rainfall to maximum 60-minute values. An inspection of the 6- and 24-hour amounts indicated that conversion for these periods was unnecessary.

The plot of rainfall intensity versus return period, which was used to define the curves of figure 181, showed little scatter from the average curve, which indicated that no extreme storms had occurred during the period.

The U.S. Weather Bureau (1955b) gives rainfall intensity-duration-frequency curves for about 200 stations, including North Platte, for the years 1906–51. Comparison of the curves for Curtis with those for North Platte shows that differences are minor between the two stations for both the 2- and 5-year return periods, even though only 8 years of record was used to define the curves for Curtis. The similarity between the short- and long-term curves and the fact that no extreme amounts of precipitation fell during the short period indicate that the rainfall regimen was well represented at Curtis during the years 1951–58, even though the

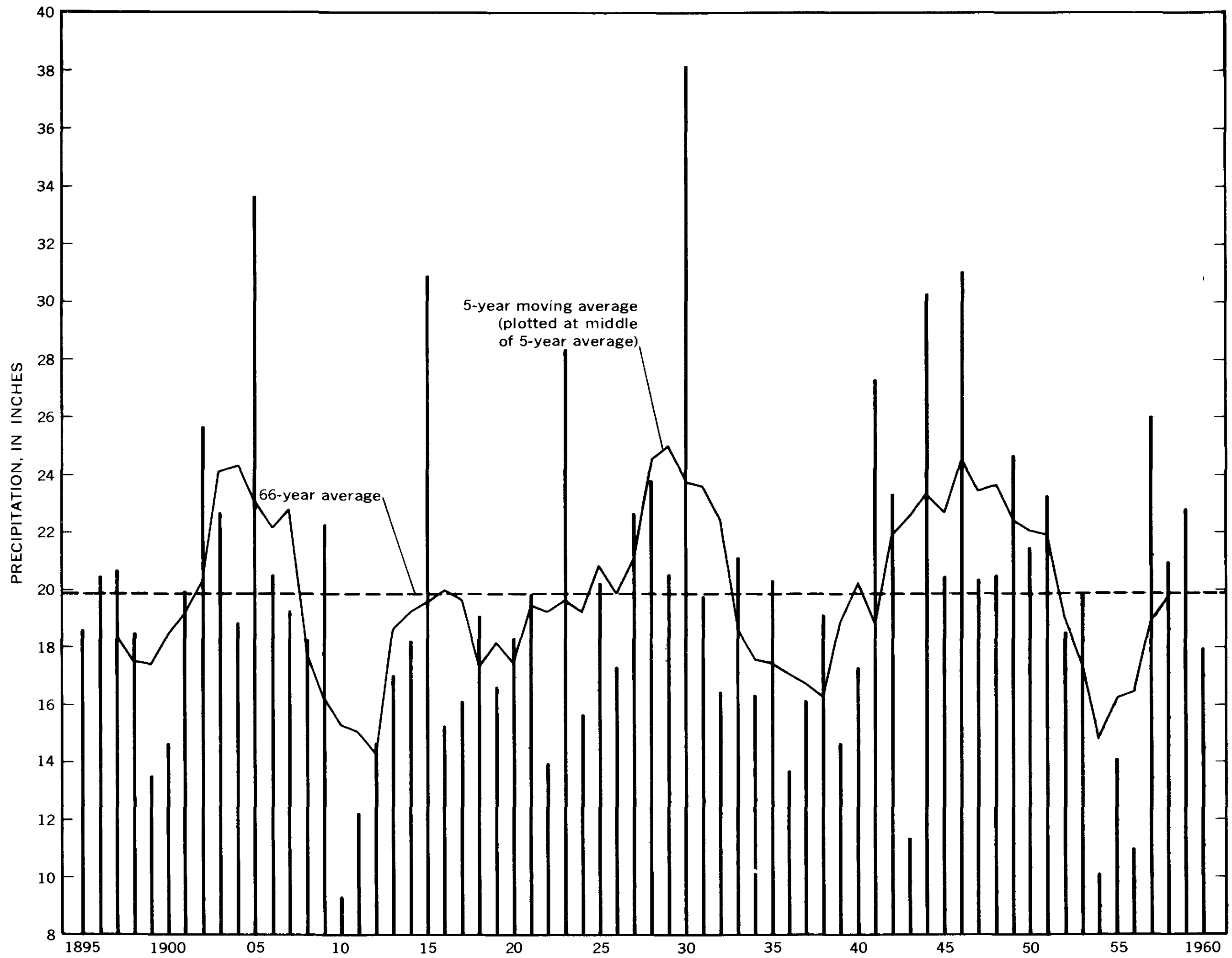


FIGURE 180.—Annual precipitation at McCook, Nebr., 1895–1960.

average precipitation for the period was somewhat lower than the long-term average.

Evaporation is also variable from year to year, although the variations probably are not as extreme as those of rainfall. The only evaporation data available are for a few years at Medicine Creek Dam, and these data were used to check evaporation maps in a technical paper by the U.S. Weather Bureau (1959a). According to the maps the average annual evaporation from a class A pan in Medicine Creek basin is about 75 inches, or about 3½ times the average annual precipitation; and lake evaporation is about 50 inches, or nearly 2½ times the average annual precipitation. Evaporation increases from north to south in the basin, but the average difference is only about 3 to 4 inches per year.

Data on wind speed and direction nearest Medicine Creek basin are those at North Platte. Because North Platte is in the valley of the Platte River, the wind speeds and directions may not be entirely representative of conditions in the Medicine Creek basin. The average wind speeds at North Platte range from about 12 to 13 miles per hour March through July and from a little less than 10 to slightly more than 11 miles per hour for the remainder of the year. December and January have the lowest average speeds with 9.8 and 9.7 miles per hour, respectively, and April has the highest average with 13.1 miles per hour. The prevailing direction is from the southeast April through August; south-southeast in September and January; northwest in February, October, and November; north in March; and west-northwest in December. The annual prevailing direction at North Platte is considered to be from the southeast (U.S. Weather Bureau, 1959b).

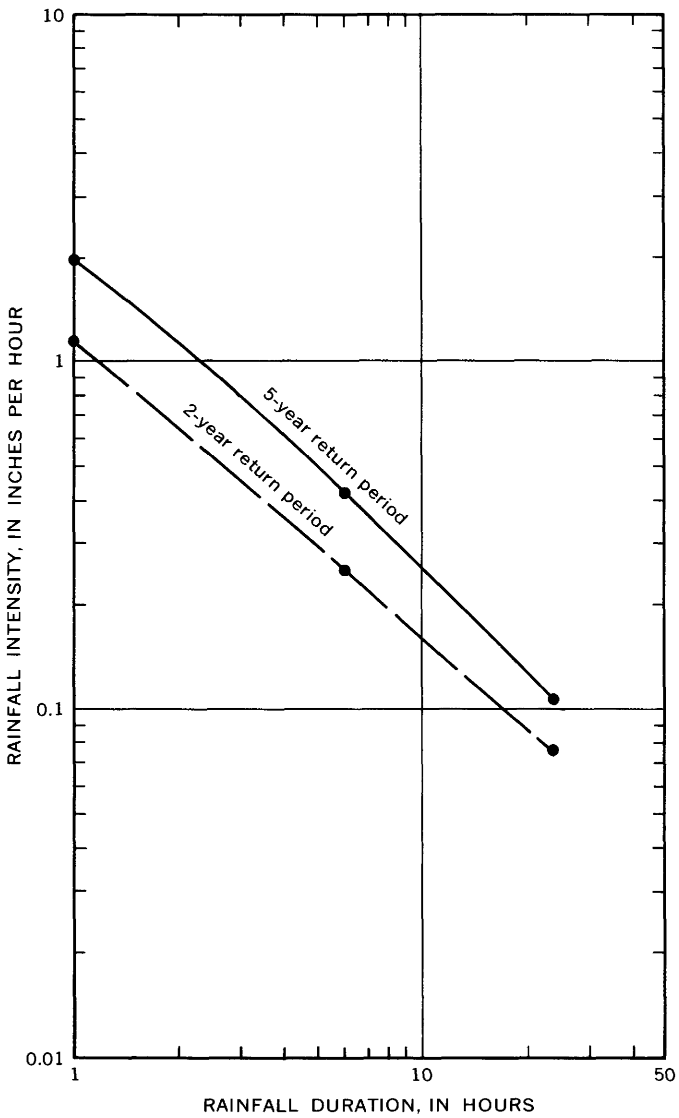


FIGURE 181.—Rainfall intensity-duration-frequency curves for Curtis, Nebr., 1951–58.

VEGETATION AND PALEOCLIMATE
CLIMAX PLANT COMMUNITIES

The Medicine Creek basin lies in a transitional zone between the tall-grass region to the east (prairie grassland) and the short-grass region to the west (plains grassland). Trees are restricted to valley bottoms, except where they have been artificially planted.

Some information regarding the history of plant communities appears in the notes of surveyors for the General Land Office who made brief reference to the grasses they saw while laying out the land-division grid in 1869–72.[1] Their comments also indicate the condition of the vegetal cover before white settlement. The following excerpts are from the notes of Deputy Surveyor D. V. Stephenson, made in the Medicine Creek basin during the summer of 1872: "land broken by steep ravines running in almost every direction, in bottoms of some of which there is some blue grass. The upland is about three-fourths covered with short buffalo grass. * * * grass almost entirely short buffalo, growing in bunches." Deputy Surveyor J. L. Slocum made the following notes, also in the summer of 1872: "Soil is dry and sandy, produces only short buffalo grass in scattering bunches—unfit for cultivation or grazing. * * * Considerable good grass in bottom of ravines, upland is sparsely covered with short buffalo grass." Deputy Surveyor Charles Wimpf wrote as follows, in August of 1869: "Bottoms of ravines filled with a thick very good grass which gives an excellent hay. The hills are covered with a short sweet grass." Although the term "buffalograss" may have been used loosely by the early surveyors, their comments do indicate that during 1869–72 the uplands and valley-side slopes were covered with a rather sparse growth of short grass, and the valley bottoms with a thicker growth of tall grass.

E. J. Dyksterhuis(writen commun. 1958), range conservationist for the Soil Conservation Service, considers that the climax community on the uplands in regions of climate and soils like those of the Medicine Creek basin contains a dominance of midgrasses with an understory of short grasses. He also says that the dominant midgrasses include western wheatgrass, needlegrasses, and little bluestem; little bluestem, side-oats grama, and blue grama dominate on the valley sides, and big bluestem and switchgrass on the valley bottoms.

CHARACTERISTICS OF NATIVE GRASSES

Characteristics of native grasses are summarized in this section from Weaver and Albertson (1943, 1944), U.S. Department of Agriculture (1948), and Phillips Petroleum Co. (1956).

Big bluestem is a coarse perennial native bunchgrass that reaches a height of 6 feet under favorable conditions. The root system is extensive; it may penetrate to a depth of about 8 feet and form a dense mat to a depth of 1 foot. Under favorable conditions it, together with other species of its community, will form a continuous sod; under less favorable conditions it forms separate, scattered bunches. Both rainfall and dust are largely intercepted by the foliage before reaching the ground. According to Clark (1937), a prairie covered by big bluestem may intercept as much as 53 tons of water per acre during a rainfall of 1 inch per hour, whereas a prairie covered by buffalograss will inter-

[1] Field notes of survey are on file at the Dept. of Educational Lands and Funds, State Capitol Bldg., Lincoln, Nebr.

cept about 28 tons per acre. Such intercepted rainfall commonly evaporates from the leaves of the plant without reaching the ground.

Buffalograss is native, sod forming, fine leaved, and perennial and typically grows to a height of 4 to 6 inches. The roots of well-developed buffalograss extend to a depth of 4 to 5 feet and form a very thick mat to a depth of 1 foot. Blue grama is a low native perennial grass whose flowering stems reach a height of about 18 inches. It is the most drought resistant of all the native prairie grasses, and it spreads, even during drought, mainly by means of seedlings. The root system is similar to that of buffalograss.

All these native grasses may form a dense thick, continuous sod, although the bluestems and blue grama are more likely to form separate bunches than buffalograss. The taller grasses intercept a greater amount of rainfall, which is usually lost to the soil; but a corresponding decrease in erosion by raindrop impact is effected. Windblown dust is retained more effectively by the taller grasses.

EFFECTS OF DROUGHT

Some insight into the influence of ancient arid climatic regimes on native grasses and on the ability of these grasses to prevent erosion may be gained by study of the effects of the drought of 1933–40 in Kansas and Nebraska. Such study was made by Weaver and Albertson (1943, 1944). These authors took for a base station Hays, Kans., which has an average annual precipitation of about 22.9 inches and which is located about 120 miles south of the Medicine Creek basin. Total precipitation at Hays for the 6 years preceding 1933 was below normal. Precipitation during each of the 4 driest years was about 16 inches.

According to Weaver and Alberston, decrease in grass cover as a result of drought varied with the intensity of grazing and of burial by dust and also with the type of grass cover, as grasses with shorter roots underwent greater destruction. The basal cover of short grasses in Kansas ranged between 80 and 95 percent in 1932, and this cover was commonly reduced to 20 percent or less during the worst years of the drought. In some localities, particularly those that had been overgrazed or covered by blown dust, the native plant population was reduced almost to zero. Where the effects of drought were moderate, the sod was interrupted by patches of bare ground, a square foot or less in area, that formed an irregular but continuous network. Where the effects of drought were more severe, the patches of bare ground were larger, up to several square yards in area; and in the most severely affected localities, the grass was so decimated that nearly all the ground was bare. These bare patches, described by Weaver and Albertson and noted by the writer (Brice, 1958) throughout the Medicine Creek basin in 1953–56, are important in slope erosion because erosion scarps commonly form at their edges.

The influence of ancient droughts and ancient episodes of aridity on the grasses of the Medicine Creek basin can be inferred from Weaver and Albertson's study. Short-term droughts would have reduced the cover of climax grasses, but erosion would not have been severe because these grasses are replaced by weeds during drought and recover rapidly after drought. Sheet-wash and raindrop impact would have removed soil from the irregular patches of bare ground between sod-covered areas, and low sod scarps would have formed on the slopes. During ancient episodes of aridity that lasted for hundreds or thousands of years, a climax community of grasses adapted to prevailing climate and rainfall distribution would have become established. Such a community would probably have consisted of an association of short grasses similar to the association now in eastern Colorado, where the average annual precipitation is about 15 inches. If this short-grass association were significantly different from that established before the arid episode, stream profiles and slopes would have been regarded by gullying and other erosional processes.

EFFECTS OF LAND USE

The pronounced effect of land use is strikingly shown by the contrast in vegetation on either side of a fence that follows the north-south section line between sections 15 and 16, T. 9 N., R. 27 W. (See fig. 182, *upper*.) The heads of two tributaries to East Fork of Dry Creek are isolated by this fence, and the aspect of the vegetation in these tributary heads is unlike that observed at any other place in the Medicine Creek basin. Although no information on the land-use history of the tributary heads was obtained, the contrast in vegetal cover at the fence is evident on both the 1937 and the 1952 aerial photographs. Therefore, the fence had divided areas of contrasting land use for at least 15 years, and the aspect of the vegetation in the tributary heads in 1953 suggested that it may have been disturbed in no important way since white settlement. Besides the much greater thickness of the sod and the dominance of tall grasses in the tributary heads, the thickness of brush such as wild plum, sumac, buckbrush, and wild rose is exceptional (fig. 182, *middle*). A few ash trees were observed on the

FIGURE 182.—Photographs showing effect of land use on native vegetation, East Fort Dry Creek, August 1953. *Upper*, Areas separated by a fence and contrasting sharply in vegetal cover. Denser vegetation is at right of fence. Although sparse, the vegetation at left of fence was better than average for the Medicine Creek basin in 1953. *Middle*, Dense cover of grass and brush in ungrazed valley head. View looking west. Vegetation more dense on south side of valley. *Lower*, Sparse cover of short grass, yucca, and weeds in heavily grazed valley head, 1.5 miles southeast of valley head shown in *middle*. Valley is oriented in north-south direction.

valley bottoms. The termination of the small valley-bottom gullies (fig. 182, *upper*) before reaching the fence may be fortuitous, but no gullies were observed in the tributary heads. By contrast, gullies are in most tributary heads in this part of Dry Creek (fig. 182, *lower*). Step scarps occur on the steep slopes of the heavily vegetated area, but they are much subdued and seem to be inactive. The upland drained by the tributary heads is planted in row crops or small grain, as elsewhere in the basin.

NATIVE TREES AND DENDROCHRONOLOGY

During the period 1869–72 General Land Office surveyors reported that trees in the Medicine Creek basin were confined to stream valleys, in which they identified cottonwood, ash, boxelder, elm, hackberry, and cedar. These same kinds of trees now grow from place to place in the valleys, but the wider valley flats have been mostly cleared of trees.

A tree-ring indication of precipitation during the past 400 years in western Nebraska, including the vicinity of North Platte, was reported by Weakly (1940, 1943). According to his interpretation, the climate has been characterized by frequent dry years and by less frequent droughts that lasted 5 years or more. The 13 droughts (period of five or more successive dry years) had an average duration of 13 years, and the average interval between droughts was about 20 years. The longest drought lasted from 1539 to 1564 (26 yr), but other lengthy droughts were from 1587 to 1605 (19 yr) and from 1688 to 1707 (20 yr).

PRE-PLEISTOCENE ROCKS

UNEXPOSED ROCKS

Neither the lithology nor the structure of unexposed rocks in the Medicine Creek basin has any apparent direct influence on the present relief. The Paleozoic and Mesozoic formations that overlie the Precambrian basement dip gently to the west and are overlain unconformably by Tertiary formations that dip gently to the east.

EXPOSED ROCKS

NIOBRARA FORMATION

The Niobrara Formation of Late Cretaceous age crops out along the banks of Harry Strunk Lake and from place to place along Medicine Creek downstream from the lake, but it is not exposed elsewhere in the basin. Where exposed, the Niobrara consists mainly of orange or white chalk interbedded with thin layers of altered volcanic ash.

OGALLALA FORMATION

Outcrops of the Ogallala Formation of Tertiary (Pliocene) age are mainly restricted to valley sides and channels of larger streams in the Medicine Creek basin, and the best exposures are along Medicine Creek and Cedar Creek in the vicinity of Stockville. No outcrops were observed in the northern parts of the basin where the loess cover is thickest. Available well logs indicate that the Ogallala underlies most of the basin and that its thickness increases from about 200 feet in the southern part to about 400 feet in the northern part. (See figs. 183 and 184.)

Exposed sections of Ogallala at seven localities were measured and described in detail. Thicknesses of described sections ranged from 6 feet at one locality on Cedar Creek to 73 feet at another locality downstream, and the total thickness of described sections was 290 feet. In general, the Ogallala consists of clay, silt, volcanic ash, sand, and gravel, poorly sorted into different beds that are cemented with (and partly replaced by) different amounts of carbonate. Five rock types were distinguished, and the total thickness of each type as represented in the seven measured sections is given in table 1.

TABLE 1.—*Thickness and percentage of each rock type in seven exposed sections of the Ogallala Formation*

	Thickness (ft)	Percent of total thickness
Gravel and sand	22	7.5
Sand, pebbly, and silt; loosely cemented, locally concretionary	156	54.0
Limestone, sandy, rather uniformly cemented	62	21.4
Ash, volcanic, and silt	26	9.0
Clay; alternating beds of fine-grained limestone	24	8.1

With regard to the origin of the Ogallala, Frye and others (1956) have presented convincing evidence that it was deposited by streams flowing eastward from the Rocky Mountain region. In the earlier part of their history these streams occupied broad, relatively shallow valleys eroded into Cretaceous bedrock. However, as alluviation proceeded, the deposits progressively overlapped the gentle valley sides, most divides were buried, and eventually a coalescent alluvial plain was formed.

PLEISTOCENE AND RECENT DEPOSITS

TERRACES

Three terraces were identified along Medicine Creek and its tributaries. The highest of these is named the Wellfleet terrace after the village of Wellfleet, Nebr., which is on Medicine Creek. Although Wellfleet is not built on the terrace surface, conspicuous flat-topped remnants of the terrace stand about 125 feet above the valley flat at intervals of a mile or more between Wellfleet and Maywood, Nebr. For example, the remnant in the SE¼ sec. 8, T. 8 N., R. 29 W., about 1 mile north of Maywood, is well defined both in the field and on the Curtis NW quadrangle sheet. There are similar flat-topped remnants along Well Canyon and other major tributaries, but the originally flat surface of the terrace has been dissected in most places.

The best preserved and most continuous terrace in the Medicine Creek basin is named the Stockville terrace after the town of Stockville, Nebr., which is built on a remnant of the terrace, along the west side of Medicine Creek. The Stockville terrace is represented along Medicine Creek by broad remnants that stand above the valley flat at a height of about 50 feet in the lower course of the creek and about 30 feet in its upper course. The Stockville terrace can be traced almost continuously along most tributary channels in the basin. Moreover, the sides and heads of valleys are broadly graded to the level of the Stockville terrace.

The lowest terrace of general importance in the Medicine Creek basin is named the Mousel terrace after the Mousel School, which is in sec. 25, T. 5 N., R. 26 W., on the east side of the valley of Medicine Creek. (See fig. 176.) The Mousel terrace is represented along Medicine Creek by widely scattered remnants that stand 15 to 20 feet above the valley flat. Similar remnants are along most major tributaries, such as Well Canyon, Cedar Creek, and Fox Creek; but the Mousel terrace cannot be traced along most minor tributaries because its surface has been buried by late Recent alluvium. Even where the terrace is well defined, there has been little grading of the valley sides to the level of the terrace; the slope that forms the riser of the Stockville terrace rises abruptly above the tread of the Mousel terrace.

A sequence of well-defined terraces appears along most streams in Nebraska, but general agreement has not been reached as to terrace nomenclature. Condra and others (1950) describe a sequence of six terraces in central Nebraska; and Schultz and others (1951) describe a sequence of five terraces that applies to Nebraska generally. Neither sequence would be expected to apply to all Nebraska streams because of complications, such as overlap of an older terrace deposit by a younger terrace deposit, that may be peculiar to a single stream.

Schultz and others (1948, 1951) have specifically applied their terrace sequence to alluvial terraces

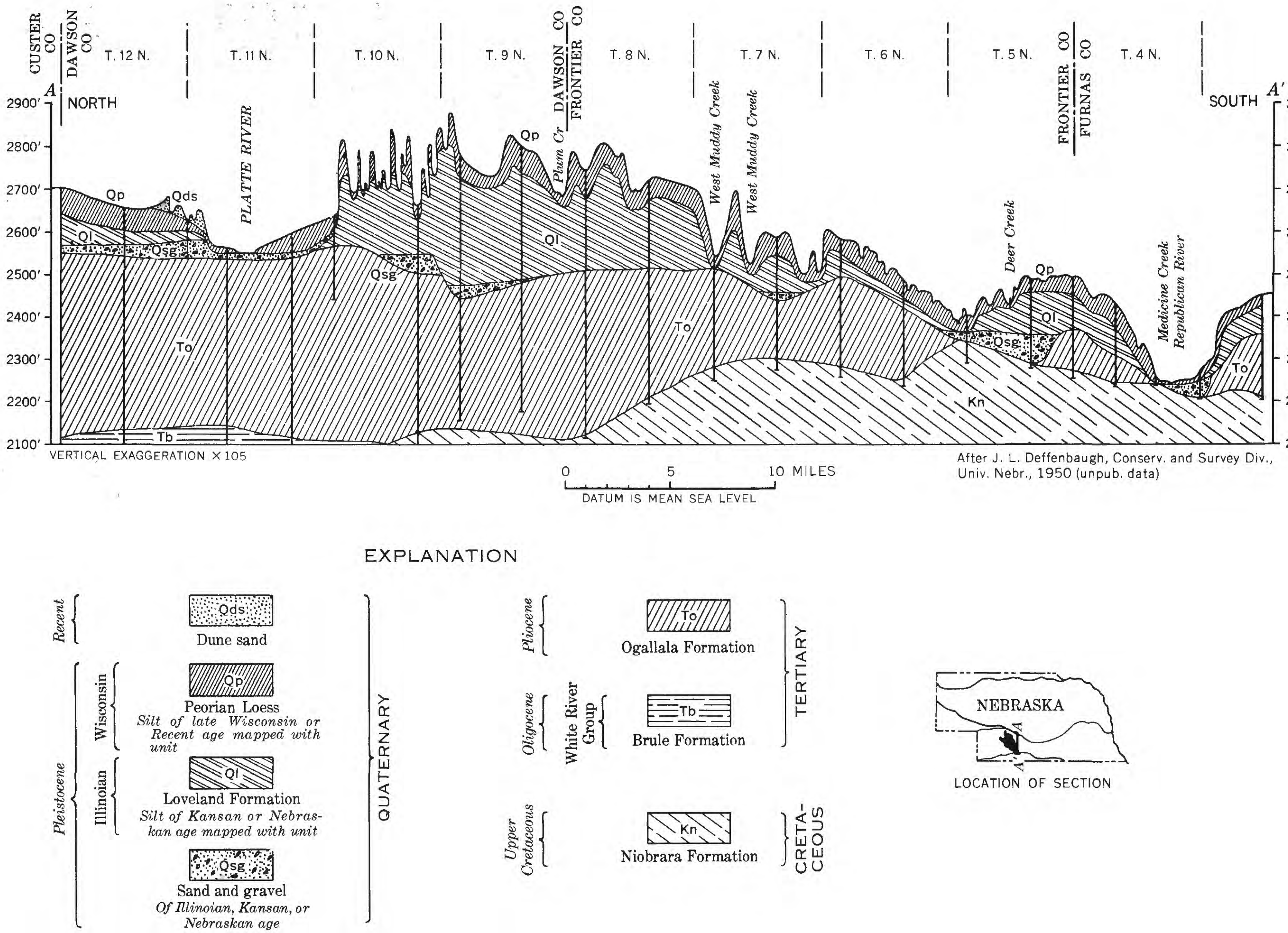


Figure 183.—Geologic section along a north-south line that crosses the lower tip of basin.

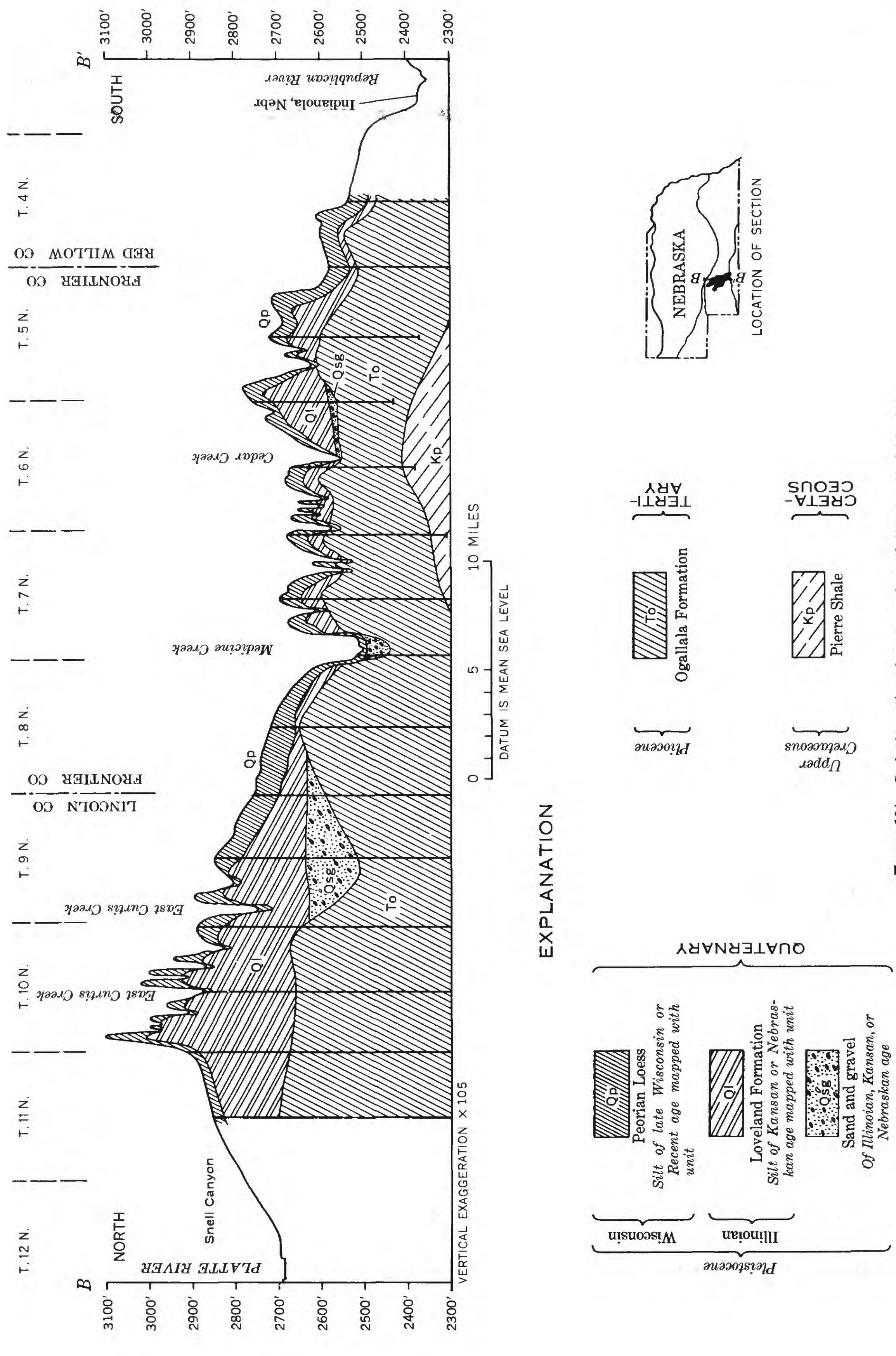


Figure 184.—Geologic section along a north-south line across the basin.

in the southern part of the Medicine Creek basin, in particular along Lime Creek. According to their nomenclature, alluvial terraces in Nebraska are numbered upward from the youngest and lowest, which is called Terrace-0, to the highest and oldest, which is called Terrace-5. Although their numerical system of terrace nomenclature is not used, the terrace sequence in this report is based on, and in general agreement with, the work of Schultz and others. Correlation of terrace deposits with Pleistocene time units is uncertain, particularly in view of the present controversy about the units. A tentative correlation of the Medicine Creek terrace sequence with other terrace sequences and with the Pleistocene time units is given in table 2.

The Stockville terrace of this report corresponds physiographically to Terrace-2 of Schultz and others (1948, 1951), and the Stockville terrace deposits correspond to fill A of Terrace-2. No terrace deposits corresponding to fill B of Terrace-2 were observed in the Medicine Creek basin by the writer.

The Wellfleet terrace, which is underlain by the upper part of the valley fill of the Peorian Loess, corresponds physiographically with the Terrace-3 of Schultz and others and with the Terrace no. 3 of Condra and others (1950, p. 35). No physiographic expression of the Terrace-4 of Schultz and others nor of the Terrace no. 4 of Condra and others was recognized in the Medicine Creek basin. At a locality on Medicine Creek (sec. 11, T. 5 N., R. 26 W.), Schultz and others (1948, p. 36) have identified a surface as the tread of Terrace-3. This surface is interpreted by the writer as a long valley-side slope graded to the level of the Stockville terrace. At this same locality the surface identified as Terrace-4 by Schultz and others is interpreted as the tread of Terrace-3, or the Wellfleet terrace. A terrace equivalent to Terrace-4 was doubtless once present in the Medicine Creek basin, but the physiographic expression has been obliterated by deposition of the upper part of the Peorian Loess and by grading of the valley sides during the time that the Stockville terrace deposits were accumulating.

GENERAL STRATIGRAPHY OF THE PLEISTOCENE AND RECENT

Stratigraphy of the Pleistocene deposits in Nebraska is well established, and satisfactory correlations have been made with the deposits of Kansas and other adjoining States, although nomenclature differs somewhat from State to State. For regional descriptions of the stratigraphic units the reader is referred to publications of the Nebraska Geological Survey (Condra and others, 1950; Lugn, 1935) and of the Kansas Geological Survey (Frye and Leonard, 1952). Leonard (1950, 1952) has established the ranges of land snails that are generally abundant in the Pleistocene deposits of Kansas.

The general relations of Pleistocene and Recent stratigraphic units in the Medicine Creek basin are shown in figure 185, and in table 2 correlation is tentatively made with formally named units in Nebraska and Wyoming. Long profiles of terrace deposits along the course of Medicine Creek are shown in figure 186. Correlation of the upper Wisconsin and Recent units is based on carbon-14 age determinations and on physiographic expression as terraces. Correlation of the older units is based on fossil evidence, on soil markers such as the Sangamon soil, and on lithology. Pleistocene and Recent deposits in the Medicine Creek basin consist of dune sand, loess, and alluvium, overlying a pre-Pleistocene (or lower Pleistocene) surface cut into the Ogallala Formation. The deposits of Nebraskan or Kansan age are mainly of alluvial silt and sand; gravel, in lesser amounts, is confined to the bottoms of former

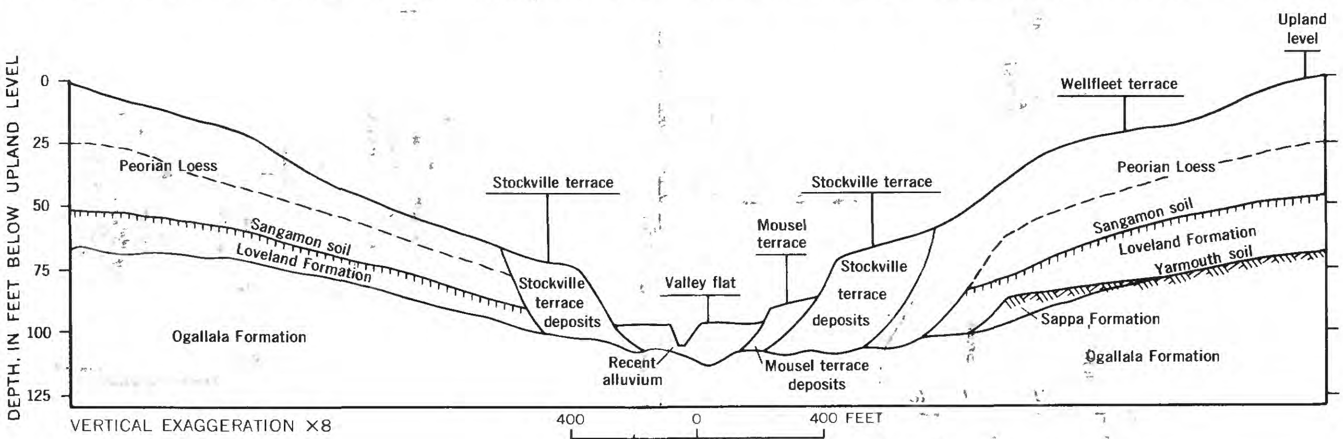


FIGURE 185.—General topographic and stratigraphic relations of Pleistocene and Recent deposits in the Medicine Creek basin. Differences in stratigraphy and relief on either side of the figure represent the range of differences among valleys in the basin.

TABLE 2.—*Correlation of stratigraphic units and terraces of the Pleistocene and Recent in Nebraska and Wyoming*

Age		Central Nebraska (Condra and others, 1950)		Nebraska (Schultz and others, 1951)		Wyoming (Leopold and Miller, 1954)		Medicine Creek, Nebraska (This report)		Generalized alluvial sequence western United States (Miller, 1958)
Recent				WWWWW Wisconsin "VI" silt Soil Z Late Cochrane silt WWWWW	Terrace-0	WWWWW Lightning fm	Lightning terrace	WWWWW Recent alluvium (420±160)[2]	Recent valley flats and terrace	WWWWW Deposition 3 Began A.D. 1200–1500[3] ended 1880
Recent				Early Cochrane silt (2,140±150)[1] Soil Y	Terrace-1	WWWWW Moorcroft-deposition or stability WWWWW Kaycee fm	Moorcroft terrace	WWWWW Mousel terrace deposits (1,343±240)[5] (2,200±200)[2]	Mousel terrace	WWWWW Deposition 2 Upper part—no younger than A.D. 1100–1200[3] Lower part—dates 2,200–2,400[4]
Recent	Altithermal					WWWWW Paleosol		WWWWW Soil development		WWWWW
?—?—? Wisconsin	Mankato	Bignell silt WWWWW	Terrace no. 2	Late Mankato silt WWWWW Early Mankato silt		Ucross fm	Kaycee terrace	Stockville terrace deposits	Stockville terrace	Deposition 1 (Probably correlates with a late Wisconsin glacial substage. Available dates suggest an age of 7,200–7,800[4])
Wisconsin		Brady soil		Soil YY (9,880±670)[1]	Terrace-2 fill A			WWWWW Brady soil	Wellfleet terrace	
Wisconsin	Cary	Upper Peorian silt	Terrace no. 3	Late Cary silt WWWWW Early Cary silt	Terrace-2 fill B			Peorian Loess		
Wisconsin		Soil development		Brady soil						
Wisconsin	Tazewell	Middle Peorian silt		Late Tazewell silt WWWWW Early Tazewell silt						
Wisconsin		WWWWW Soil development		Soil W	Terrace-3			WWWWW		
Wisconsin	Iowan	Lower Peorian silt Todd Valley sand WWWWW	Terrace no. 4	Todd Valley fm WWWWW Early Iowan silt				Peorian Loess		
Pleistocene	Sangamon	Loveland soil		Sangamon soil	Terrace-4			Sangamon soil		
Pleistocene	Illinoian	Loveland fm Crete fm WWWWW		Loveland fm Crete fm				Loveland Formation WWWWW		
Pleistocene	Yarmouth	Sappa soil		Yarmouth soil Sappa fm				Yarmouth soil		
Pleistocene	Kansan	Upper Sappa fm Pearlette ash lenticle Lower Sappa fm Grand Island fm WWWWW		Grand Island fm WWWWW Red Cloud fm				Sappa Formation WWWWW		
Pleistocene	Aftonian	Soil development		Fullerton fm						
Pleistocene	Nebraskan	Fullerton fm Holdrege fm		Holdrege fm						

1/ Years B.P., C^{14} dates reported by Schultz and others (1951)
2/ Years B.P., C^{14} dates given in this report
3/ Dates from pottery and dendrochronology
4/ Years B.P., C^{14} dates from various localities
5/ Years B.P., C^{14} date reported by Wedel and Kivett (1956)

WWWWW Denotes major periods of valley incision

(bracket) Encloses the units underlying a physiographically expressed terrace. Wind-laid silt deposited subsequently on terrace surface is not shown

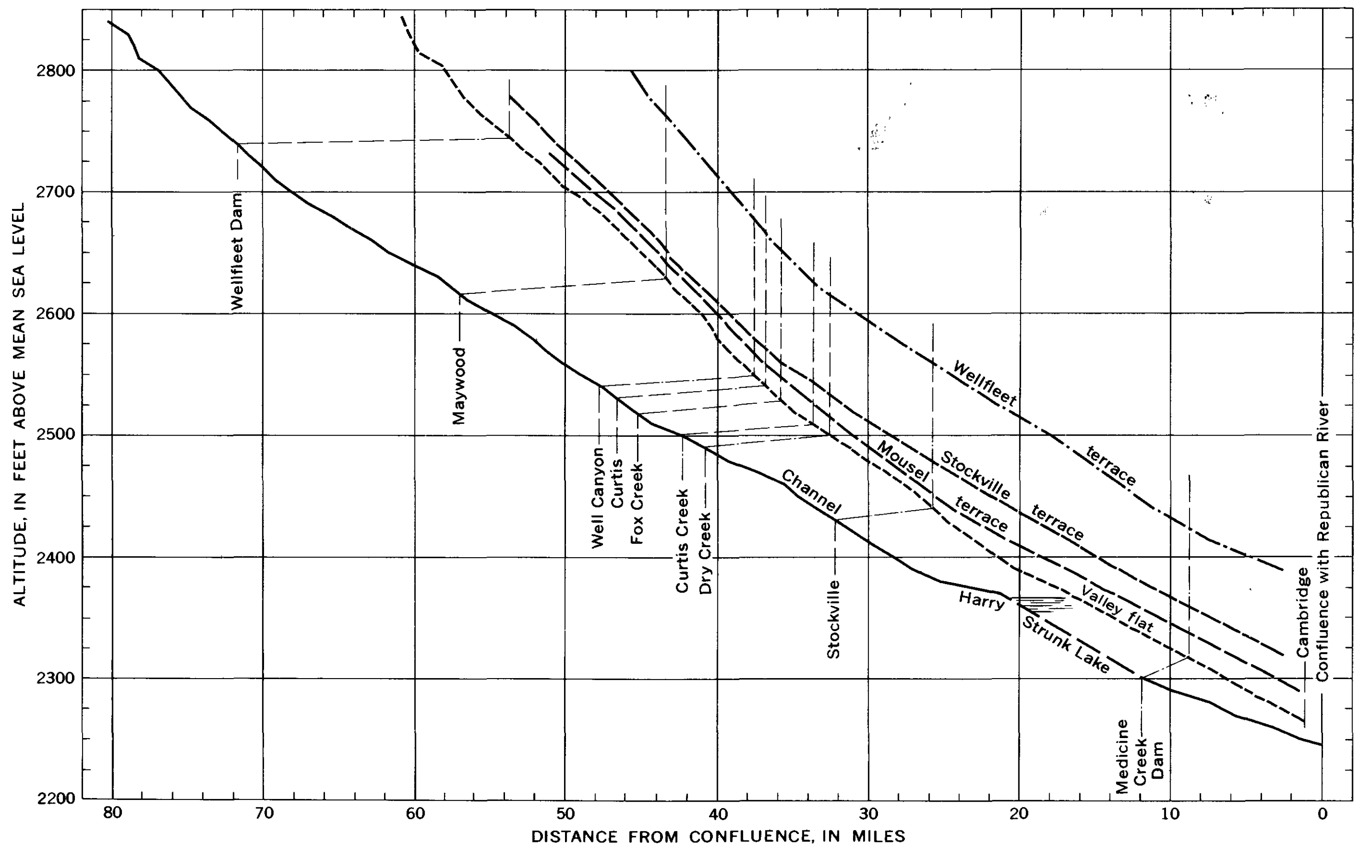


FIGURE 186.—Channel profile, valley flat profile, and terrace profiles along the main course of Medicine Creek.

valleys (figs. 183 and 184). Although loess may have been deposited during either Kansan or Nebraskan time, no loess of Kansan or Nebraskan age has been identified with certainty either on Medicine Creek or elsewhere in Nebraska. At two localities in the Medicine Creek basin, a paleosol was identified as the Yarmouth soil on the basis of snail fauna and high content of volcanic ash. Silts beneath the Yarmouth soil are correlated with the Sappa Formation. No deposits of ash of the Pearlette Ash Member of the Sappa Formation were seen in the Medicine Creek basin, but deposits up to 30 feet in thickness crop out in areas adjacent to the basin. No Pleistocene deposits older than the Sappa were recognized with certainty in the Medicine Creek basin.

The thickness and areal distribution of pre-Wisconsin stratigraphic units cannot be determined without data from drilling. Moreover, the logs must include full and accurate descriptions of the rocks that are penetrated, because the different Pleistocene stratigraphic units are similar in rock type to one another and to the Ogallala Formation. Two geologic sections (figs. 183 and 184) have been compiled from logs of test holes that were drilled by the Nebraska Conservation and Survey Division in cooperation with the U.S. Geological Survey. Figure 183 is simplified from an unpublished section by J. L. Deffenbaugh, based on his interpretation of logs of test holes drilled in 1948. On his original section, Deffenbaugh distinguishes the Loveland, Sappa, and Grand Island Formations. Figure 184 represents an interpretation, made by the writer, of logs of test holes drilled in 1960. Although the logs include full descriptions of the rocks penetrated, the writer was not able to distinguish with confidence any formational boundaries beneath the Sangamon soil and above the Ogallala Formation. To facilitate comparison of figures 183 and 184, some of the stratigraphic units distinguished by Deffenbaugh were combined in order that they correspond with the units shown on figure 184.

STRATIGRAPHY ON CEDAR CREEK NEAR STOCKVILLE

Along Cedar Creek, about 3 miles southwest of the village of Stockville (Bartley NW quad., NE1/4 sec. 18, T. 6 N., R. 27 W.), several sections have been exposed by lateral cutting of the creek, and the terrace sequence is more complete and distinct than

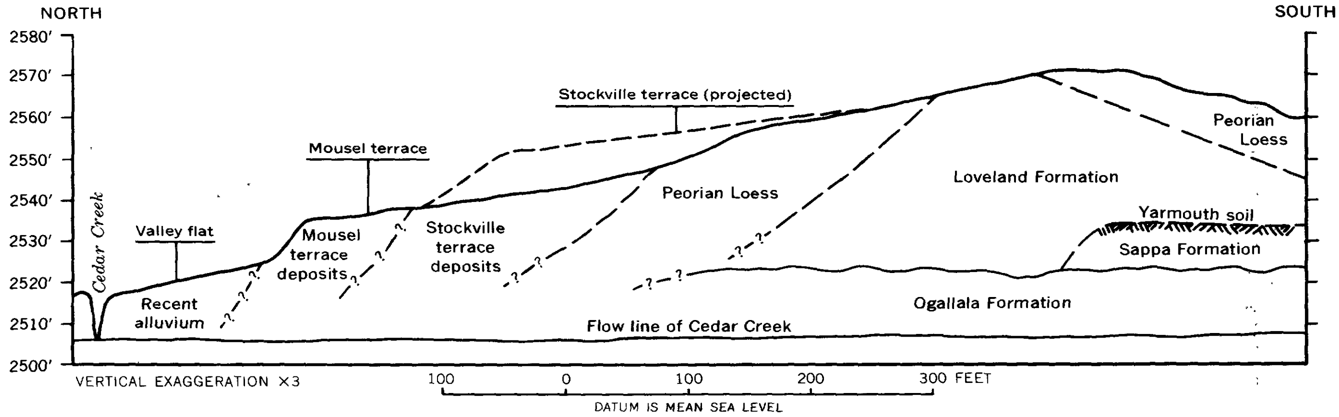


FIGURE 187.—Profile and geologic section on Cedar Creek.

usual for the Medicine Creek basin. The section described below applies to the right-hand (south) side of figure 187:

	Depth (ft)
Peorian Loess:	
Silt, pale-yellow (2.5*Y* 7/3 dry, 2.5*Y* 6/3 moist), calcareous. Surface soil not present	0–15
Loveland Formation:	
Silt, very pale brown (10*YR* 7/4 dry, 10*YR* 5/4 moist); a few streamers of fine sand near base	15–20
Gravel, sand, and silt, crossbedded, calcareous, locally cemented with carbonate	20–22
Silt, pale-brown (10*YR* 6/3 dry, 10*YR* 4/2 moist), noncalcareous; indistinct sedimentary lamination	22–26
Yarmouth soil:	
Silt, clayey, gray-brown (10*YR* 5/2 dry, 10*YR* 4/2 moist). Weak columnar structure, columns irregular, 2 to 5 in. wide; noncalcareous. Upper contact gradational	26–28.9
Sappa Formation:	
Sand, fine, and ashy light-gray (2.5*Y* 7/2 moist) silt; a few thin white irregular seams of volcanic ash. Upper 0.5 ft mottled with darker gray, gradational with unit above. Upper 2 ft is C_{ca} horizon of Yarmouth soil; contains meshwork of fine carbonate veinlets	28.9–32
Sand, fine, and ashy silt; a few streamers of sand and fine gravel near base; noncalcareous	32–35
Gravel and other debris from Ogallala Formation; crossbedded; a few streamers of fine sand	35–37
Ogallala Formation:	37–53

A snail fauna was collected from the lower part of the soil identified as Yarmouth and from the upper part of the unit identified as Sappa, and identification was made by Dr. W. J. Wayne of the Indiana Geological Survey. In the following table, the number of individuals of each species is given in the right-hand column.

Gastrocopta tappaniana (C. B. Adams)	2
proarmifera Leonard	3
Gyraulus circumstriatus (Tryon)	21
Helicodiscus parallelus (Say	3
Physa anatina Lea	2
Retinella electrina (Gould)	3
Lymnaea [Fossaria] parva	2
Vallonia gracilicosta Reinhardt	15
Valvata tricarinata (Say)	4

According to Leonard (1950), *G. proarmifera* is restricted to the Yarmouth, and none of the species in the collection is restricted to deposits younger than the Yarmouth. Correlation of the soil with the Yarmouth and of the underlying silt with the Sappa is, therefore, supported by the faunal evidence. *V. tricarinata* is aquatic, and the fauna as a whole indicates a moist environment such as would be afforded by a valley.

The stratigraphic and topographic relations shown in figure 187 indicate that the valley of Cedar Creek was cut not later than Kansan time and that at least five episodes of valley alluviation, each followed by cutting, have taken place since Yarmouth time.

STRATIGRAPHY ON CUT CANYON NEAR CURTIS

Near the confluence of Cut Canyon with Fox Creek, a significant section of Pleistocene deposits is exposed along the county road that descends eastward from the upland and crosses Cut Canyon in the NW¼ sec. 29, T. 9 N., R. 28 W. The presence of deposits of the Sappa indicates that the canyon was cut not later than Kansan time, and the Pleistocene sequence of pre-Wisconsin age seems to be complete. Both the Yarmouth and the Sangamon soils are well developed. Of the terrace deposits of late Wisconsin and Recent age, however, only the Stockville is exposed (fig. 188).

A stratigraphic section along the road, beginning 1,500 feet west of Cut Canyon bridge and ending 1,150 feet west of the bridge, is as follows:

	Depth (ft)
Peorian Loess:	
Silt, yellowish-gray, massive, homogeneous	0–30

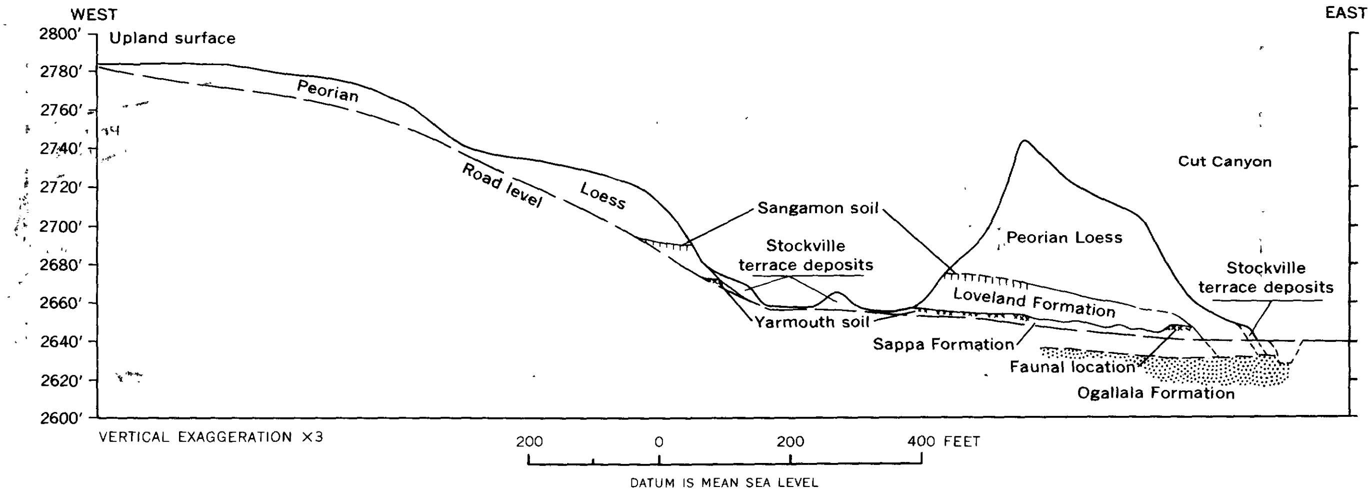


FIGURE 188.—Profile and geologic section along road entering Cut Canyon.

	Depth (ft)
Sangamon soil and Loveland Formation:	
Silt, yellowish-brown (10*YR* 5/4 when moist), friable; no distinct structure	30–32
Silt, light-yellowish-brown (10*YR* 6/4 when moist); weak prismatic structure, noncalcareous	32–38
Silt, clayey, approximately same color as unit above, but has pinkish cast	38–38.5
Silt, streaked and veined with abundant soft carbonate	38.5–43
Yarmouth soil:	
Silt, light-brownish-gray (5*Y* 7/2 when dry, 10*YR* 6/2 when moist), clayey; streaked with carbonate from unit above, but otherwise noncalcareous. Breaks into irregular small polyhedrons (5 to 10 mm in diameter) that fit together. Contact with unit above sharp but irregular	43–46.5
Silt, yellowish-brown (10*YR* 5/4 when moist); contains abundant small iron concretions	46.5–47

A stratigraphic section 800 feet west of the bridge is similar to that described above, except the Sappa Formation is exposed and the Yarmouth soil is somewhat different, as shown below:

	Depth (ft)
Yarmouth soil:	
Silt, olive-gray (5*YR* 4/2 when moist)	0–1
Silt, light-gray (10*YR* 7/2 when moist); crumb structure	1–2.5
Silt, light-gray, mottled with rust color; structure weakly prismatic, prisms have irregular sides, 1 to 3 cm wide	2.5–4.1
Silt, light-gray; no distinct structure	4.1–7.5
Sappa Formation:	
Sand, fine-grained, and silt; cross-laminated	7.5–9.5

No fossils were found at this section, but fossils were found in gray ashy silt, correlated with the Sappa, about 600 feet to the east. The faunas were identified by the writer, and the identification was checked and corrected by Dr. W. J. Wayne of the Indiana Geological Survey. The number of each species found is indicated in column at right in the following list:

Carychium exile canadense Clapp	2
perexiguum Baker	2
Gastrocopta pentodon (Say)	6
proarmifera Leonard	2
Gyraulus circumstriatus (Tryon)	19
Pupilla muscorum (Linné)	1
muscorum sinistra Franzen	1
Retinella electrina (Gould)	1
Vallonia gracilicosta Reinhardt	10
Valvata tricarinata (Say)	24
Vertigo nylanderi Sterki	3

According to Leonard (1950), *G. proarmifera* and *P. muscorum sinistra* are restricted to the Yarmouth and *C. perexiguum* is restricted to deposits of Nebraskan and Yarmouth age; none of the species found is restricted to deposits younger than Yarmouth age. Therefore, correlation of the ashy silt with the Sappa Formation is reasonable.

STRATIGRAPHY ON ELKHORN CANYON NEAR MAYWOOD

The Peorian Loess, Stockville terrace deposits, and late Recent alluvium are exposed along Elkhorn Canyon about 2 miles southwest of the village of Maywood, near a bridge where the county road crosses the canyon (Curtis SW quad., center of section line between secs. 31 and 32, T. 8 N., R. 29 W.). The exposure was studied after it had been thoroughly moistened by rainfall and runoff, because moistening greatly increases visibility of the sedimentary structures and textures. The relations between the different units are shown in figure 189, and a general view of the locality is shown in figure 190. Evidence was found in the late Recent alluvium for two episodes of cutting and filling, which took

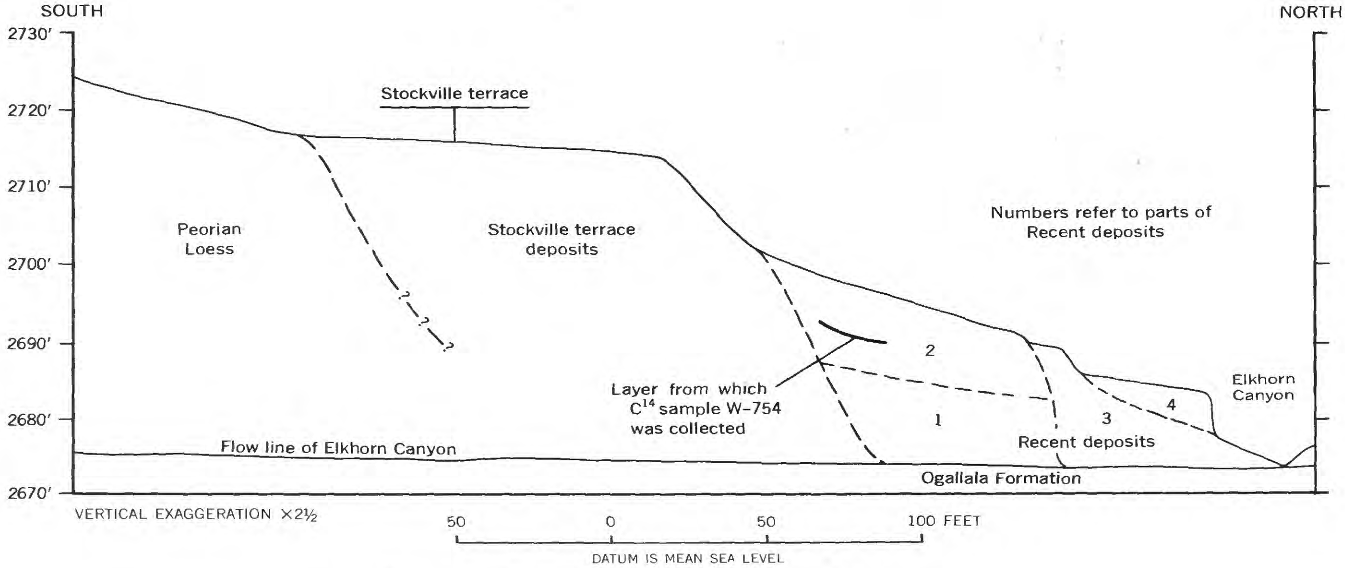


FIGURE 189.—Profile and geologic section on Elkhorn Canyon.

place (according to a carbon-14 age determination) within the past 300 to 400 years.

The late Recent alluvium consists of four parts, which are designated by the numbers 1 through 4 on figure 189. Part 1 is oldest, lightest in color, and most compacted, whereas the younger parts are successively darker in color and less compacted. The contact between part 1 and part 2, which lies at a depth of about 12 feet below the ground surface, is conformable and nearly horizontal. Beneath the contact, the deposits of part 1 show no evidence of erosion or of leaching. Part 2 is characterized by light brownish gray bands of fine sand and silt (2.5*Y* 6/2 moist) alternating with darker grayish brown bands of clayey silt (2.5*Y* 4/2 moist), whose darker colors result from a finer texture and a higher content of organic matter. Part 1 is also banded, but the banding is inconspicuous because of the relatively lighter color of the clay-rich layers. Part 2 is riddled with worm burrows, which are partly filled with castings and dark silt, and many of which terminate in a round cavity partly filled with castings. The darker clay-rich bands seem to have been preferred by the worms, for these bands contain castings in greatest abundance. Worm castings are much less apparent in part 1, although dark vertical streaks, which probably represent the filled burrows of worms, were seen from place to place, and the bedding is apparently riddled by worm burrows. A lens of charcoal and wood ashes, mixed with silt and containing a single large fragment of charred bone, was found interbedded in part 2 at a depth of about 7.5 feet below the ground surface and 3 to 4 feet above the contact with part 1. Charcoal (Geol. Survey sample W–754; analysis by Meyer Rubin) from the lens yielded a carbon-14 date of 420±160 years B.P. (before present).

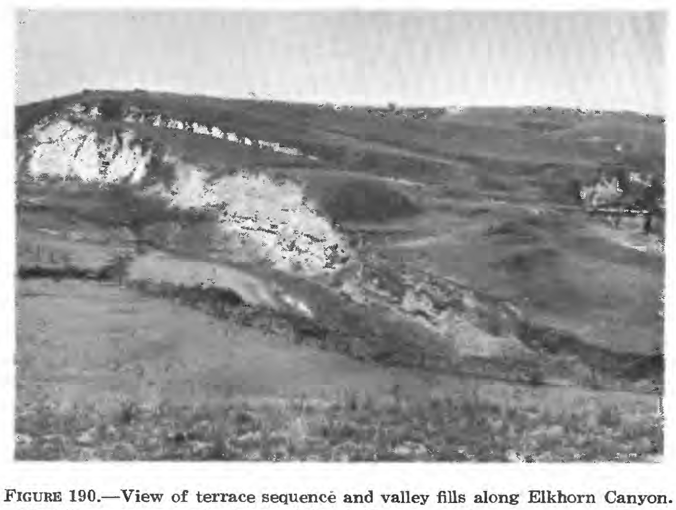


FIGURE 190.—View of terrace sequence and valley fills along Elkhorn Canyon. Prominent scarp marks front of Stockville terrace; lower scarp marks contact between parts 3 and 4 of late Recent alluvium.

Parts 1 and 2 of the late Recent alluvium are described here because the contact between these parts is considered to mark a distinct change in the rate of accumulation of the late Recent alluvium; the rate of accumulation of part 2 is considered to be much the more rapid. Furthermore, the more rapid accumulation of part 2 probably reflects an increase in rate of erosion on the uplands and valley sides. Part 1 is lighter in color because its slower rate of accumulation permitted a greater degree of oxidation of finely divided organic matter, which was originally intermixed with the silt and clay. A slower rate of accumulation of part 1 is also indicated by the greater destruction of its sedimentary structures by earth worms. If the described changes from part 1 to part 2 do in fact reflect a change in rate of accumulation, this change took place about 500 years ago, as indicated by the position of the radiometrically dated charcoal. According to archeologic evidence, a period of drought may have begun about 500 years ago, when the region was apparently evacuated by people of the Upper Republican Culture.

Parts 3 and 4 of the late Recent alluvium are dark gray brown (10*YR* 5/2 moist) and show rather distinct banding. Carbonized fragments of grass stems, having an average length of about 0.5 mm, are scattered throughout, but they are more abundant in the darker, clay-rich bands. Dark laminae formed of ashes and charcoal, which probably represent the debris from grass fires, were seen from place to place. Much of the alluvium seems to have passed through the digestive tracts of earth worms, whose castings dominate the texture and account for the loose consolidation.

The steeply dipping erosional contact that separates parts 1 and 2 from part 3 is attributed to the passage of a major gully head scarp along the valley of Elkhorn Canyon. Part 3 of the late Recent alluvium, which was deposited in the gully left by this head scarp, was in turn trenched by a second head scarp following consecutively behind the first. The former sides of the trench made by the second head scarp are represented by a pair of low terraces that were traced (on aerial photographs) to their terminus about 3 miles upvalley. Deposits formed behind the second head scarp (part 4) were in turn trenched by a third head scarp following consecutively behind the second. In 1952 the third head scarp was 13,300 feet upvalley from this locality, and it advanced about 500 feet during the period 1937–52.

Relatively little time is required for the formation of a series of low terraces by the passage of consecutive gullies, because deposition is rapid on the floor of a gully and the head scarps travel rapidly as a result of concentration of flow on the gully bottom. The average rate of advance of the third head scarp during the period 1937–52 is probably conservative, partly because the head scarp has reached bedrock. An average advance of about 200 feet a year, attained by some head scarps in the Medicine Creek basin during the period 1937–52, would be adequate to account for passage of the events described during a period of about 350 years. On the other hand, these events would not likely be compressed into a period of much less than 350 years.

LOVELAND FORMATION AND SANGAMON SOIL

The most useful and distinctive soil marker within the Pleistocene deposits is the Sangamon soil, which is developed on the Loveland Formation. No other soil in the region, including the modern soil, approaches the Sangamon in depth of profile or in degree of development of the C_{ca} horizon. On the uplands the Loveland consists of loess, which mantles the valley sides and merges into contemporaneous valley-fill deposits of silt and sand. The maximum observed thickness of Loveland in the Medicine Creek basin is 35 feet (along Cedar Creek), and the average thickness is about 20 feet. At some exposures in valleys, the Loveland is missing and the Sangamon soil is developed on the Ogallala Formation.

Moist loess of the Loveland is typically light yellowish brown (10*YR* 6/4), but darker colors (10*YR* 5/3 and 10*YR* 5/4) were observed at some localities. The Sangamon soil, as observed from a distance, is a distinct dark-brown humus-rich band that separates loess of the Loveland from the distinctly lighter colored loess of the Peorian. (See fig. 191.) This band ranges from about 4.5 to about 2 feet in thickness and from yellowish brown (10*YR* 5/4) where the soil is weakly developed to very dark gray brown (10*YR* 4/3) where it is strongly developed. A C_{ca} horizon is nearly everywhere present in the soil, but its depth below the dark band ranges from about 2 feet in some localities to about 25 feet in others, and its thickness is also variable. The variations indicate that development of the Sangamon in some localities was nearly continuous, whereas in other localities the developing soil was intermittently buried by fresh accumulations of silt.

In spite of the conspicuous development of the humus-rich part of the Sangamon soil profile, it contains an abundance of fresh ferromagnesian min-

FIGURE 191.—Valley fill of the Peorian Loess set unconformably against Sangamon soil and Peorian Loess. Steeply dipping unconformity, indicated by arrows, is exposed on either side of the small valley, and the valley fill of the Peorian is between the arrows.

erals and hence has undergone little chemical weathering. About 20 species of heavy minerals were identified under the petrographic microscope; of these, clinozoisite, green hornblende, apatite, and brown hornblende are by far the most abundant. In addition, calcic feldspar (labradorite) was identified among the light minerals.

PEORIAN LOESS, BRADY SOIL, BIGNELL LOESS, AND MODERN SOIL

An account of the involved history of the terms "Peoria" and Peorian has been given by Leonard (1951, p. 323). In this report, the term Peorian Loess is applied to deposits that are stratigraphically above the Sangamon soil and terminate in the Brady soil. The absolute time at which the Sangamon Interglaciation ended has not been determined, but a reasonable estimate can be made by extrapolating from existing carbon-14 dates; the estimate of Frye and Willman (1960, p. 2) is between 50 and 70 thousand years B.P., as measured by carbon-14. The Brady soil has been dated, by means of a carbon-14 age determination on organic carbon from the A horizon of the soil, at 9,160±250 years B.P. (Rubin and Suess, 1956, p. 443). This date is probably too young because of root hairs in the sample.

In general, the Peorian Loess mantles the whole of the Medicine Creek basin except the modern valley flats and the Stockville and Mousel terraces. On the uplands the Peorian consists of massive silt, which grades laterally (at least at the surface) to fine sand in the vicinity of dune areas. This massive silt is called loess because its topographic position indicates that it is eolian and because the snails that it contains are not aquatic. In valley locations also, the greater part of the thickness of the Peorian consists of massive silt, except in the valleys in the vicinity of dune areas, where it consists of silt and fine sand. The lowermost 10 to 20 feet of the Peorian in the valleys commonly consists of silt interbedded with fine gravel, silty clay, or sand; and this lowermost part contains, in some localities, aquatic snails or pelecypods. The massive silt of the valleys is not called loess because its agent of deposition is not apparent. Where a vertical face cut in this silt is exposed to wind and rainwash, it commonly shows well-defined lamination that could be attributed either to wind or to water. Eolian deposition of silt on the uplands was probably accompanied by an equal or greater amount of eolian deposition in the valleys, but the silt in the valleys was probably reworked by water before final deposition. Deposits of the Peorian in valley locations, whether of massive silt or of some other sediment type, are called the valley-fill deposits of the Peorian.

Leonard (1951) recognizes three biostratigraphic zones in the Peorian Loess of Kansas, but these zones are not marked by any physical discontinuities in the loess. The basal zone, which is devoid of molluscan fossils, is overlain by a lower molluscan faunal zone and an upper molluscan faunal zone. Between the upper and lower faunal zones is a transitional faunal zone, which bears elements of both the lower and upper faunal assemblages.

A snail fauna was collected about 25 feet stratigraphically above the Sangamon soil at a locality on Dry Creek to ascertain the approximate position of these faunal zones relative to the total thickness of the loess of the Peorian in the Medicine Creek basin. The locality is in the NW¼ sec. 16, T. 9 N., R. 27 W. The stratigraphic position of the fauna is about midway of the total thickness of the loess on Dry Creek. A sample of loess weighing about 25 pounds was collected, and the contained snails were obtained by washing the loess through a sieve. Identification of the snails was made by Dr. W. J. Wayne of the Indiana Geological Survey, and the faunal list is as follows (the number of individuals of each species is given in right-hand column):

Columella alticola (Ingersoll)	2
Discus cronkhitei (Newcomb)	2
shimeki (Pilsbry)	24
Euconulus fulvus (Müller)	2
Pupilla muscorum (Linné)	4
Succinea grosvenori Lea	16
Vallonia gracilicosta Reinhardt	2
Vertigo modesta (Say)	3
tridentata Wolf	10

Of the nine species listed, five belong to the upper and transitional zones of Leonard, and four occur in all three zones. Because of the absence of *S. avara* and the numerical dominance of *D. shimeki* and *S. grosvenori*, which are upper zone species, the assemblage is assigned by the writer to the upper zone. The fauna in this single locality indicates that at least half of the total thickness of the Peorian in the Medicine Creek basin was deposited during the time represented by the upper faunal zone of Leonard. Leonard correlated his upper zone with the Tazewell Stade of the Wisconsin Glaciation.

During accumulation of the Peorian on the uplands, a period of incision to bedrock took place in the valleys. Valley fill of the Peorian that accumulated after this incision is set unconformably against the Loveland Formation, the Sangamon soil, and the lower part of the Peorian. (See figs. 185 and 191, both of which show valley fill of the Peorian set unconformably against the Sangamon soil and the lower part of the Peorian.) From a distance the valley fill of the Peorian looks almost white, whereas the loess of the Peorian that overlies the Sangamon soil has a yellowish cast. On the uplands no physical discontinuity within the Peorian was discerned.

Molluscan fauna collected from the base of the valley fill of the Peorian at two localities indicates that deposition of the valley fill began in Tazewell time. The first locality is on the bank of Dry Creek, about 700 feet upstream from the gaging station, in the SE¼ sec. 24, T. 8 N., R. 28 W. Here the valley fill rests unconformably on the Ogallala Formation. Identification of the fauna was made by the writer, with the assistance of Dr. W. J. Wayne. The faunal list is as follows:

Columella alticola (Ingersoll)
Discus cronkhitei (Newcomb)
shimeki (Pilsbry)
Gyraulus circumstriatus (Tryon)
Physa anatina Lea
Pupilla muscorum (Linné)
Retinella electrina (Gould)
Succinea grosvenori Lea
Vallonia gracilicosta Reinhardt
Vertigo gouldi coloradensis Cockerell
modesta (Say)
Zonitoides arboreus (Say)

According to Leonard (1952, p. 19), *D. shimeki* and *D. cronkhitei* are reliable indexes to the upper (Tazewell) faunal zone of the Peorian. None of the other species in the assemblage is restricted to deposits either older or younger than this upper faunal zone.

A second fauna from the valley fill of the Peorian was collected at the side of Mitchell Creek, near a county road in the NW¼ sec. 9, T. 6 N., R. 26 W. Identification was made by the writer, with the assistance of Dr. W. J. Wayne. The faunal list is as follows:

Discus cronkhitei (Newcomb)
Euconulus fulvus (Müller)
Gastrocopta armifera (Say)
Lymnaea (Stagnicola) palustris (Müller)
Retinella electrina (Gould)
Succinea grosvenori Lea
Vallonia gracilicosta Reinhardt
Vertigo tridentata Wolf

Although this assemblage is different from the assemblage collected from the valley fill of the Peorian on Dry Creek, a correlation with the upper molluscan faunal zone of Leonard (1951, 1952) is indicated by the presence of *D. cronkhitei* and *S. grosvenori*.

The average thickness of the loess of the Peorian in the Medicine Creek basin is about 50 feet, and the maximum thickness is about 80 feet. Thicknesses were measured at exposures in upland localities and from the logs of test wells drilled by the Nebraska Conservation and Survey Division. (See figs. 183 and 184.) The thickness of the loess reaches a maximum in the vicinity of the Platte River, gradually decreases southward to a minimum in a belt which is about 30 miles south of the Platte River and 10 miles north of the Republican River, then again increases in thickness in the direction of the Republican. A well near the north side of the Republican River valley penetrated a thickness of 60 feet of loess, whereas a well near the south side of the valley penetrated a thickness of only 30 feet. About 50 feet of loess of the Peorian is exposed in the vertical wall of a deep pit, 1.5 miles west of Eustice, Nebr. (fig. 192).

The valley fill of the Peorian is thicker than the loess. The exposed thickness of valley fill of the Peorian on the main stem of Medicine Creek, as measured from the surface of the Wellfleet terrace to the modern valley flat, is about 125 feet. On the assumption that the valley fill extends to bedrock, as it does on Dry Creek, the total thickness on Medicine Creek is about 200 feet. On the same assumption, the total thickness on Well Canyon, at a locality about 7 miles north of Curtis, is 180 feet. The exposed thickness in the upper reaches of Dry Creek is 42 feet, and the total thickness is about 65 feet.

Loess of the Peorian in the Medicine Creek basin is a massive friable light-colored silt, similar to loess that has been described in other regions. The loess when dry is typically light gray (10*YR* 7/2) and when moist is light brownish gray or pale

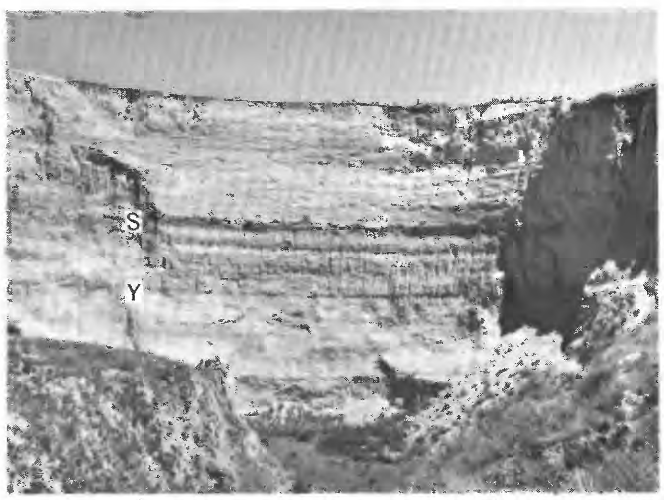


FIGURE 192.—Peorian Loess (50 ft thick) overlying a horizon of Sangamon soil (upper dark band, marked S). Units beneath Peorian Loess are Loveland Formation (20 ft), Yarmouth soil (lowermost dark band, marked Y), Sappa Formation (33 ft), and Pearlette Ash Member of Sappa Formation (20 ft). Excavation, made for removal of Pearlette, is 1.5 miles west of Eustice, Nebr. Photographed by C. H. Hembree, 1956.

brown (10*YR* 6/2 or 6/3). Although the loess appears to be homogeneous when viewed from a distance, closer inspection reveals abundant hollow tubules made by rootlets, worm burrows, and small botryoidal structures which are worm castings. Within 5 feet of the ground surface, the loess may show such an abundance of these botryoidal structures as to indicate that all of it has passed through the digestive tracts of earth worms. Snail shells are generally present and are locally abundant. Lamination, although not usually observable, may appear where erosion by wind and raindrops has been sufficiently delicate to etch the laminae into relief.

Thin sections of seven samples of loess of the Peorian, collected at different localities in the Medicine Creek basin, were studied under the petrographic microscope. The most distinctive textural features of loess, when viewed at high magnification, are the rather close packing arrangement and the presence of birefringent clay coatings around detrital silicate grains. Grains larger than 125 microns in maximum diameter constitute less than 1 percent by volume of the samples, and grains larger than 31 microns constitute 55 to 75 percent by volume. Particles larger than 31 microns may be regarded as the framework or skeleton of the loess, and particles smaller than 31 microns may be regarded as the matrix. The clay grain coatings, which are evidently authigenic, may be regarded as cement. The framework grains are mainly separated by their clay coatings and by the matrix. Contacts between framework grains are mainly tangential or long, and an average of about two contacts per grain was observed.

The birefringent clay coatings around detrital silicate grains consist of crystalline flakes oriented parallel with the surface of the coated grain. These coatings merge with the matrix and probably account in considerable part for the coherence of the loess and for the ability of loess to maintain a vertical face. Clay coatings on flat grains, such as mica flakes and glass shards, are in general thicker than coatings on equant grains. Clay coatings on grains are not characteristic of siltstones deposited under water. In loess the coatings are probably formed by wetting and drying of the surface layer during deposition. Kubiena (1938, p. 134) has attributed the formation of grain coatings in soils to such wetting and drying. After rainfall, the soil solution may fill all pore spaces in the soil, but evaporation at the ground surface causes the soil solution to retreat to the angles of the intergranular spaces and to the surfaces of grains. As the soil dries, substances that were peptized or dissolved in the soil solution are left as coatings on grains. Although the grain coatings described by Kubiena were of humus, coatings of clay also probably form by wetting and drying.

In this region loess of the Peorian is generally calcareous, but the calcium carbonate is not uniformly disseminated. Calcium carbonate in the loess occurs in the form of silt-sized grains, which are doubtless primary; as powdery streaks and vein fillings; as fine-grained aggregates that line or fill rootlet tubules, worm burrows, or other openings; and as concretions. Many loess outcrops show zones up to several feet thick that are noncalcareous. Frankel (1957) has reported vertical variations in the distribution and concentration of secondary calcareous concretions and in the abundance and state of preservation of fossil mollusks in the loess in Nebraska. He attributes these variations to an intermittent rate of loess deposition. Slow deposition of loess is accompanied by solution of snail shells and by accumulation of secondary carbonate at depth. Rapid accumulation of loess is indicated by unaltered snail shells. Frankel suggests that many phantom soils are present. The writer has observed that massive silt, accumulated as valley fill and indistinguishable from upland wind-laid loess, is more commonly noncalcareous than upland loess.

The Brady soil was named and described by Schultz and Stout (1948) from a locality on the steep south side of the Platte Valley near Bignell, Nebr. This locality is also the type section for the overlying Bignell Loess (Schultz and Stout, 1945). According to the writer's observations, the humic zone of the type Brady soil is about 1.3 feet thick, and the soil is weakly calcareous throughout; soft streaks and films of carbonate appear to a depth of 2.2 feet from the top of the soil, and these are conspicuous from 1.3 to 2.2 feet. Overlying the Brady soil is a thickness of 8 to 10 feet of Bignell Loess, on which the modern soil is developed. This modern soil is noncalcareous to a depth of 3.2 feet and shows a distinctly columnar structure to a depth of 1.3 feet. Above the modern soil is about 1 foot of lighter silt, evidently colluvial and related to cultivation of fields upslope from this locality. The modern soil appears to be more strongly developed than the Brady soil.

In spite of the fact that Medicine Creek basin is adjacent to the type locality of both the Brady soil and the overlying Bignell Loess, the Brady soil, as separately developed from the modern soil, was observed at only three exposures, all in the northern part of the basin.

General deposition of a thin layer of Bignell Loess over the uplands of the Medicine Creek basin is indicated by abnormally thick A horizons that commonly appear in the modern soil. The modern soils of Lincoln County, Nebr., have been mapped and described by Goke and others (1926); and the soils of Frontier County, Nebr., by Bacon and others (1939). The Medicine Creek basin lies within these two counties. Principal soils of the loess-mantled areas are the Holdredge very fine sandy loam and the broken phase of the Colby very fine sandy loam. The Holdredge soil, which is developed mainly on areas of flat or rolling upland, is mature. The B horizon of the Holdredge lies between 10 and 24 inches in depth and shows an imperfectly developed columnar structure; and the C_{ca} horizon, which contains a concentration of carbonate in the form of streaks, splotches, or threads, lies between 3 and 4 feet in depth. A dark-brown zone, probably representing the Brady soil, lies between the B horizon and the C_{ca} horizon at many localities.

STOCKVILLE TERRACE DEPOSITS

Typical relations of the Stockville terrace deposits to other stratigraphic units are shown in figure 185. Along major valleys, the unconformity between the Stockville terrace deposits and older units is rarely marked by a scarp; if one were originally present, it has been obliterated by erosion on the valley-side slopes. Along minor valleys, the unconformity is usually marked by a distinct scarp.

The Stockville terrace deposits consist mainly of calcareous silt. In minor valleys the silt is less compact, the color is darker, and the bedding is less well defined than in major valleys. Dark humus-rich bands, beneath which the silt is leached to a depth of a foot or two, are observable at most exposures of the Stockville terrace deposits. The depth of burial of the uppermost band ranges, in different parts of the basin, from about 2 to 20 feet; and the number of bands varies from one exposure to the next. These bands, together with the underlying leached zone, probably represent immature soils that formed during periods of slow deposition. The Stockville terrace deposits occur in nearly all valleys of the present drainage system, including valleys of first order. The thickness, which depends on the size of the valley, is about 100 feet along Medicine Creek and Well Canyon, about 60 feet along Lime Creek, and about 30 feet along Dry Creek.

A fauna of snails and pelecypods was collected from the Stockville terrace deposits exposed along Medicine Creek in the NE cor. sec. 13, T. 6 N., R. 27 W. According to Dr. W. J. Wayne, who identified the fauna, none of the species is extinct, and all are fresh-water species that now inhabit parts of central United States. Leonard (1952, p. 16) concludes, from his study of Bignellian molluscan faunas in Kansas, that the environment of Bignell Loess deposition was very much like present conditions in the Great Plains. The Bignell Loess is considered by the writer to be the upland counterpart of the Stockville terrace deposits.

MOUSEL TERRACE DEPOSITS

The Mousel terrace deposits consist mainly of silt and differ from the Stockville terrace deposits only by being somewhat darker in color and more compact. In some localities the Mousel terrace deposits contain fragments of carbonized grass stems, which are rare in the Stockville terrace deposits. Along the main course of Medicine Creek, two buried humus-rich bands, which are interpreted to be immature soils, were observed in deposits of the Mousel terrace.

Charcoal suitable for carbon-14 age determination was collected from the Mousel terrace deposits on Dry Creek in the NW¼NE¼ sec. 1, T. 7 N., R. 28 W. The charcoal was in a lens of wood ashes and silt, buried at a depth of 14.5 feet below the ground surface. The age was reported as 2,200±200 years (J. L. Kulp, Lamont No. 239C).

RECENT ALLUVIUM

Where valley trenching has exposed the full thickness of the late Recent alluvium—as at localities on Dry Creek, Cedar Creek, Elkhorn Canyon, and Lime Creek—the alluvium rests on the bedrock floor of the valley. Therefore, at these localities the valleys were incised to bedrock during the episode of incision that followed accumulation of the Mousel terrace deposits. Incision to bedrock may have been confined to localities where the bedrock is high beneath the valley floor. In some valleys, such as Dry Creek and Elkhorn Canyon, accumulation of the late Recent alluvium has been interrupted by one or more episodes of incision during which the valley was trenched for part of its length by the upstream migration of intermittently spaced channel scarps. In other valleys, such as Well Canyon and Fox Creek, accumulation of the late Recent alluvium has evidently proceeded without the interruption of valley incision.

In the upper reaches of Dry Creek, where the previously untrenched valley flat is being trenched by headward migration of a major channel scarp, the silty late Recent alluvium consists of a banded

FIGURE 193.—Banding in late Recent alluvium, Dry Creek. (SW¼NE¼ Sec. 29, T. 9 N., R. 27 W.)

upper part, about 14 feet thick, and a lower part that is indistinctly banded and lighter in color. (See fig. 193.) The dark bands of the upper part are somewhat more clayey than the light bands, and the dark color is a result of a finer texture and a higher content of organic matter. Both light and dark bands are composed mostly of loosely consolidated silt, through which abundant fragments of carbonized grass stems are scattered. Earth-worm castings are a conspicuous feature of the upper banded part, but they are less apparent in the more compact silt of the lower part.

A similar division of the late Recent alluvium of Elkhorn Canyon into an upper part that is banded and a lower part that is indistinctly banded has already been described. The banded fill is attributed to a rate of accumulation so rapid that time has not been available for oxidation of finely divided organic matter in the clayey bands. If the accumulation of banded fill began at the same time on Dry Creek as on Elkhorn Canyon, the banded fill shown in figure 193 has accumulated during the past 500 years, approximately. This corresponds to an average rate of accumulation of about 0.34 inch per year, although the appearance of the banding indicates that the rate of accumulation was not uniform.

The banded alluvium seems to be characteristic of valleys that are being actively trenched, whereas the more compact unbanded alluvium is characteristic of more stable valleys. For example, the alluvium beneath the valley flats of Well Canyon and Fox Creek, which are not being actively trenched, is unbanded. On the other hand, distinctly banded alluvium is exposed in the walls of rapidly advancing trenches on Dry Creek and Curtis Creek Canyon.

The present rate of accumulation of alluvium on valley flats must be known in order to relate sediment discharge by streams from the drainage basin (sediment yield) to the amount of sediment that is eroded from uplands and valley-side slopes (gross erosion). In spite of a thorough search, exposures of the late Recent alluvium yielded no artifacts nor other materials that would give an accurate indication of the rate of accumulation. Valley flats in many localities were examined after runoff events, and the depth of accumulation of freshly deposited sediment was measured. The thickness of the freshly deposited silt layer ranges widely (from a fraction of an inch to about 6 in.) from one locality to another, and almost as great a range was observed from place to place at a single locality. Moreover, freshly deposited alluvium may either remain at its place of deposition or be removed during the next runoff event. Farmers were asked about the time required for fenceposts on the valley flat to become wholly or partly buried. In the upper part of Dry Creek, two farmers estimated independently that 5 or 6 feet of sediment had accumulated on the valley flat between 1920 and 1953. On Well Canyon one farmer estimated an accumulation of 2 feet on the valley flat in the past 40 years (1916–56) and another estimated an accumulation of 2 feet in the past 30 years (1926–56). On Medicine Creek, about 4.5 miles north of Cambridge, a farmer reported that the wire of a hogpen, last used before the 1935 flood on Medicine Creek, was buried to a depth of 6 feet by 1957. An average rate of accumulation of about 1 inch per year on the valley flats of the drainage basin is probably of the right order of magnitude. A range between ½ inch and 3 inches is estimated, and this range would be found not only from valley to valley but also from place to place within the same valley.

The rate of accumulation of alluvium within a trenched channel, downstream from an actively advancing channel scarp, must be considered separately from the rate of accumulation on an untrenched valley flat. Examination of freshly deposited alluvium on the floor of trenched channels, several hundred feet downstream from an actively advancing channel scarp, indicates that 0.5 foot or more of alluvium can be deposited during a single runoff event. At several localities on Dry Creek, tin cans and wire were found buried to a depth of several feet in alluvium that had accumulated on the floor of the trench. Evidently, alluvium accumulates rapidly in trenched channels but is susceptible to removal by a second episode of trenching.

SIGNIFICANCE OF CARBONIZED FRAGMENTS OF GRASS

In this region the younger a fluvial deposit is, the darker is its color. The dark color is due in part to finely divided organic matter and in part to fragments of carbonized grass stems, which are more abundant in the younger deposits. The carbonized fragments are attributed to grass fires, inasmuch as uncarbonized plant fragments would decay in this environment. The scarcity of carbonized stems in the older deposits might mean that grass fires were uncommon during the deposition of these deposits, or it might mean that any fragments originally present have been destroyed by oxidation or by the activities of earth worms. In an effort to decide between these alternatives, five thin sections of the Stockville terrace deposits, one thin section of the Mousel terrace deposits, and two thin sections of the late Recent alluvium were examined. In mineralogy, degree of development of clay coatings around grains, and packing of particles, all these thin sections were similar to thin sections of loess. However, the upper Recent alluvium shows many open spaces, which are attributed mainly to the activity of earth worms. Although carbonized fragments in the Stockville terrace deposits are small, they show no signs of partial oxidation. The tentative conclusion is that grass fires were more common during deposition of the Mousel terrace deposits and the upper Recent alluvium than during deposition of the Stockville terrace deposits. A greater incidence of grass fires might reflect a drier climate, or it might reflect a greater use of fire drives as a method of hunting game. The extent to which fire drives were used by prehistoric man on the Great Plains is largely speculative (Wedel, 1961, p. 76).

SAND DUNES

The sand dunes within the Medicine Creek basin are part of a much larger dune area that is an outlier of the Sandhills of Nebraska. The geomorphology of the Sandhills has been briefly described by Smith (1955). In general, the dune relief in the Medicine Creek basin is irregular and hummocky, dominated by innumerable blowouts, most of which are stabilized by grass. However, an indistinct linear pattern was observed in aerial photographs of areas about 7 miles north and 10 miles northwest of Wellfleet. The pattern is made by low, discontinuous longitudinal dunes in subparallel arrangement. The dunes have a maximum length of about one-fourth of a mile, an average width of about 200 feet, and heights ranging from 10 to 30 feet; they show the furrowed crest that is typical of longitudinal dunes in the Sandhills. They are probably relicts of a more extensive dune system that has in most places been destroyed by blowouts but has in some places been modified into U-shaped dunes. Although the longitudinal dunes are oriented about N. 65° W., the ends of most of the U-shaped dunes are oriented more northerly. Elongated blowouts tend to be oriented at about N. 20°–30°W. Evidently, the prevailing wind direction has shifted since the formation of the longitudinal dunes. Most of the blowouts are clearly man induced, for they are associated with areas that formerly were or currently are cultivated.

The stream-dissected relief of the loess-mantled part of the basin is separated from the sand-dune relief by a transitional belt of ground that is intermediate both in relief and in particle size of underlying materials. The relief of this transitional belt is characterized by broad undrained depressions, generally elongated northward and separated by nearly level ground or by broad, rounded elevations. The underlying material, which is intermediate in particle size between dune sand and loess, is restricted to upland locations. The mixture of dune sand and loess, on which the Anselmo fine sandy loam and the Colby fine sandy loam are developed, is generally less than 3 feet thick and is underlain either by dune sand or by loess (Goke and others, 1926; Bacon and others, 1939). Because of seasonal shifts in wind direction, silt from the loess-mantled areas has become mixed with sand from the dune areas.

In general, the dune sand does not seem to have transgressed very much over the loess-mantled areas since the end of deposition of the Peorian—that is, within the past 12,000 years. In areas bordering the Sandhills, the surface of the Wellfleet terrace is generally free of windblown sand.

ARCHEOLOGY AND HUMAN OCCUPATION

RESULTS OF ARCHEOLOGIC INVESTIGATIONS

Archeologic investigations have been made in the Medicine Creek basin by the Nebraska State Historical Society, by the Nebraska State Museum, and by the River Basin Surveys of the Smithsonian Institution. Three cultural aspects have been distinguished. These are represented by the Early Lithic sites, which are buried about 35 feet beneath the surface of the Stockville terrace (Terrace-2); by Woodland sites on the Mousel terrace (Terrace-

1); and by Upper Republican sites on the Stockville terrace.

Personnel of the University of Nebraska State Museum have excavated two sites on Lime Creek, designated Ft–41 and Ft–42, and one site on Medicine Creek about a half a mile downstream from the mouth of Lime Creek (Ft–50). All these sites are in the lower part of the Stockville terrace (Terrace-2) at occupation levels marked by abundant artifacts and many hearths. No human remains were found. Schultz and others (1951), who investigated both the geologic and archeologic aspects of the sites, report dates of 9,167±600 years B.P. and 9,880±670 years B.P. from two charcoal samples taken from the bone-artifact zone of site Ft–41. A charcoal sample from the lower occupation zone of Ft–50 yielded a date of 10,493±1,500 years B.P.

Two Woodland sites in the Medicine Creek Dam area are described by Kivett (1949). Habitation areas (marked by shallow basins, post molds, shallow pits, flint tools, and scant pottery fragments) were on the Mousel terrace (Terrace-1) and were covered by about 18 inches of silt. The remains give Wedel (1949) the impression of a rather uncertain hold on the region by a culturally simple group. According to Kivett, calcite-tempered ware found at the site is a marker for the Keith focus, which is one of several western Woodland cultural complexes. Although no radiocarbon dates were obtained at the Woodland sites on Medicine Creek, a radiocarbon date of 1,343±240 years B.P. has been obtained from a Keith-focus site on Prairie Dog Creek in northern Kansas, about 60 miles southeast of the Medicine Creek sites (Wedel and Kivett, 1956).

The Upper Republican Aspect represents the latest wholly prehistoric culture on Medicine Creek and is the most abundantly represented by archeologic remains, which are on the Stockville terrace and are buried under a silt mantle 6 to 18 inches thick (Kivett, 1949). The date of the culture is estimated to be about 500 to 600 years B.P. (Kivett, oral commun., 1957).

The geologic significance of these archeologic researches may now be considered. Radiocarbon dates on charcoal from occupation levels in the lower part of the Stockville terrace indicate that deposition of the Stockville terrace deposits began about 10,000 years ago. If the Woodland sites on the Mousel terrace do indeed belong to the Keith focus and if this focus is correctly dated, then the terrace is older than 1,300 years. The silt mantle ranging in thickness from 6 to 18 inches covers Woodland sites on the Mousel terrace and Upper Republican sites on the Stockville terrace. Most of the sites are not adjacent to upland areas from which colluvium might be readily derived, and no fluvial sedimentary structures were observed. Probably most of the silt was deposited on both cultural sites by the wind after the passing of the Upper Republican Aspect—that is, during the past 500 years. Conditions under which the silt was deposited were of more than local magnitude, as the silt mantle appears on Upper Republican sites throughout the Republican River basin in southern Nebraska from Frontier County eastward to Webster County (Wedel, 1941). Probably the Upper Republican people inhabited the region during a wet period and emigrated about 500 years ago at the onset of a dry period. During the wet period a humic zone developed, which was buried by windblown silt accumulated during one or more later dry periods.

SETTLEMENT AND LAND USE

One of the first settlers of the basin came to the Stockville area in 1860. His dwelling was used for the formal organization of Frontier County in 1872, when the population of the county consisted of a few stockraisers and only two permanent settlers. Through the later 1870's, settlers gradually entered Frontier County, and a little village arose at Stockville. By 1880 farmers had begun to claim land and to settle on the divides. Until the Free Range Law was repealed in 1885, farming on the uplands was of little consequence. By 1900 most of the desirable land had been taken under the Homestead, Timber Claim, and Preemption Acts.

Bacon and others (1939) note that corn has been the main crop since farming began. The first settlers did not understand how to adjust their farming methods to the highly variable precipitation, and their practices were crude and wasteful. A series of dry years, accompanied by plagues of grasshoppers, culminated in the disastrous droughts of 1893 and 1894. Many of the early farmers were forced to leave the region, and agricultural development was delayed. The farmers who remained acquired larger holdings and gradually adjusted their farming methods to local conditions. Although corn remained the most important crop, increasing amounts of wheat, oats, rye, barley, and sorghums were grown.

Census figures have not been published for the basin as a unit, but satisfactory approximations of the population may be made from the precinct census. The total population was 7,750 in 1930, 6,400 in 1940, and 5,900 in 1950. The total population of the basin decreased by 23 percent between 1930 and 1950, and the proportion of persons living in the towns has increased from 42 percent in 1930 to 51 percent in 1950. Population density of the basin in 1950 was 8.7 persons per square mile.

The number of settlers and domestic animals in the basin before 1875 was too small to have any significant effect on erosion and deposition. The sparseness of the grass cover on the uplands during 1869–72 reported by surveyors cannot be attributed to grazing by livestock. According to the Federal census, cattle and horses in Frontier County increased from about 30,000 in 1890 to about 43,000 in 1935. Farming could have had little geologic importance before 1879, when, according to the Federal census, only about 600 acres in Frontier County had been plowed. Only about 104,000 acres of plowed land was reported in Frontier County in 1889, whereas about 425,000 acres was reported in 1929.

DRAINAGE SYSTEM

EVOLUTION OF THE DRAINAGE SYSTEM

According to the stratigraphic evidence presented in this report, major valleys of the Medicine Creek basin, such as Cut Canyon and Cedar Creek, were in existence during the Kansan Glaciation, and their bedrock floors were at about the same depth as at present. In the Republican River valley also, the bedrock floor has not been deepened since Kansan time according to a geologic section of the river valley near McCook, Nebr. (Bradley and Johnson, 1957 pl. 38). Drilling along two traverses between the Republican and the Platte Valleys (figs. 183 and 184) revealed buried valleys, cut into the Ogallala Formation and filled with pre-Wisconsin deposits. These valleys, which evidently had an eastward trend, were probably filled with alluvium and abandoned in Nebraskan or early Kansan time. Plum Creek, which flows eastward into the Platte River, is probably a relic of the early Pleistocene drainage. Deposits of Pearlette Ash Member of the Sappa Formation of Kansan age are distributed along the valley of Plum Creek and its former westward extension, which was captured by Deer Creek after deposition of the Peorian.

The valleys of most major tributaries (fifth and higher order) were established by incision and probably by extension of the drainage system during the episode of incision that followed deposition of the Sappa Formation. These incised valleys were subsequently filled with the Loveland Formation to levels that are generally 10 or 20 feet above the modern valley flats. Most valleys of lower order than fifth were probably not in existence in Sangamon time, for the Sangamon soil does not dip toward them.

There is no evidence of extension of the drainage system between the end of Sangamon time and the initial deposition of loess of the Peorian, although the valleys may have been incised. After about half of the total thickness of the Peorian had accumulated on the uplands, the valleys were incised to bedrock. The incision was followed by an episode of deposition during which the upper part of the Peorian accumulated in the valleys and on the uplands.

The landscape as it existed at the end of deposition of the Peorian can be reconstructed (fig. 194) from remnants such as those shown in figure 195 (*upper*). In a few places, as for example at the eastern tip of Dry Creek, the valley heads of Peorian time have been preserved. Deposition of the Peorian Loess and development of the Brady soil are tentatively assigned to the interval 60,000 to 12,000 years B.P.

The drainage system was developed to approximately its present pattern and extent during the episode of incision that followed deposition of the Peorian (fig. 194*B*). The incision is perhaps associated with a rapid retreat of late Wisconsin ice sheets and a rather abrupt climatic warming about 11,000 years B.P., the evidence of which is presented by Broecker and others (1960). Valleys were probably incised to about the same bedrock altitudes as during previous erosional episodes, but drainage was gradually increased. The extent of incision and increase in drainage density is strikingly shown in an area just outside the Medicine Creek basin, where the head of North Plum Creek was captured by Deer Creek. Although the Deer Creek drainage was incised about 100 feet below the surface of the Peorian, the North Plum Creek drainage just east of the point of capture was not incised, and the surface of the Peorian has been preserved almost intact. (See fig. 196.)

The lengthy duration of the episode during which the Stockville terrace deposits accumulated is indicated by extensive grading of valley-side slopes and valley heads to the level of the Stockville terrace. In profile, the valley-side slopes that join the Stockville terrace to the upland are straight for most of their length, gently convex upward at their intersection with the upland and gently concave upward at their intersection with the terrace. Most of the slopes are graded across the Peorian, but some are graded across older rock units, including the Ogallala. Accumulation of the Stockville terrace deposits and grading of slopes are assigned tentatively to the interval between the climatic warming of about 11,000 years B.P. and the middle of the Altithermal, about 5,000 B.P. The Stockville terrace and slopes graded to the terrace can be identified nearly every-

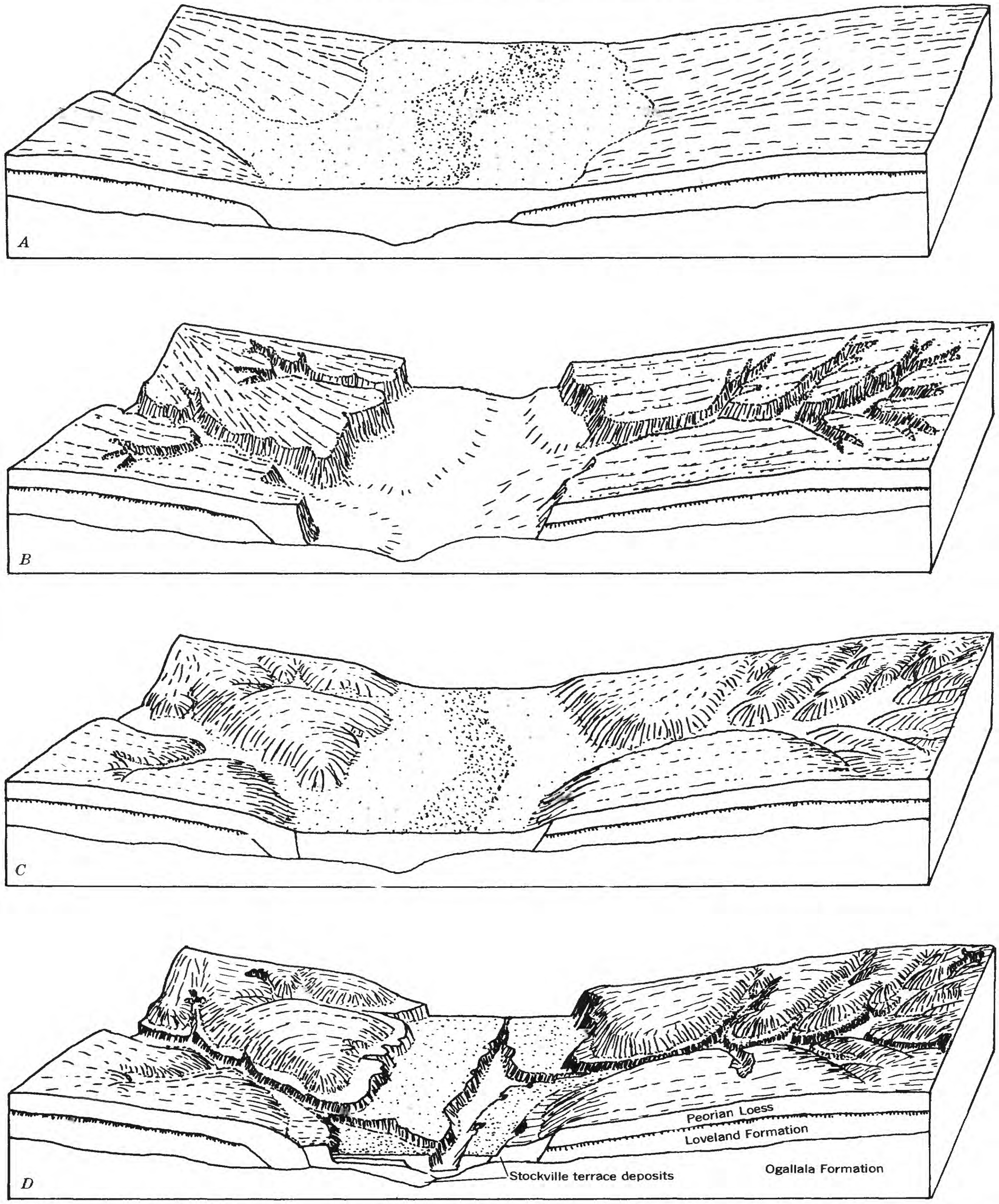


FIGURE 194.—Evolution of the relief since deposition of the Peorian Loess. *A*, Valleys were broad and valley sides gently sloping at end of deposition of the Peorian, about 12,000 years B.P. *B*, Drainage system was incised, extended, and branched during episode that lasted from about 12,000 to 11,000 years B.P. *C*, Valley sides and valley heads were graded during accumulation of Stockville terrace deposits, from about 11,000 to 5,000 years B.P. *D*, Relief was modified during the several episodes of incision and deposition that occurred during the past 5,000 years.

FIGURE 195.—Remnants of the side slopes and valley flats of former drainage systems. *Upper*, Looking south from the Platte-Republican drainage divide (in the NE¼ sec. 31, T. 11 N., R. 28 W.) along a fourth-order tributary to Fox Creek. Remnants of the valley sides of Peorian time are preserved on the divides between side tributaries, and these remnants show the general aspect of the former valley. *Middle*, Looking north along Well Canyon in the SW¼ sec. 27, T. 10 N., R. 29 W. Gentle slope on horizon (left) is slope of valley side of Peorian time. Steeper converging slopes on horizon (left center) are slopes of valley side of Stockville time. Remnant of the valley flat of Stockville time is in middle distance, and below this is a remnant of the valley flat of Mousel time. Narrow trench on modern valley flat showed little or no change from 1937 to 1952. *Lower*, Looking southeast from the upper end of a fifth-order tributary to Cut Canyon, in the NE¼ sec. 26, T. 10 N., R. 29 W. Crest of interstream divides between side tributaries in background indicate approximate level of valley flat of Peorian time. Valley head in foreground was graded in Stockville time, as were the steep side slopes leading to it.

where in the basin and constitute a reference surface to which the incision of later erosional episodes can be related.

The Stockville terrace was formed at some time before 2,200 years B.P., which is the carbon-14 date obtained from Mousel terrace deposits on Dry Creek. Tentatively, the Stockville terracing is placed at about 5,000 years B.P., and the cause is assigned to drought during the Altithermal, which was a well-established warm-dry climatic episode that lasted from about 6,000 to 4,000 B.P. In minor valleys (of fifth and lower order) the effects of this terracing cannot generally be distinguished from the effects of the Mousel terracing. During one or the other of these two episodes of erosion, trenching extended to the heads of many minor valleys. Other minor valleys were trenched for only part of their length, and still others escaped being trenched.

Deposition of the Mousel terrace deposits began at some time before 2,200 years B.P. and ended at some time before 420 years B.P. (carbon-14 date from late Recent alluvium on Elkhorn Canyon). Tentatively, this deposition is assigned to the interval 4,000 to 1,000 years B.P., which corresponds roughly with the dates of the "Deposition 2" described by Miller (1958, p. 38) in his generalized alluvial sequence in Western United States. (See table 2.) The terracing of the Mousel terrace must have been brief, inasmuch as the thickness and properties of the late Recent alluvium indicate that not much less than a thousand years would be required for its accumulation.

A tentative chronology of post-Sangamon depositional and erosional episodes in the Medicine Creek basin is summarized below:

	Years B.P.
Local incision of valley bottoms	Present to 500.
Accumulation of late Recent alluvium	Present to 900.
Terracing of Mousel terrace	900 to 1,000.
Accumulation of deposits of Mousel terrace	1,000 to 4,000.
Terracing of Stockville terrace	4,000 to 5,000.
Accumulation of deposits of Stockville terrace.	5,000 to 11,000.
Incision and extension of the drainage system to approximately its present pattern.	11,000 to 12,000.
Accumulation of Peorian Loess and development of Brady soil.	12,000 to 60,000.

MORPHOMETRY

Detailed measurements were made of the drainage basins of six major tributaries of the Medicine Creek basin, the locations of which are shown in figure 176. The purpose of the measurements was to determine the drainage-basin characteristics that correlate most closely with water and sediment yield and with the development of gullies. Where gaging

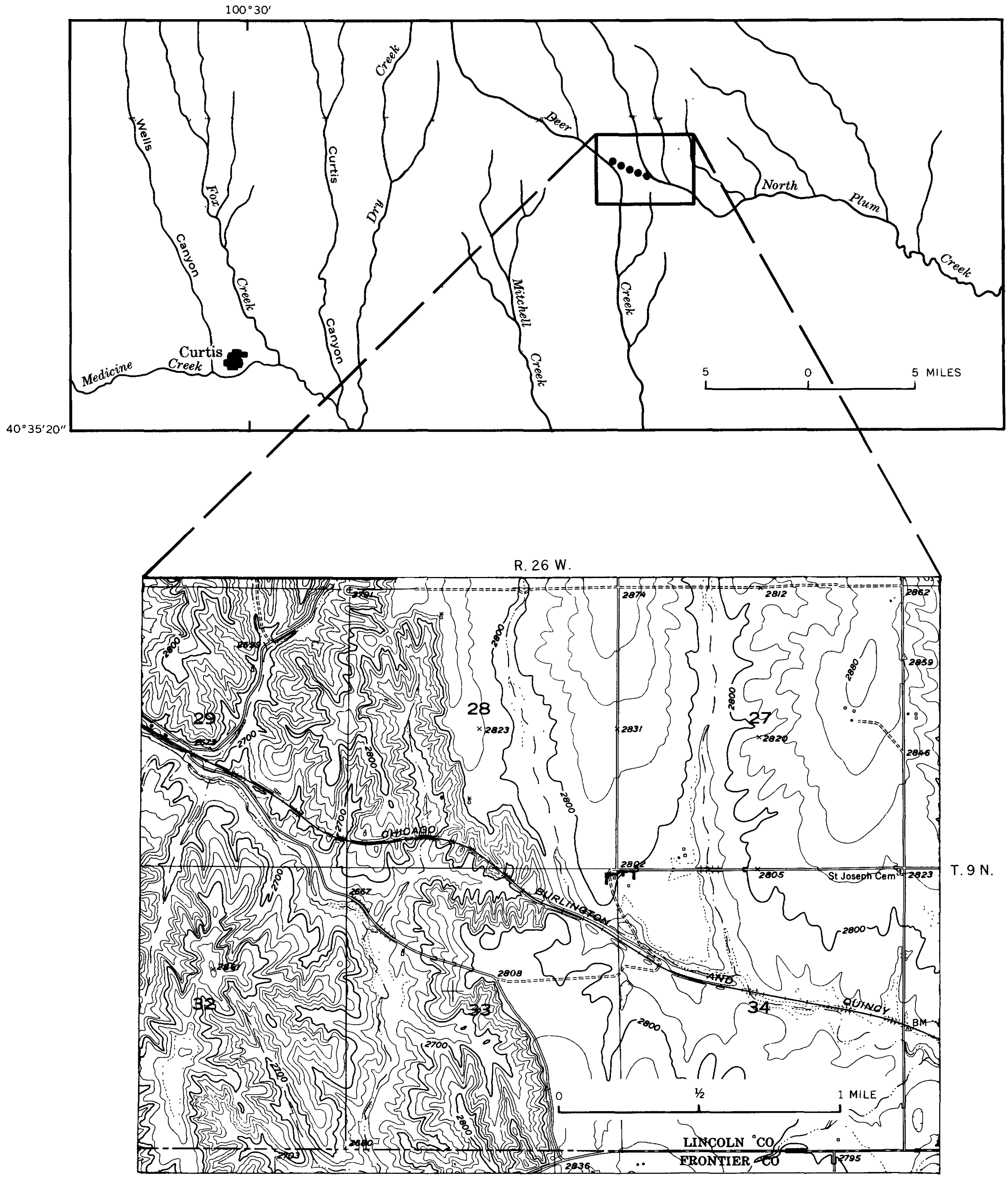


FIGURE 196.—Capture of head of North Plum Creek by Deer Creek. In inset, which is reproduced from the Stockville NE quadrangle, relict topography of the depositional surface of Peorian time is shown at right.

stations (also shown on fig. 176) are not at the mouth of a basin, only that part of the basin upstream from the station was measured.

Ordering of the drainage system was carried out according to the method of Strahler (1952, p. 1,120), which is a modification of the method of Horton (1945, p. 281). Strahler's method is not only more objective and convenient, but it is also more valuable for many hydrologic purposes. A channel segment of third or higher order obtained by Strahler's method is of approximately uniform cross-sectional area throughout its length, but this is not true of channels obtained by Horton's method. The word "channel" is used here in the same sense that the word "stream" is used by Horton and Strahler in connection with ordering. A channel is an established watercourse that may transmit water continuously, intermittently, or ephemerally. The flow of water in most channels of the Medicine Creek basin is ephemeral, and the term "stream" is inappropriate for them.

Properties of fluvially eroded landforms and recommended symbols for these properties are summarized by Strahler (1958, p. 282–283). The properties discussed in this report and the symbols used are listed below. Measured properties are those that can be directly measured or counted, and derived properties are those that cannot be directly measured but must be computed from measurements.

Measured properties:

- Total area of drainage basin, A
- Area of upland in drainage basin, Aa
- Area of valley system in drainage basin, A^* ($A^* = A - Aa$)
- Channel order, u (for examples: u_1, first order; u_2, second order)
- Number of channels of order u, N_u
- Channel length, L
- Channel length, mean length of segments of order u; L_u
- Basin relief, H
- Basin length, L_b

Derived properties:

- Channel slope, S_c
- Valley slope, S_v
- Bifurcation ratio, R_b

$$\left(R_b = \frac{N_u}{N_{u+1}} \right)$$

- Channel length ratio, R_L

$$\left(R_L = \frac{L_u}{L_{u-1}} \right)$$

- Channel frequency, F_u

$$\left(F_u = \frac{N_u}{A} \right)$$

- Adjusted channel frequency, F_u^*

$$\left(F_u^* = \frac{N_u}{A^*} \right)$$

- Drainage density, D

$$\left(D = \frac{\Sigma L}{A} \right)$$

- Relief ratio, R_h

$$\left(R_h = \frac{H}{L_b} \right)$$

- Elongation ratio, R_e

$$\left(R_e = \frac{\text{diameter of a circle}}{L_b} \right)$$

For practical purposes first-order channels in the Medicine Creek basin are defined as the lowest order of channels represented by V-shaped bends in contour lines on the available topographic maps. Fortunately, the accuracy of the topographic maps in representing small drainage channels is excellent, and the scale (1:24,000) and contour interval (10 ft) are also favorable for representation of small channels. Drainage patterns of several fifth-order basins were plotted both on aerial photographs and on topographic maps, and comparison showed that results obtained by the two methods were very similar.

Nearly all the first-order channels represented by V-shaped bends in contour lines are channels that formed immediately before or during accumulation of the Stockville terrace deposits, and the valley sides leading to these channels show some degree of grading. In only a few places has modern gullying proceeded far enough to form channels where no channels had existed previously.

Each of the six major subbasins was separately outlined on the topographic maps, and each subbasin area was measured with a polar planimeter. In addition, the area of upland in each subbasin was measured. Upland is defined as undissected remnants of the land surface that existed at the end of deposition of the Peorian. For practical purposes upland is distinguished on topographic maps by smooth contour lines—that is, by contour lines that do not have V-shaped indentations. Where areas of upland are continuous around the periphery of a drainage system—as in basins I–1′, A′, 0–4′, and C–2′ of figure 197—the area of upland was determined by measuring with a polar planimeter the area actually occupied by the drainage system and subtracting this area from total basin area.

For Dry Creek and Lime Creek, every channel of every order was drawn in color on topographic maps, counted, and measured individually. Sampling procedures, similar to those described by Leopold and Miller (1956, p. 16), were tested for the approximation of number, mean slope, and mean length of first- and second-order channels in the other subbasins. These procedures were used for Mitchell Creek, Well Canyon, Fox Creek, and Brushy Creek.

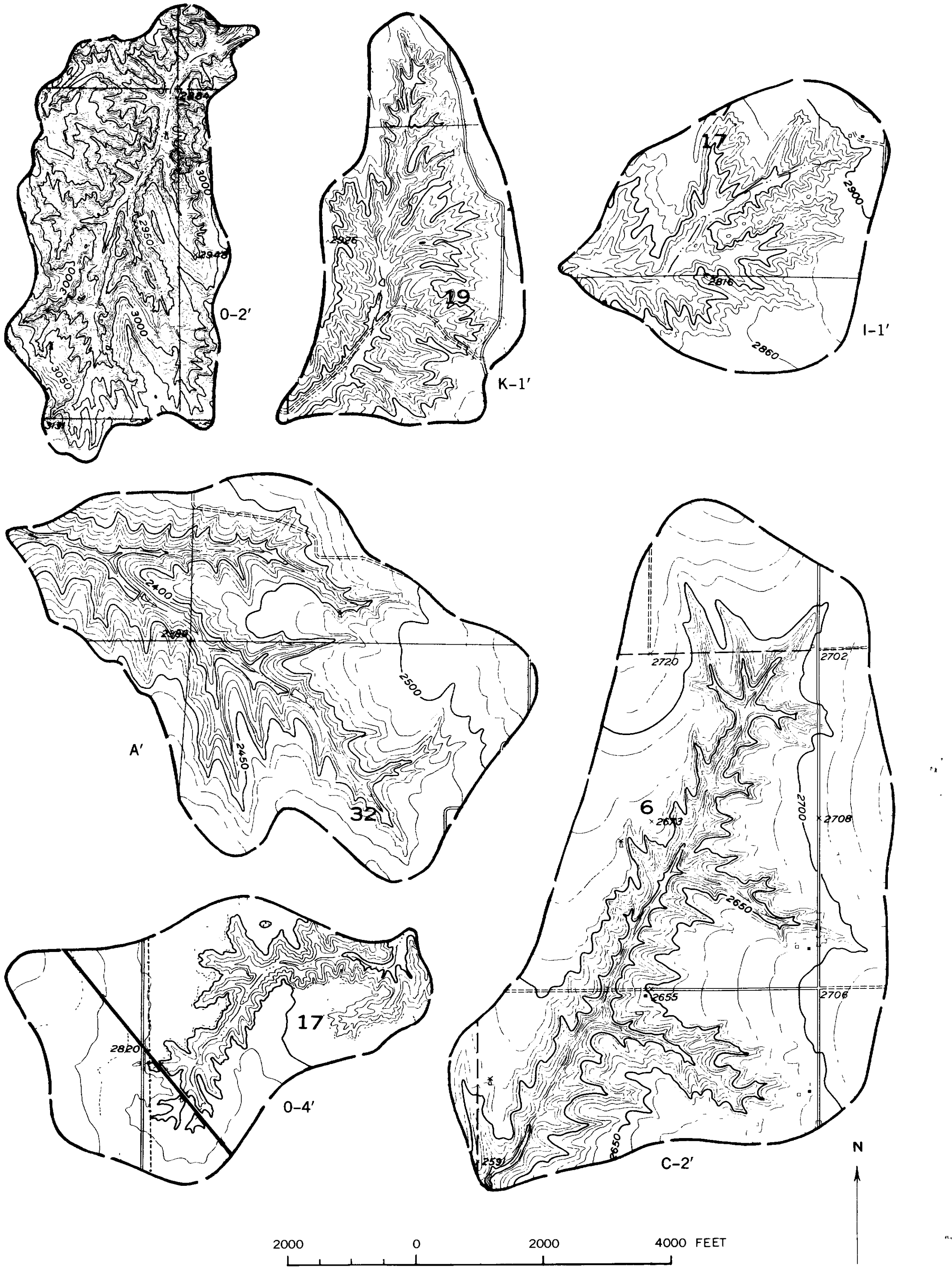


Figure 197.—Variations in drainage texture in the Medicine Creek basin. Basins shown are fourth or fifth order.

Two derived properties—drainage density and channel frequency—commonly are used but are ambiguous for so-called immature or youthful basins in which areas of undissected upland remain. For such basins a distinction must be made between the properties of the drainage system and the properties of the drainage basin. If a particular drainage system were transferred without any change in properties to a larger drainage basin, the values of drainage density and channel frequency would change regardless of the constancy of the drainage system. Drainage density is also ambiguous for another reason: a drainage system consisting of short channel segments may have the same total channel length as another drainage system that consists of fewer but longer segments. Melton (1958, p. 36) has proposed that the ratio of F/D^2 is constant for mature drainage basins, but this is not true of Medicine Creek, which for the most part is immature. To compare the channel frequency of two immature drainage systems whose drainage basins differ in percentage of upland, drainage basin area must be adjusted by subtracting the area of upland. Channel frequency, expressed as number of channels per square mile of area actually occupied by the valley system, is here called adjusted channel frequency.

Relief ratio was defined by Schumm (1956, p. 612) as the ratio between H, basin relief, and L_b, the longest dimension of the basin as measured parallel to the principal drainage channel. Basin relief is the difference in altitude between the highest and lowest points in the basin. A measure of basin shape, also devised by Schumm, is the elongation ratio, which is derived by dividing the diameter of a circle having area equal to that of the basin by the basin length, L_b.

A measure of mean valley-side slope is difficult to obtain because the side slopes leading to low-order channels are steeper than side slopes leading to high-order channels. For example, measurements on topographic maps indicate that slopes leading to first-order channels on the lower part of Dry Creek have a mean angle of about 25°, whereas slopes leading to the main channel (which is seventh order) have a mean value of about 12°. Slopes leading to the main channel of lower Dry Creek were measured in the field during the preparation of 12 transverse valley profiles. Of 23 slopes, 13 ranged from 8 to 11°, only 2 were greater than 15°, and none were less than 6°. The mean angle was 11.5°; the mean deviation, 3.3°; and the mode, 10°. Mean side slopes of third- and fourth-order channels probably represent the best approximation to mean values for the drainage system as a whole and are, therefore, quoted in table 3.

DRAINAGE TRANSFORMATION AND VARIATIONS IN DRAINAGE TEXTURE

Variations in drainage texture are accompanied by variations in most drainage-basin characteristics. The major variations in drainage texture within the Medicine Creek basin are illustrated by the representative fourth- and fifth-order drainage basins in figure 20. Basins 0–2′ and K–1′ are typical of the upper part of Medicine Creek; I–1′ and 0–4′, of the

TABLE 3.—*Measured and derived properties for the Medicine Creek basin and its major subbasins*

Drainage basin	Total area, A (sq mi)	Area of upland, A_a (percent)	Area of valley flat (percent)	Valley slope of main segment (ft per ft)	Mean valley side slope (ft per ft)	Mean upland slope (ft per ft)	Relief ratio, R_h	Elongation ratio, R_e	First-order channels: Mean length, L (ft)	First-order channels: Mean slope, S_c (ft per ft)	First-order channels: Adjusted frequency, F^*u (channels per sq mi)
Lime Creek	11.6	37.0	14.0	—	0.179	0.026	0.0114	0.662	410	0.110	140
Mitchell Creek	52.1	51.8	11.5	0.00299	.200	.013	.0050	.416	370	.100	165
Brushy Creek (above gage)	73.8	25.9	16.0	.00367	.412	.022	.0064	.734	192	.234	260
Dry Creek (above gage):											
Total	21.1	34.8	14.2	—	.360	.032	.0079	.475	267	.187	203
Upper only	12.6	25.0	—	.00550	—	—	—	—	260	.195	214
Lower only	8.5	49.5	—	.00366	—	—	—	—	287	.160	185
Fox Creek:											
Total	72.5	16.5	27.2	.00360	.363	.037	.0059	.445	250	.241	250
Upper only	57.0	12.6	—	.00386	—	—	—	—	—	—	—
Lower only	15.5	30.4	—	.00310	—	—	—	—	—	—	—
Well Canyon:											
Total	53.3	20.4	22.6	.00286	—	.036	.0052	.335	245	.251	235
Upper only	22.7	12.3	—	.00290	—	—	—	—	—	—	260
Lower only	30.6	26.5	—	.00284	—	—	—	—	—	—	220
Medicine Creek above gage above reservoir	549.0	30.0	—	—	—	—	.00435	—	—	—	200

central part; and A′ and C–2′, of the lower part. Major differences in these small basins, as in the larger subbasins of which they are representative, lie in the percentage of upland, the length and frequency of first-order channels, and relief ratio. These differences can be conveniently related to differences in geomorphic history.

In basins A′ and C–2′ valleys at the end of Peorian deposition were broad and shallow, and the gently sloping valley sides were graded all the way to the interstream divides. Divides were rounded, and no areas of flat upland remained. These valleys were deeply incised during the episode of erosion that preceded deposition of the Stockville terrace deposits, and channel frequency was increased. During accumulation of the Stockville terrace deposits, the transformed drainage system was smoothly graded, and the gently sloping tips of first-order tributaries were extended nearly to the former drainage divides. Basin C–2′ represents a less advanced stage of grading than Basin A′, which is nearer the mouth of Medicine Creek; it was incised first, and consequently underwent a longer period of grading during accumulation of the Stockville terrace deposits.

Basins I–1′ and 0–4′ are representative of the central part of the Medicine Creek basin, where the valleys at the end of deposition of the Peorian were more narrow than those in the lower part and were separated by broad, nearly flat uplands. Later, these valleys were deeply incised, and the drainage was extended into the upland; however, large areas were left undissected. The sides and heads of first- and second-order valleys were smoothed and somewhat reduced in angle during deposition of the Stockville terrace deposits, but they remained rather steep. The surface into which basin 0–4′ was incised is unusually flat, because it represents the valley flat and gently sloping valley side of Medicine Creek at the end of deposition of the Peorian.

In basin 0–2′, valleys at the end of deposition of the Peorian were narrow and steep sided (average slope angle about 14°). The channel frequency, already considerably higher than that in the lower part of Medicine Creek, was greatly increased during the episode of incision preceding deposition of the Stockville terrace deposits. Moreover, the newly incised valleys, although somewhat graded during Stockville time, retained their steep sides and heads. Later episodes of incision have further increased the frequency of first- and second-order channels. Basin K–1′ is similar in history, but it formed on a less steeply sloping surface and underwent a greater degree of grading during the deposition of the Stockville terrace deposits.

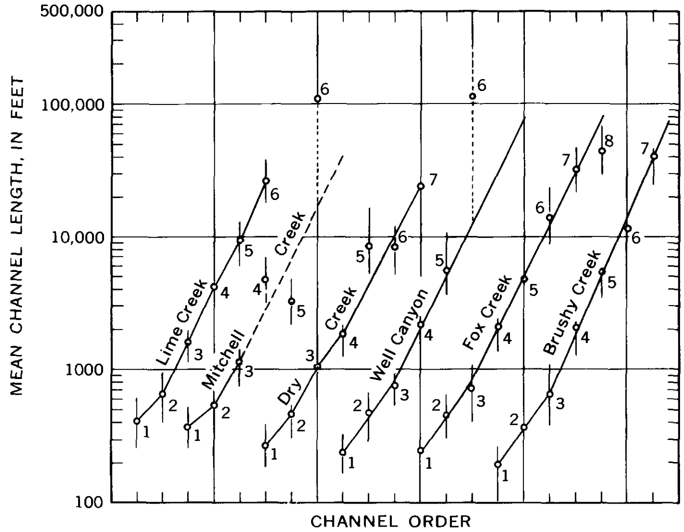


FIGURE 198.—Mean channel length in relation to channel order.

In summary, variations in the modern drainage pattern are related to two conditions that existed at the end of deposition of the Peorian—the extent of drainage transformation that preceded deposition of the Stockville terrace deposits and the amount of grading that took place during deposition of the Stockville terrace deposits. To a minor extent, the drainage pattern has been modified by episodes of incision that followed deposition of the Stockville terrace deposits. At the end of Peorian deposition, valleys were broad and shallow in the lower part of the basin, narrow and separated by flat divides in the central part, and narrow but separated by narrow divides in the upper part. Grading during deposition of the Stockville terrace deposits reached an advanced stage in the lower part of the basin, and in general the stage of grading decreases in an upstream direction.

The curves representing the relation of mean channel length to channel order (fig. 198) can be arranged in a sequence that illustrates some of the major variations in drainage texture. The length of channel segments (of orders one through five) shows a consistent decrease from Lime Creek, in the lower part of the basin, to Brushy Creek, in the central part. Also, R_L between orders one and two, as well as between orders two and three, is less than R_L between higher orders. The change in slope at the lower end of the curves applies only to orders one and two for Lime Creek, but it applies to orders one through four for Dry Creek and to orders one through three for Well Canyon, Fox Creek, and Brushy Creek.

An upward concavity of the curves representing the relation of mean channel length to channel order,

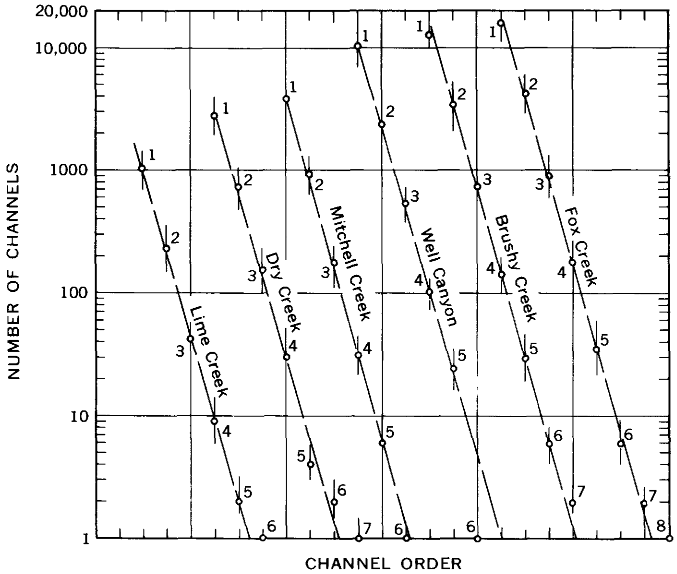


FIGURE 199.—Number of channels of each order in relation to channel order.

as plotted on semilogarithmic paper with channel order as independent variable, was noted by Strahler (1952) and Broscoe (1959, p. 5). Broscoe concluded that Horton's (1945) "law of stream lengths" may not apply when Strahler's method of ordering the drainage system is used. However, the basins analyzed by Strahler and Broscoe were of fourth or smaller order; basins of larger order must be analyzed for proper definition of the relation. In the Medicine Creek basin the relation is exponential, but the exponent changes at second or third order (fig. 21).

If a drainage system having low density of channels is transformed by the growth of new first- and second-order channels without extension of the higher order channels, a marked absolute shortening of lower order channels can take place without much shortening of higher order channels. The order of higher order channels may change, but the absolute length remains nearly constant. A transformation of this kind took place in the Medicine Creek drainage basin at the end of deposition of the Peorian. Furthermore, the transformation can take place without much change in the bifurcation ratio. The bifurcation ratios of the same subbasin, as well from one subbasin to another, are remarkably constant. (See fig. 199.) One result of a transformation of the kind described is a change in slope, at lower channel orders, of the curve relating mean channel length to channel order. The major subbasins that have undergone the greatest drainage transformation and, consequently, have the highest frequency of first-order channels are those that show the change in slope extending to third or even fourth order. In a sense the change in slope of the curve relating mean channel length to channel order is a measure of disequilibrium of the drainage system.

GULLY EROSION

DEFINITION AND CLASSIFICATION OF GULLIES

In a region such as the Medicine Creek basin, where many of the drainage channels have steep, unvegetated sides and are incised in massive silt, the distinction of a gully from other drainage channels is difficult. According to general usage, the essential features of a gully are its size (which is larger than a rill), recency of extension in length, steepness of sides and head, incision into unconsolidated materials, and ephemeral transmission of flow. Gullies in the Medicine Creek basin are incised into the sides, head, or bottom of previously established drainageways, which are deepened or extended by development of the gully. The lower limit of depth for a gully is placed at about 2 feet because channel head scarps that are less than 2 feet in height show a very slow rate of advancement. Most of the actively advancing head scarps in the Medicine Creek basin are greater than 6 feet in height. The lower limit of width is arbitrarily placed at about 1 foot. The criterion of recency of extension requires that some evidence be obtained for extension within a period of a few years. Extension can be established by comparison of aerial photographs, by comparison of field measurements made at intervals of a few years, or by indirect evidence observed in the field. If the sides and head of a drainage channel have a slope less than about 45°, the channel is probably not actively advancing and hence would not be considered a gully. In this report the following definition of a gully is followed: A gully is a recently extended drainage channel that transmits ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than about 1 foot, and a depth greater than about 2 feet.

The sides and heads of gullies in the Medicine Creek basin are steep slopes, straight in profile, that are here called erosional scarps or simply scarps.

In addition to the erosional scarps at the sides and heads of gullies, other erosional scarps are conspicuous elements of the landscape. These include step scarps on slopes (Brice, 1958), scarps that form the fronts of terraces, and scarps at the base of valley-side slopes. The inclination of a scarp ranges from about 45° to nearly 90°, and the height ranges from a foot to about 40 feet. Generally, the top of a scarp meets the surface into which it is cut at a sharp angle, but the base of the scarp decreases in slope as it merges with the surface below. The term "channel scarp" is appropriate for a scarp that forms a break in the long profile of a well-defined channel. If a particular channel scarp is the headward terminus of a gully and attention is to be drawn to this fact, the channel scarp may be called a head scarp. Not all gully head scarps are channel scarps. The term "head cut," although commonly applied to the headward terminus of a gully, is unsatisfactory because it may refer either to the scarp at the head of a gully to to the whole gully head. Moreover, a channel may have many scarps along its length, and the designation of several of these as head cuts is confusing. The scarps that form the sides of a gully along its length are here called side scarps.

Study of gullies in the field and on aerial photographs of the Medicine Creek basin has shown that the depth of a gully, its areal pattern, and its rate of growth are more closely related to the topographic position of the gully head than to any other single factor. Of particular significance is the location of the gully head in relation to the previously established drainage system. On the basis of location, gullies are classified as valley-bottom gullies, valley-head gullies, and valley-side gullies. Inasmuch as valley bottoms grade smoothly into valley heads and valley sides, the distinction among the different classes of gullies is arbitrary. Moreover, a valley-bottom gully becomes a valley-head gully as its head scarp migrates into the valley head. The valley-head gullies are by far the most numerous kind, and nearly all of these are in steep valley heads that border areas of upland.

The size of a gully depends on its depth and areal dimensions; but because of the irregular shape of gullies, the areal dimensions cannot be expressed simply and consistently. For complexly branching gullies, it is not clear whether or not the unconsumed area between the branches should be considered part of the gully. The best approximation to an expression of gully size seems to be the maximum width of the gully head. Inasmuch as gully depth increases roughly in proportion to width of gully head, the width of the gully head is an indirect expression of gully depth. In an arbitrary ranking of gullies according to width of gully head, valley-side and valley-bottom gullies must be considered separately from valley-head gullies, which are relatively wider in proportion to depth.

AGE AND ACTIVITY OF EROSIONAL SCARPS

Obviously, a scarp is younger than the surface into which it is cut. All the scarps in the Medicine Creek basin are considered to be younger than the Stockville terrace deposits. Some of the slopes graded to the level of the Stockville terrace are steep, especially those in the upper parts of the drainage basin; but these slopes are not regarded as scarps because they have an inclination less than 45°. Also, the steepest part of these slopes (in a particular area of the basin) is graded to about the same angle, and the upper parts of the slopes decrease in angle as they merge with the older Peorian surfaces.

Regardless of the age of the surface it cuts, a scarp may be either active or inactive. A scarp is considered to be active if it has migrated a distance that can be measured by comparing of aerial photographs made in 1937 and in 1952 or if it shows field evidence of recent movement. In the field, inferences as to activity were made from the type of vegetation on the scarp, from the degree of inclination, or from evidence of recent or imminent slumping. A thick sod of native grass indicates an inactive scarp; a cover of brush (such as wild rose, buckbrush, or currant) indicates a moderately active scarp; and lack of vegetal cover, or a cover of weeds, indicates an active scarp. In general, the more nearly vertical a scarp, the more likely it is to be active. However, many scarps that were bare and nearly vertical showed little or no migration during the interval 1937–52. Even a bare and nearly vertical scarp was not regarded as active unless recently slumped silt was observed at the scarp base or unless fissures were observed on the ground surface beyond the scarp.

CHANNEL SCARPS AND VALLEY-BOTTOM GULLIES

Varieties of valley-bottom gullies are distinguished on the basis of position with respect to one another and to different topographic levels produced by trenching of the drainage system. The main varieties are indicated by numerals in figure 200. The two gullies at upper left (1), which are in the same valley bottom but are separated by a reach of undissected valley, are of the sort called discontinuous by Leopold and Miller (1956, p. 29). When the head scarp of a downvalley gully reaches the tail of an upvalley gully, a stage of coalescence is reached; and the two gullies are integrated into a single trench as the downvalley scarp advances. Similarly, the advance of a major scarp in a large valley is commonly preceded by the advance of a minor scarp (2). A scarp may be initiated on the floor of a trench, where it may advance either into freshly deposited sediment (3) or into previously undisturbed alluvium. Channel scarps on the floor of a

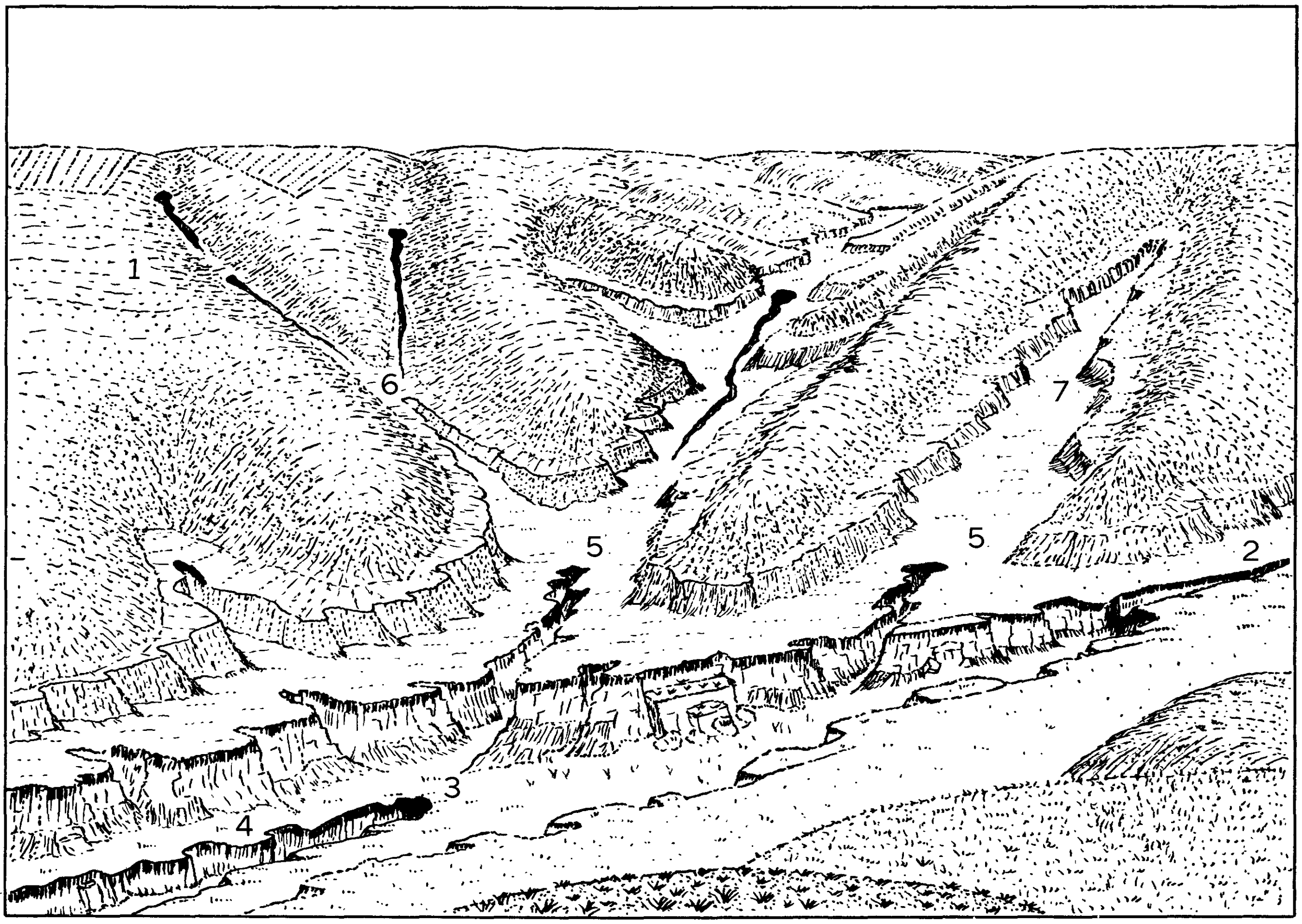


FIGURE 200.—Composite sketch, based on field sketches and photographs, showing the different varieties of valley-bottom gullies. Actively eroding scarps are indicated by darker shading. Numbered features are described in text.

trench are here described as inset. Remnants of the original gully floor, left along the gully sides after passage of an inset scarp, constitute an inset terrace (4). Another variety of valley-bottom gully is illustrated by the two gullies (5) in the middle ground of figure 200. Unlike the discontinuous gullies, which have no relation to the topographic level formed by trenching elsewhere in the drainage system, these gullies were initiated at the side scarps of the gully in the foreground and are accordant with its floor.

The location of the head scarps of major valley-bottom gullies in the Medicine Creek basin is shown in figure 201. Most of the gullies are in the size category of very large, but some are in the category of large. The scarps range in height from 10 to 25 feet and are in valleys of fourth or higher order. Advance of the scarps during the period 1937–52 ranges from a maximum of about 3,400 feet (for gully B4 on fig. 201) to a minimum of about 200 feet. Two significant facts relevant to the origin of the scarps are indicated by their areal distribution: Scarps are most numerous in the central and lower part of the basin, and scarps in large valleys are commonly upstream from the confluence of a large tributary.

The greater abundance of the scarps in the central and lower part of the basin is attributed to the relative narrowness of the valley bottoms there. (See table 4.) In general, the width of a valley bottom is much affected by the degree of trenching both before and after deposition of the Stockville terrace deposits. The branching valley at upper left (6) in figure 200 was represented by a relatively narrow and shallow trench before deposition of the Stockville terrace deposits. During deposition of the Stockville terrace deposits the valley sides were graded, and the valley has been little affected by post-Stockville trenching. By contrast, the valley at upper right (7) was represented by a relatively deep and wide trench before deposition of the Stockville terrace deposits. Post-Stockville trenching has extended to the valley head, and only narrow

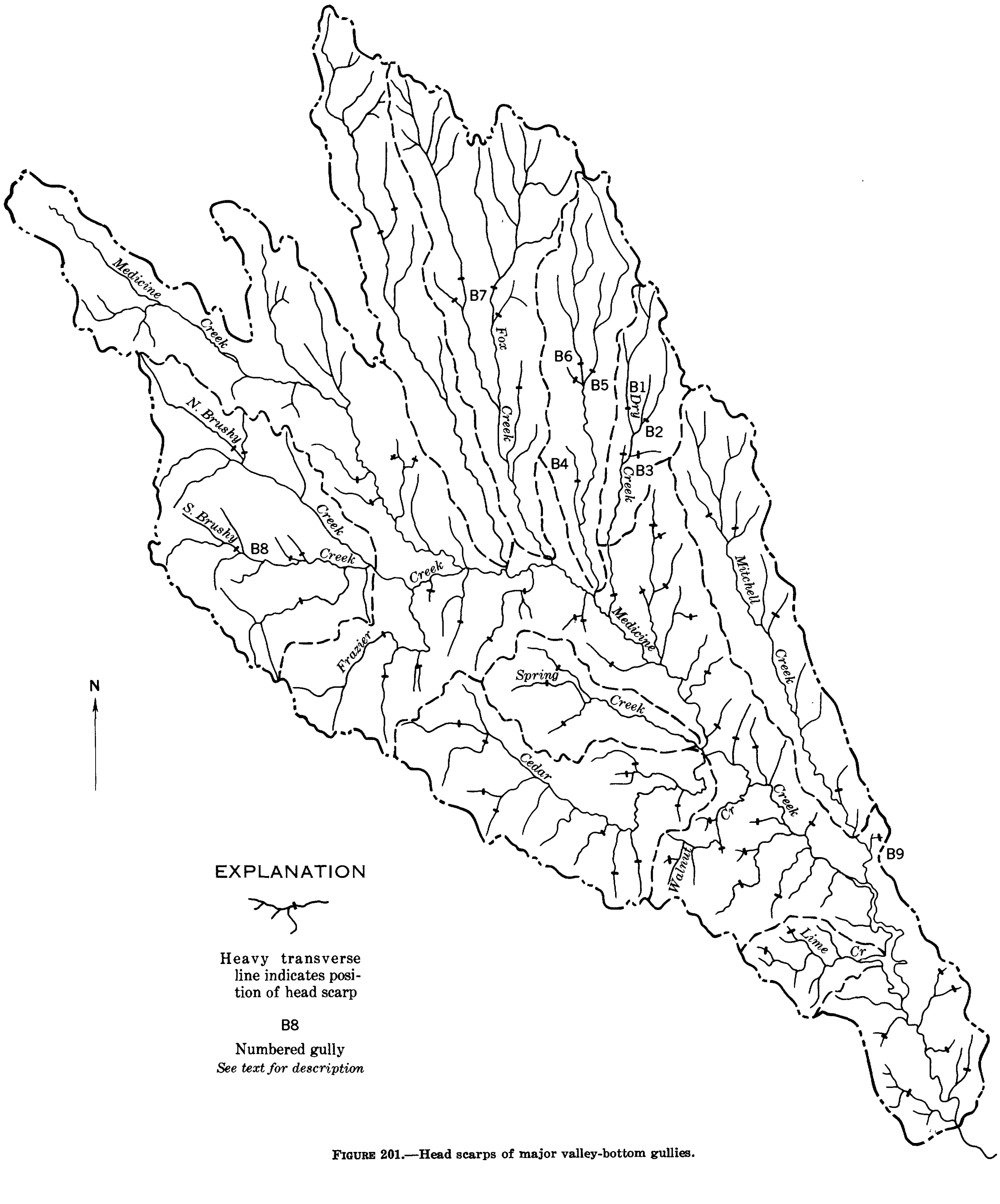


FIGURE 201.—Head scarps of major valley-bottom gullies.

TABLE 4.—*Drainage system properties, listed according to channel order, for major subbasins of the Medicine Creek basin*

Subbasin	Channel order	Number of channels	Mean channel length (ft)	Mean channel slope (ft per ft)	Mean width of valley flat (ft)	Area of valley flat (sq mi)
Lime Creek	1	1,020	410	0.1100	25	0.37
	2	233	670	.0517	50	.28
	3	42	1,600	.0185	105	.25
	4	9	4,110	.0111	120	.16
	5	2	9,200	.00545	150	.10
	6	1	26,000	.00384	500	.47
Mitchell Creek	1	3,940	370	.100	35	1.83
	2	950	537		55	1.00
	3	172	1,170		90	.68
	4	31	4,970		140	.77
	5	6	3,320		160	.11
	6	1	114,000		400	1.63
Dry Creek	1	2,824	267	.187	35	.95
	2	725	458	.0673	60	.71
	3	153	1,023	.0343	96	.54
	4	30	1,816	.0155	125	.24
	5	4	8,830	.0088	160	.20
	6	2	8,600	.00576	200	.12
	7	1	25,500	.00296	260	.24
Well Canyon	1	10,310	245	.251	35	3.17
	2	2,460	480		70	2.85
	3	545	772		110	1.75
	4	104	2,195		140	1.23
	5	24	5,375		190	.88
	6	1	126,000		545	2.18
Fox Creek	1	15,900	250	.241	35	4.98
	2	4,250	460	.100	70	4.90
	3	904	725	.0465	120	2.82
	4	177	2,040	.0215	150	1.94
	5	35	4,085	.0101	190	.97
	6	6	14,850	.0055	270	1.71
	7	2	32,000	.00406	440	1.01
	8	1	45,000	.00274	880	1.40
Brushy Creek	1	12,400	192	.234	35	2.99
	2	3,500	370		60	3.39
	3	729	674		95	1.67
	4	147	2,040		135	1.44
	5	29	5,450		165	.93
	6	6	12,833		240	.66
	7	2	40,500		300	.87

remnants of the Stockville terrace remain along the valley sides. The valley at right in figure 200 is typical of the upper part of the Medicine Creek basin; and the valley at left, of the central and lower part.

The association of major channel scarps with the confluence of a large tributary is notable on Fox Creek, Cut Canyon, Curtis Creek Canyon, and Well Canyon. Although the present scarps are upvalley from the tributary confluence, the possibility is good that the scarps were initiated at the confluence, where the slope of the main valley may be locally steepened. After a valley floor has been trenched, its long profile cannot be accurately reconstructed; however, long profiles drawn from contours at 10-foot intervals on the topographic maps indicate that the main valley profile is generally, but not everywhere, steepened upstream from the confluence of a large tributary. (See fig. 202.) On Curtis Creek Canyon a conspicuous steepening of the valley profile just upstream from the confluence of a large tributary is indicated on the topographic map. The steepening is probably due to deposition of a fan at the mouth of a tributary. This fan ponds the drainage in the main valley and leads to deposition upstream from the fan. Schumm and Hadley (1957) have shown that, in small drainage basins in eastern Wyoming and northern New Mexico, discontinuous gullies can form on locally steep valley reaches.

The proposal that gullies are initiated at a local steepening of the valley slope has as a corollary the proposal that local slope in an ungullied valley reach may be adjusted to water discharge. In the absence of discharge measurements for most valley reaches, the assumption may be made that the discharge in a reach is proportional to the upstream drainage area. The relation of local valley slope to drainage area for reaches along three valleys is shown in figure 203. Cut Canyon and Dry Creek are free of major channel scarps in their uppermost reaches, as shown in figure 202, but Coyote Creek has channel scarps throughout most of its length. In spite of the fact that the floors of all three valleys are well above bedrock, local slope is not constant in a given valley reach several hundred feet in length. The values of local slope plotted in figure 203 represent the best approximation obtainable from topographic maps for mean local slope in a reach bounded by contours and having a fall of 20 feet.

A general relation between local valley slope and drainage area is apparent from figure 203. Slope values applying to gullied reaches tend to plot above the average curve representing this relation, but some slope values applying to ungullied reaches also plot above it. Aside from chance, factors other than local slope and drainage area seem to be involved in the initiation of gullies, and the most important of these is probably valley width. The upstream reaches of Coyote Creek have a greater susceptibility to gullying than reaches of Cut Canyon because of the relative narrowness of the valley bottom of Coyote Creek.

The main valley of Well Canyon is relatively free of gullies, and the few gullies present have grown slowly. The channel scarps in the long profile of Well Canyon (fig. 202) did not advance during the interval 1937–52 by an amount measurable on aerial photographs nor did the intricate small-scale meanderings of the trenched channel reaches show any observable change. The aspect of a trenched channel on Well Canyon is shown in figure 195 (*middle*).

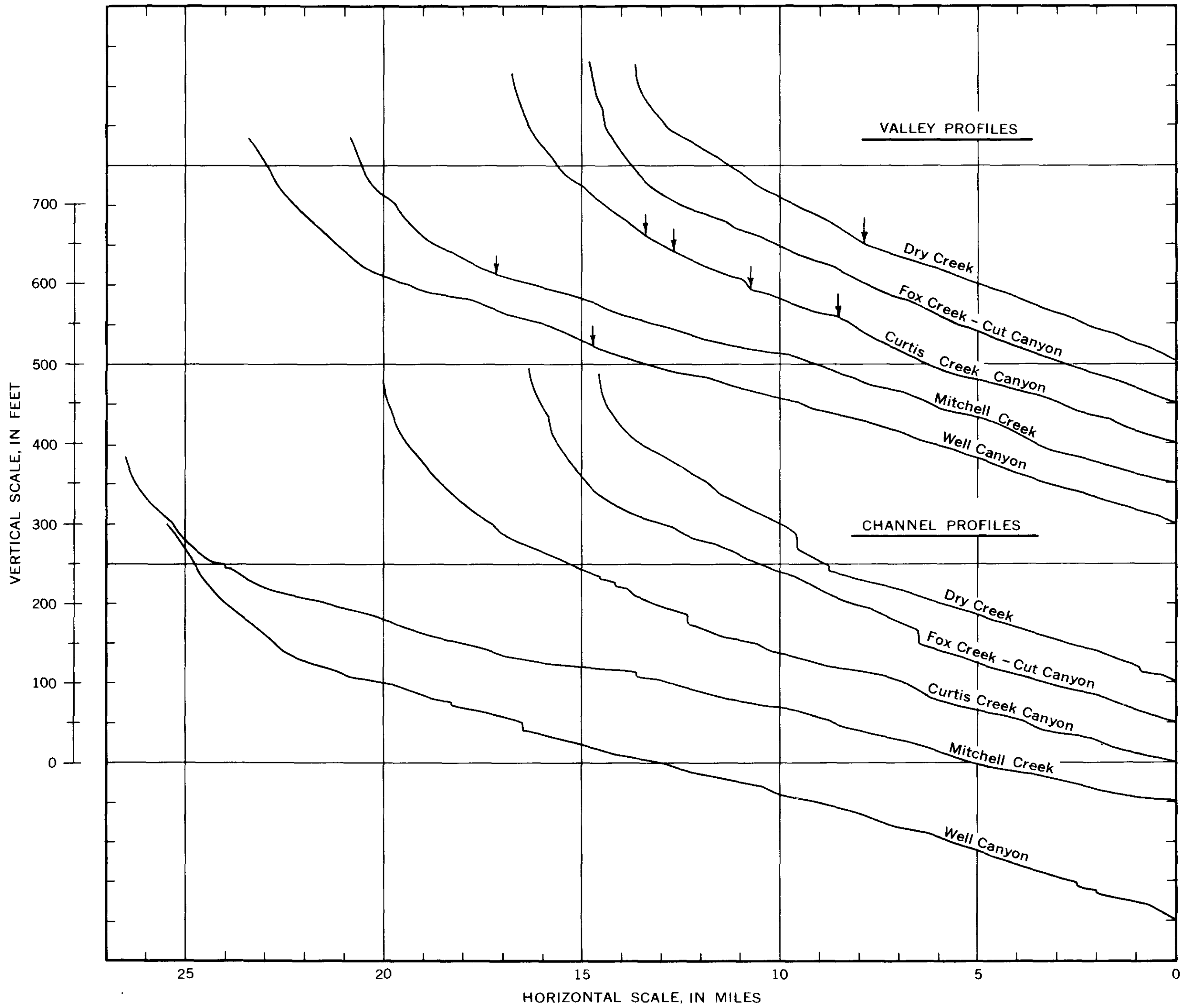


FIGURE 202.—Long profiles of valley and channel for some major tributaries to Medicine Creek. A break in the channel profile represents a channel scarp, and an arrow on the valley profile indicates the point of confluence of a large tributary. Profiles drawn from topographic maps.

The general slope of the valley profile, although somewhat less than that of Dry and Curtis Creeks, is not significantly different from that of Mitchell and Fox Creeks. The tributaries received by Well Canyon are relatively short, however, and the valley of Well Canyon is relatively wide at the point of confluence of the two largest tributaries. Upstream from the confluence of the northernmost of these tributaries, the valley profile of Well Canyon shows lccal steepening and the presence of a channel scarp. Neither local steepening nor a channel scarp occurs at the confluence of the other tributary. The inactivity of channel scarps in the main valley of Well Canyon is attributed to the lack of large tributaries, to relatively great valley width, and to the generally low valley slope.

DEVELOPMENT OF VALLEY-BOTTOM GULLIES

Photographs of typical valley-bottom gullies are reproduced in figure 204. After a gully has become large, neither the exact way in which it was initiated nor the point of initiation can be established. However, study of small gullies in various stages of development indicates that valley-bottom gullies may begin as small depressions scoured by flowing water on the valley bottom. Breaks in the sod cover—such as might result from an animal burrow, a trail, or an excavation by man—are likely spots at which scour can take place. The upstream side of a depression can evolve into a scarp and advance upvalley, meanwhile growing in height. Although most scarps in major valleys have apparently been ini-

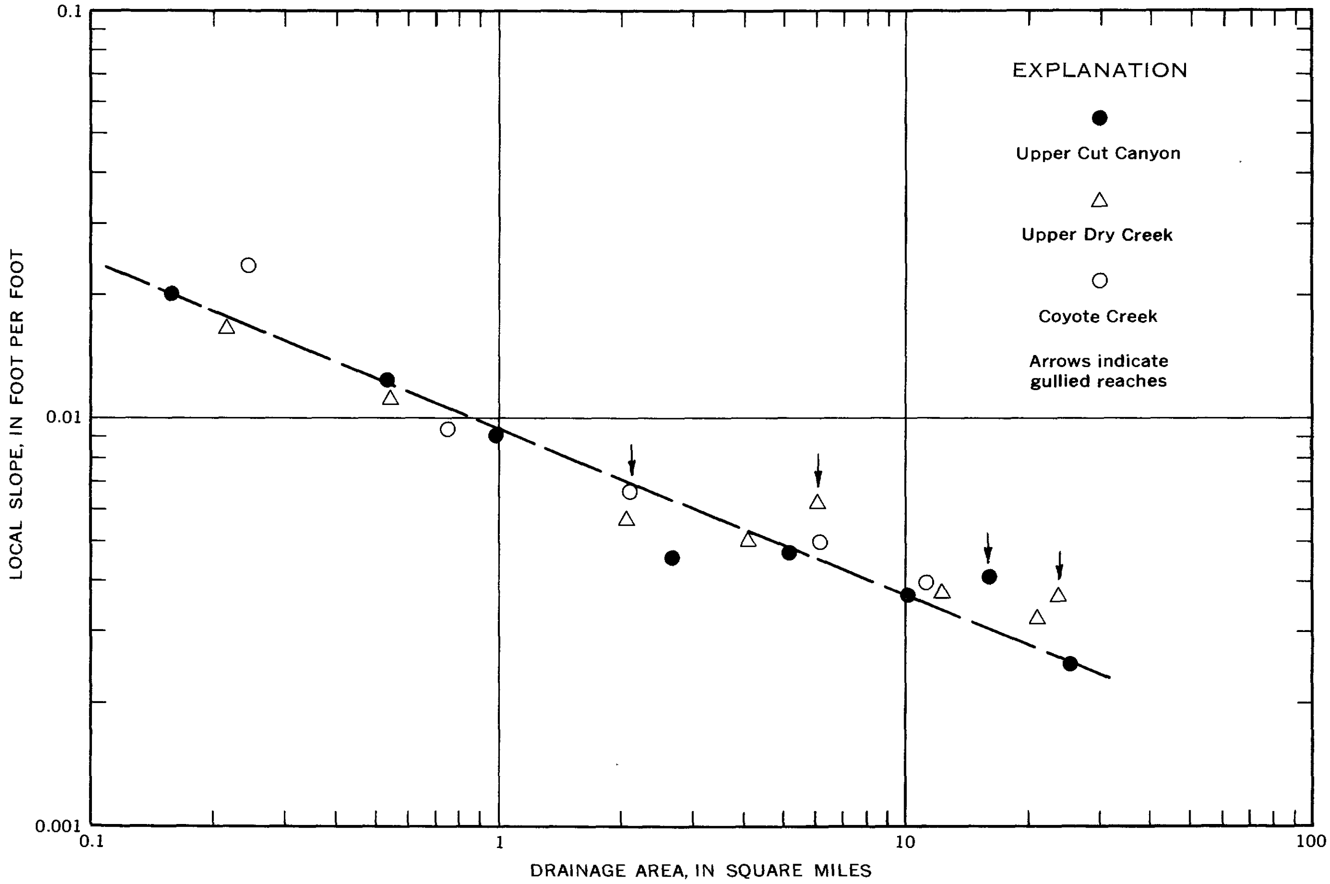
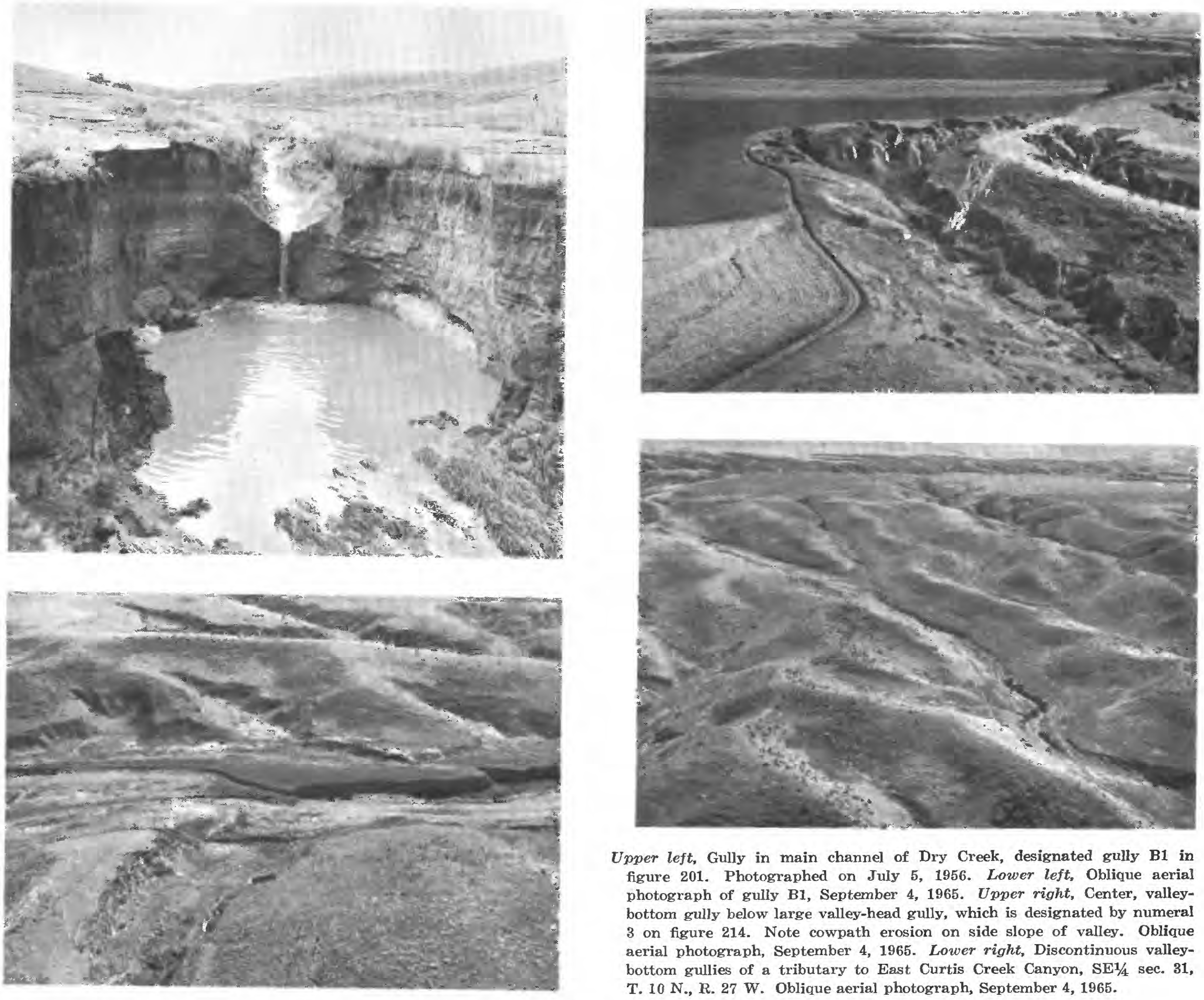


FIGURE 203.—Local valley slope in relation to drainage area for reaches along upper Cut Canyon, upper Dry Creek, and Coyote Creek.

tiated in a locally steepened valley reach, a scarp, once initiated, can continue to advance into reaches where the value of local slope is conservative in relation to drainage area (water discharge). Moreover, many gullies occur in valleys of fourth or smaller order in which no evidence of local steepening can be found. The value of the ratio of slope to drainage area that is associated with the initiation and rapid growth of a gully is not sharply defined.

Advance of a head scarp takes place as the massive silt at the base of the scarp becomes saturated and disintegrates. In this region the permeability of undisturbed dry loess in place is only about 0.8 foot per day (Holtz and Gibbs, 1952), but this value has no significance for a vertical face of loess that is immersed in water, as at the edges of a plunge pool. The loess in contact with the water continually sloughs along vertical joints and is removed by the turbulent water of the pool. In figure 204 (*upper left*) the recently collapsed base of a scarp may be seen at right of plunge pool. The cohesiveness of massive silt depends to a considerable extent on a cement formed by clay minerals that coat the silicate grains, and when wet the clay coatings have little or no cohesive effect. Gully side scarps regress by the same process. For a distance up to 12 feet from the edges of a gully, the ground is broken by cracks marking the boundaries of large blocks that have slumped because of saturation of the silt at their base. These blocks will eventually slump into the gully, as illustrated in figure 200. Head scarps can be maintained in massive silt whether or not they are capped by sod or some other resistant layer. Drainage is conveyed to many head scarps by a narrow channel, the bottom of which is bare of vegetation and is cut below the soil profile. A deep notch is formed by the intersection of this channel with the head scarp. The notch in the head scarp of gully B1 on Dry Creek changed very little between 1953 and 1957.

Downstream from a head scarp, long profiles of gullies change from year to year; the change depends on the amount of runoff. V. I. Dvorak (written commun., 1962) has compiled measurements of the long profiles of three major gullies on Dry Creek, which are designated gullies B1, B2, and B3 in figure 201. Changes in the long profile of gully B2 are typical and are represented in figure 205.



Upper left, Gully in main channel of Dry Creek, designated gully B1 in figure 201. Photographed on July 5, 1956. *Lower left,* Oblique aerial photograph of gully B1, September 4, 1965. *Upper right,* Center, valley-bottom gully below large valley-head gully, which is designated by numeral 3 on figure 214. Note cowpath erosion on side slope of valley. Oblique aerial photograph, September 4, 1965. *Lower right,* Discontinuous valley-bottom gullies of a tributary to East Curtis Creek Canyon, SE¼ sec. 31, T. 10 N., R. 27 W. Oblique aerial photograph, September 4, 1965.

FIGURE 204.—TYPICAL VALLEY-BOTTOM GULLIES

According to Dvorak, the relatively high runoff in 1951 was accompanied by gully slopes distinctly less than valley slopes, but during the succeeding drier years the gully slopes increased. Gully slope was steeper than valley slope for gully B2 in 1956 and for gullies B1 and B3 in 1960.

The maximum height attained by a head scarp is evidently controlled mainly by the steepness of the slope into which the head scarp is advancing. The highest head scarps in the basin, which reach a maximum of about 35 feet, are all in steep valley heads, whereas head scarps on the gently sloping valley bottoms all range from 10 to 25 feet in height. The height that a scarp can attain is also limited by the rate of deposition at, and downstream from, its base.

The cross profile of a valley-bottom gully changes in a direction downstream from the head scarp, but the nature of the change is not consistent from gully to gully. Typically, gully depth decreases very gradually in a downstream direction, whereas gully width reaches a maximum within a thousand feet of the head scarp and then decreases in a downstream direction. Downstream changes in the cross profile of a typical rapidly advancing valley-bottom gully (gully B4 in fig. 201) are shown in figure 206. The width of gully B4 remains nearly constant for about 5,000 feet downstream, but for other gullies the width decreases downstream at a much faster rate than depth. For example, in 1952 the width of a large valley-bottom gully on Curtis Canyon (gully B6) decreased from about 105 feet at a

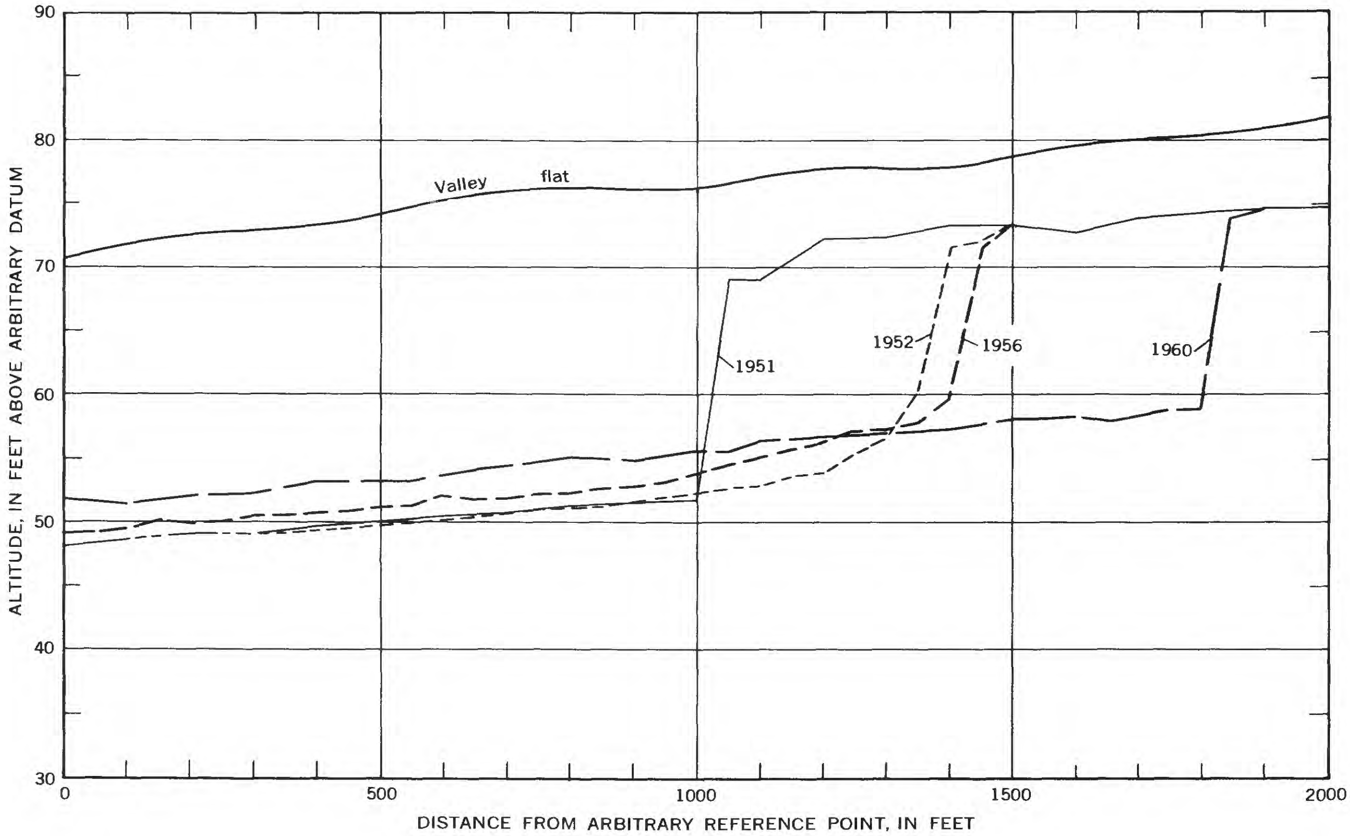


FIGURE 205.—Changes in long profile of a large valley-bottom gully on Dry Creek, 1951–60. Gully is designated B2 in figure 201. From V. I. Ovorak.

point 900 feet downstream from the head scarp to about 45 feet at a point 5,000 feet from the head scarp. Through this 5,000-foot distance, the depth of the gully changed little. Neither gully B4 nor B6 has a well-defined downstream terminus at which the gully floor merges with the valley floor; each merges downstream with a narrow but apparently stable channel that continues for miles along the valley bottom.

From his study of valley-bottom gullies on Dry Creek, Dvorak (written commun., 1962) concluded that widening downstream from the head scarp effectively ceased when the width-depth ratio was in the range of 3.5 to 5. At great width, the depth and velocity of flowing water would be insufficient to remove material that accumulated from bank slumping, and the channel bottom would assume a parabolic shape.

As is generally the case with channels in nature, the width-depth ratio that can be maintained for a gully probably depends on the magnitude of water discharge. Small gullies in the Medicine Creek basin have low values of the width-depth ratio, and large gullies have larger values. In 1956 none of the large valley-bottom gullies had attained a width-depth ratio greater than 6, which was the value measured for gully B5 at a point 390 feet downstream from its head scarp. However, none of these gullies had a drainage area greater than about 16 square miles. Gully B9, the drainage area of which was about 1.5 square miles, had in 1956 a width-depth ratio that did not exceed a value of 1 for a distance of 1,000 feet downstream from its head scarp.

The advance of major valley-bottom gullies during the period 1937–52 is given in table 5, together with pertinent information as to gully size and topographic setting. Gully advance and width of valley bottom were measured on aerial photographs; drainage area was measured on topographic maps; and height of head scarp was measured in the field. Slope of the valley bottom, which applies to the slope upvalley from the 1952 position of head scarps, was measured by field surveys for some of the gullies and on topographic maps for others. In general, the maximum depth of a gully is about equal to, or is greater than, the height of its head scarp. No correlation is apparent between the rate of advance and any of the other measurements. The estimate of the year at which active advance of the gully began is made by dividing gully length by average

TABLE 5.—*Measurements relating to the size and topographic setting of major valley-bottom gullies*

[Gully locations are indicated on fig. 201]

Gully	Drainage area in 1952 (sq mi)	Width of valley bottom (ft)	Slope of valley bottom (ft per ft)	Height of head scarp in 1956 (ft)	Advance of head scarp, 1937–52 (ft)	Estimated year of activation
B1	6.1	215	0.0056	24	900	1850
B2	5.6	210	.0055	22	750	?
B3	.8	120	.0105	20	610	?
B4	3.4	140	.0082	16	3,400	1900
B5	9.7	200	.0058	18	2,400	1920
B6	9.8	160	.0062	18	1,750	1920
B7	15.9	180	.00415	18	2,800	1910
B8	9.5	150	.0050	20	2,100	?
B9	1.4	120	.0125	23	2,100	1920

annual rate of advance during 1937–52. For Dry Creek, which has a continuous channel downstream from the head scarp, the point of origin is assumed to be at the confluence of East Fork.

Valley-bottom gullies advance only during periods of runoff. As a result of rainfall on July 4 and 5, 1956, which totaled about 1.9 inches, gully B5 advanced about 15 feet and gully B1 advanced 20 feet. The year 1937 was preceded by a period of relatively low rainfall (fig. 179) and, as observed on aerial photographs, most of the gullies were inactive in 1937 and were partly filled with sediment. A substantial part of the advance during the period 1937–52 took place in 1951 as a result of high runoff. For example, of the 750-foot advance made by gully B2 during the period 1937–52, about 350 feet was made during 1951. Differences in rate of gully advance (table 5) are probably in part due to unequal distribution of rainfall during 1951.

The development of a locally continuous channel by the coalescence of two discontinuous valley-bottom gullies, as described by Leopold and Miller (1956, p. 31), is illustrated in figure 207. Only the upper reach of the gullied valley bottom is shown in the illustration. The shallow channel shown at left continues downvalley for 1,300 feet and terminates at the head scarp of gully B3. No evidence of downvalley extension of gullies during the period 1937–56 was observed at this locality, and in general downvalley extension of a gully is uncommon. The long profile of a single discontinuous gully is rarely smooth, but it is ordinarily broken by one or more inset scarps.

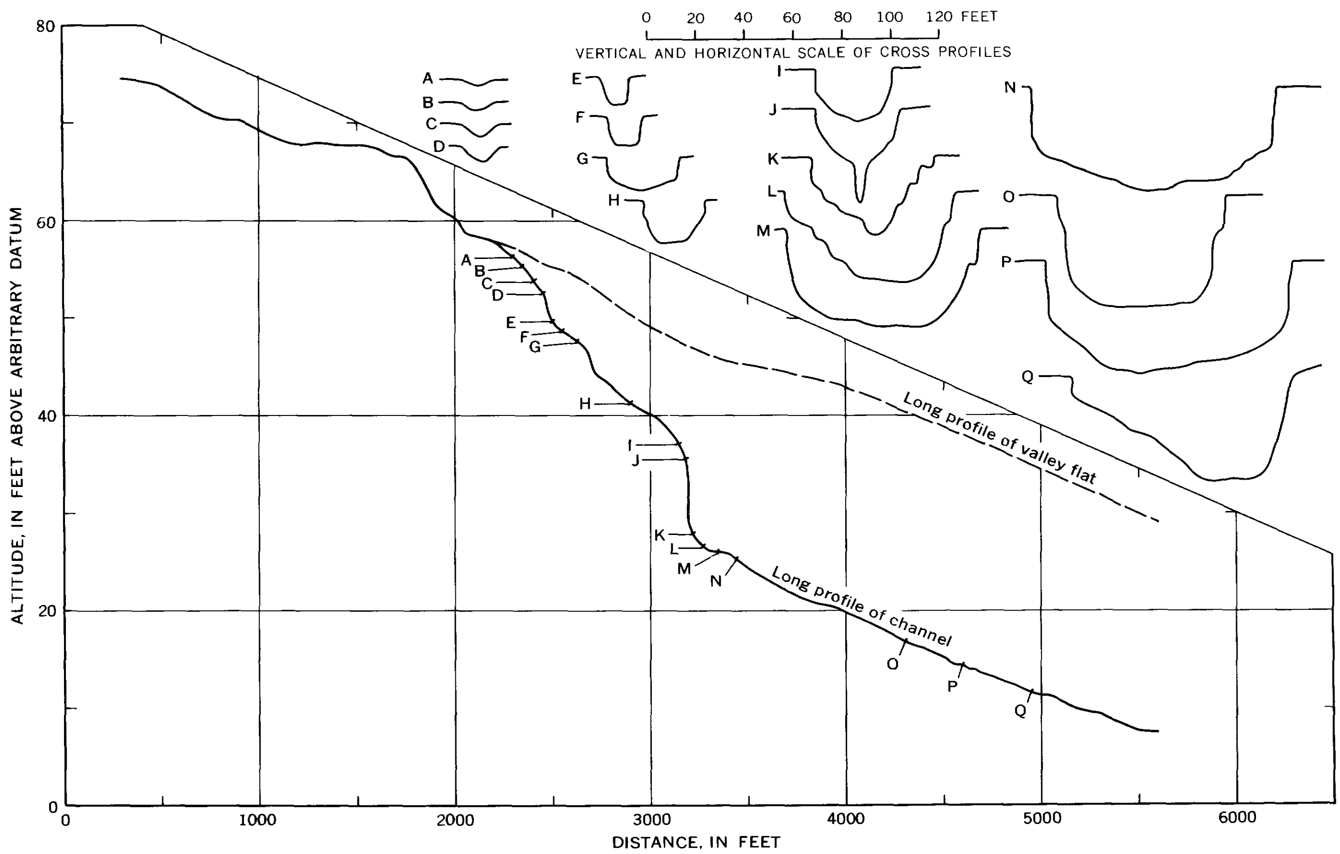


FIGURE 206.—Long profile and cross profiles of a large valley-bottom gully in a tributary to Curtis Creek Canyon. Gully is designated B4 in figure 201. Based on a field survey, 1956.

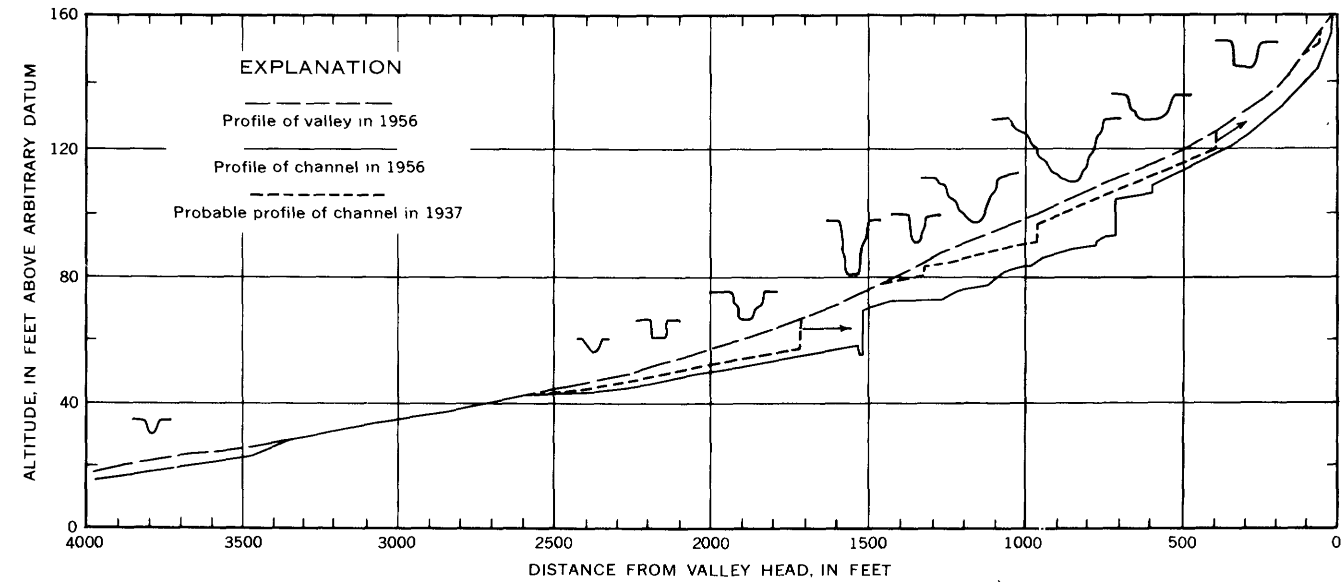


FIGURE 207.—Changes in long profile of a gullied tributary to Dry Creek, 1937–56. For the long profile in 1937, the position of head scarps was taken from aerial photographs, and other parts of the profile were estimated. Long and cross profiles in 1956 are based on a field survey.

The gradient of a discontinuous gully is less steep than the gradient of the valley floor into which it is advancing, and Leopold and Miller attribute this to the narrower width of the gully. As gullies coalesce and widen, a continuous channel is finally formed that has a gradient nearly parallel to the original valley floor. The gullies of the Medicine Creek basin, however, have not reached this final stage; channel scarps are advancing in succession along the valleys, and final regrading of a given reach will probably involve the passage of many channel scarps.

HISTORY OF LATE RECENT GULLYING ON DRY CREEK

Dry Creek was selected for detailed study of gully erosion by agencies involved in the Medicine Creek Watershed Investigations because the rate of erosion there seemed to be more severe than elsewhere in the basin. Periodic surveys were made of selected reaches of valley-bottom gullies to provide a basis for calculation of gross erosion by these gullies. A detailed geomorphic study of the Dry Creek channel and terraces was made by the writer, with the objective of deciphering the history of gullying in late Recent time and relating this history to white settlement and occupation.

A detailed long profile of Dry Creek, based on a field survey made by personnel of the Bureau of Reclamation in 1951, is shown in figure 208. The terrace profiles in figure 208 and the cross profiles in figure 209 are also based on this survey, supplemented with field surveys made by the writer. Station references used in the text and in figure 209 refer to distances in feet from the mouth of Dry Creek, are represented in figure 208.

In general, the upper reaches of Dry Creek are ungullied (fig. 210, *upper left*), the middle reaches (as represented in fig. 210, *lower left* and *upper right*) have been twice gullied in late Recent time, and the lower reaches (as represented in fig. 210, *lower right*) were ungullied until about 1937. The inset terrace (figs. 209 and 210, *lower left*) provides evidence for the two episodes of gullying. The inset terrace deposits accumulated in the wake of a major channel scarp, and the inset terrace was formed as these deposits were trenched by the advance of a second scarp. The first channel scarp probably began at about station 10,000 for the inset terrace becomes indistinct at this point. A reasonable date for the beginning of this first scarp is about 350 years ago, which is the date suggested (on the basis of a carbon-14 age determination) for gullying on Elkhorn Canyon.

The approximate age of the inset terrace deposits can be inferred from a cottonwood stump rooted on the terrace at station 43,300 (fig. 210, *lower left*) and from a tobacco tin buried to a depth of 5 feet in the deposits at station 43,700. The growth rings on the cottonwood stump indicate that it was about 40 years old at the time of cutting (1950); therefore, the inset terrace deposits had already accumulated in 1910. The tobacco tin, which is about 400 feet upvalley from the stump, was perhaps buried about this time or somewhat later. Because the inset terrace deposits accumulate in the wake of an advancing head scarp, their age decreases in an upvalley

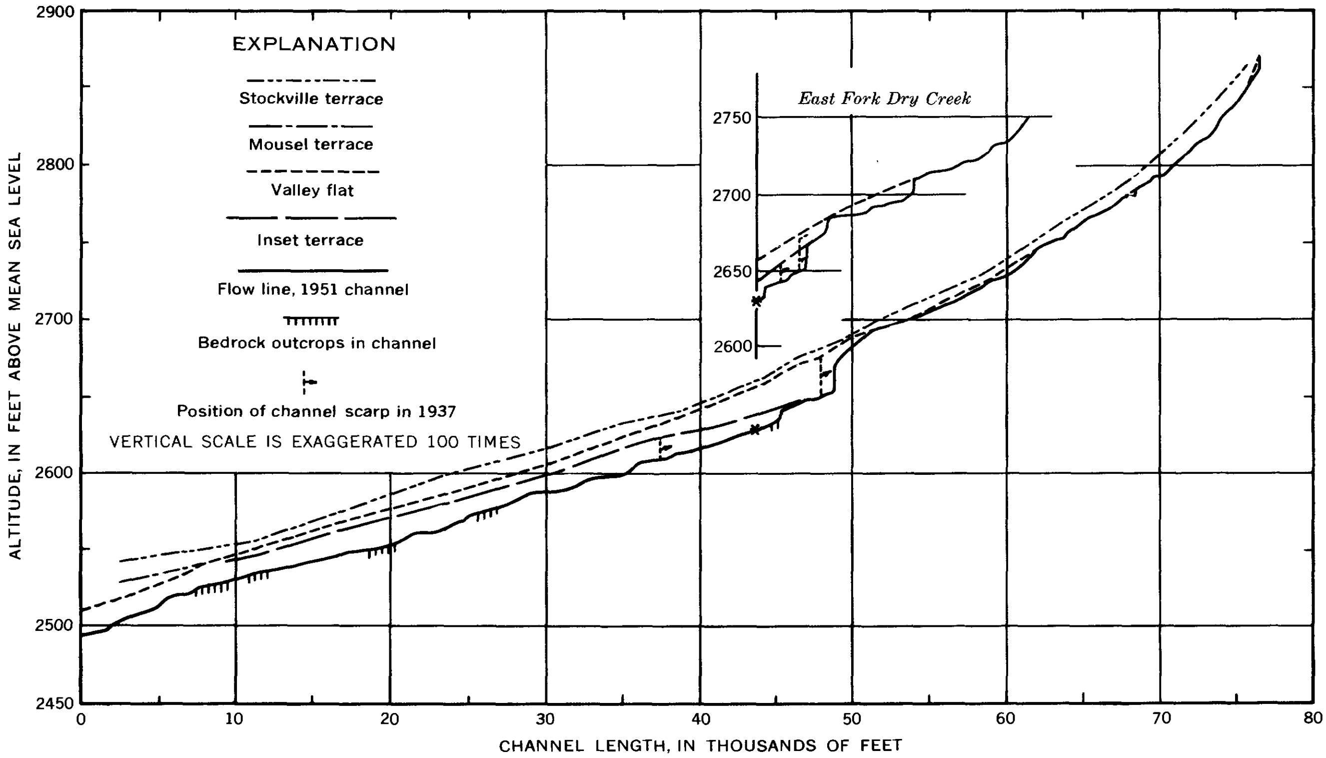


FIGURE 208.—Long profiles of channel, valley flat, and terraces on Dry Creek.

direction. The channel scarp that is trenching the deposits and thus forming the inset terrace was at station 37,400 in 1937 and had advanced 8,300 feet by 1951.

A new channel scarp began at or near the mouth of Dry Creek at a time not long before 1937, according to its position on the 1937 aerial photographs. This scarp had reached station 6,000 (fig. 210, *lower right*) by 1952, and it is moving rapidly upvalley at present.

VALLEY-HEAD AND VALLEY-SIDE GULLIES

Varieties of valley-head and valley-side gullies are distinguished mainly on the basis of shape of gully head in plan view. The main varieties in their characteristic topographic situations are illustrated in figure 211. A gully head that is on a relatively steep slope and receives a concentration of flow from a single direction, as from a narrow channel, tends to be narrow and pointed (gully 1, fig. 211). If the slope is less steep or the flow less concentrated, the gully head will be broadly lobed (2). If, on the other hand, the slope is gentle and the flow comes from diverse directions, the gully head will be complexly branching (3).

Situations favorable for the initiation of a gully are related to valley shape (as determined by past erosional history of the valley), to the presence of cultivated upland at the valley head, and to the activities of man and livestock. The valley at right has steep sides and head because it was deeply trenched both before and after deposition of the Stockville terrace deposits. The steep valley head, which receives heavy runoff from a field planted in row crops, is a favorable place for the formation of a gully. A large valley-head gully (gully 3, fig. 211), which began on the upper part of the valley head, has branched along the fence and into the field. The step scarps (4) on the steep valley sides began at animal trails along the slope contour and have grown in height as they slowly migrated upslope. The step scarp at extreme right has evolved into a valley-side gully (5). At the left side of the valley, two narrow valley-side gullies (1) are forming from cowpaths, and another valley-side gully (8) is advancing along a road ditch.

The valley at center is shallow and has a relatively gently sloping head because it was trenched to shallow depth before deposition of the Stockville terrace deposits, and post-Stockville trenching has not extended far upvalley. In addition, the valley head borders a divide rather than a tract of upland and, therefore, has a small drainage area. The three gullies in the valley head (6) are lobed and have grown slowly. In the background beyond the center valley, two gullies (7) in another valley head are

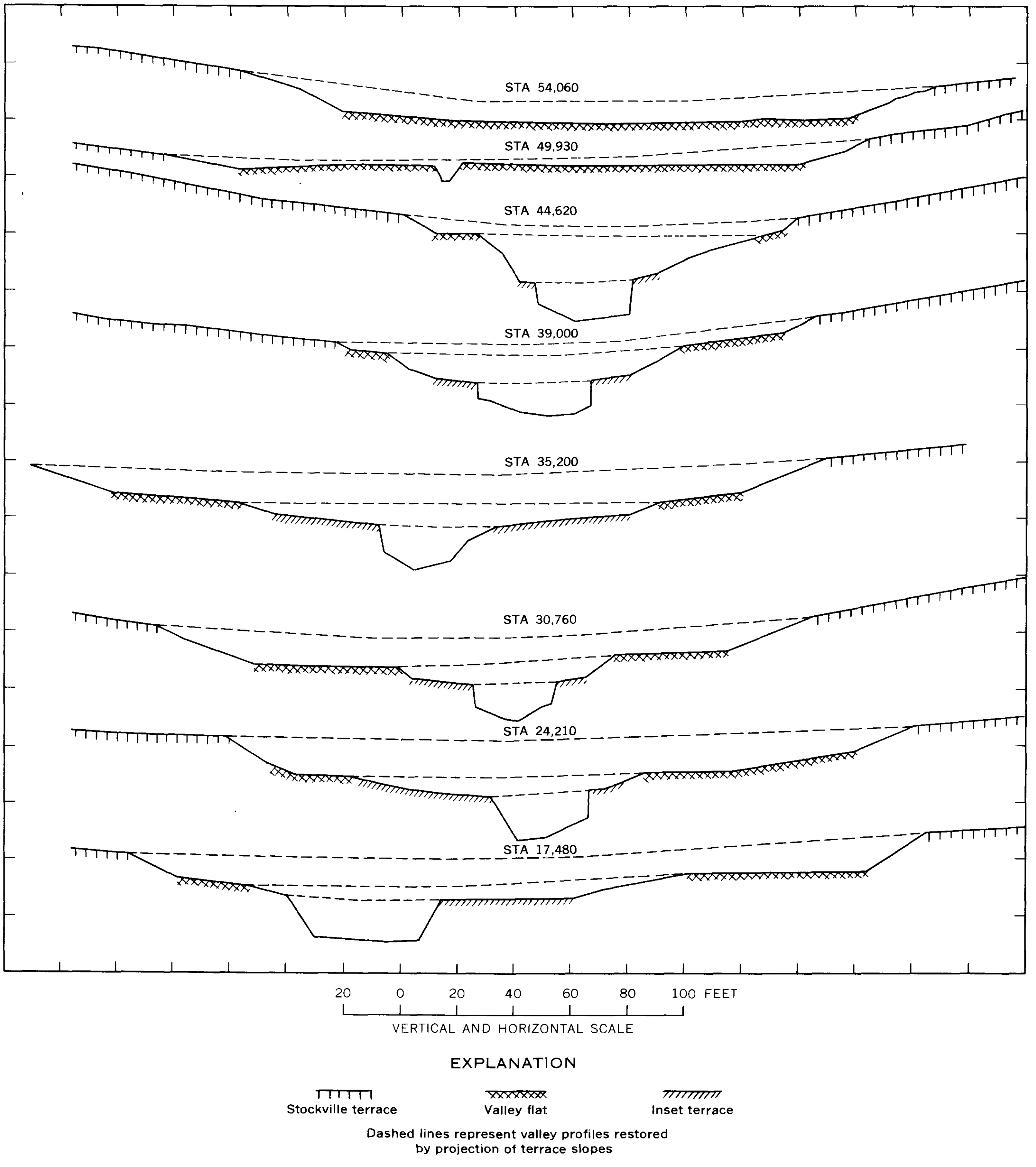


FIGURE 209.—Cross profiles of Dry Creek. Station numbers are distances in feet from mouth of creek.

Upper left, Upper reach of East Fork Dry Creek, 1953. Narrow incised channel is shown in middle ground. *Lower left,* Channel and inset terrace at station 43,300 in 1956. Cottonwood stump, near center, is rooted at outer edge of inset terrace. *Upper right,* at gaging station (sta. 17,660), August 17, 1953. Discharge about 300 cfs. *Lower right,* Channel at station 6,000 in 1953, looking downstream. On downstream side of cottonwood tree is a large channel scarp, advance of which has since felled the tree.

FIGUGE 210.—DOWNSTREAM CHANGES IN CHANNEL OF DRY CREEK

advancing rapidly—one in the direction of drainage from the road and the other in the direction of drainage from the barnyard.

The two valleys at extreme left are typical of many valleys in the upper part of the basin. Severe post-Stockville trenching has removed most of the deposits of Stockville age and left the valley sides raw and steep. The valley-side and valley-head gullies (2), which are lobed in plan view and have head scarps tens of feet in height, are advancing very slowly because their drainage area is small.

Photographs of valley-head and valley-side gullies are shown in figure 212. The valley-head gullies in figure 212 (*upper left* and *upper right*) are among the largest in the basin. As is typical, these gullies border areas of cultivated upland. The gully in figure 212 (*upper left*) extends for about 900 feet along a fence line. A narrow but deep valley-head gully, whose head scarp attains a height of 31 feet, is shown in figure 212 (*lower left*). Valley-side gullies typical of the sharply dissected upper part of the basin are shown along the sides of the three valleys in figure 212 (*upper right*). Some are moderately active and others are inactive. The growth rate of such gullies is slow because they border narrow divides and hence have small drainage areas. The valley-side gullies in figure 212 (*lower right*) originated from cowpaths and an old field road.

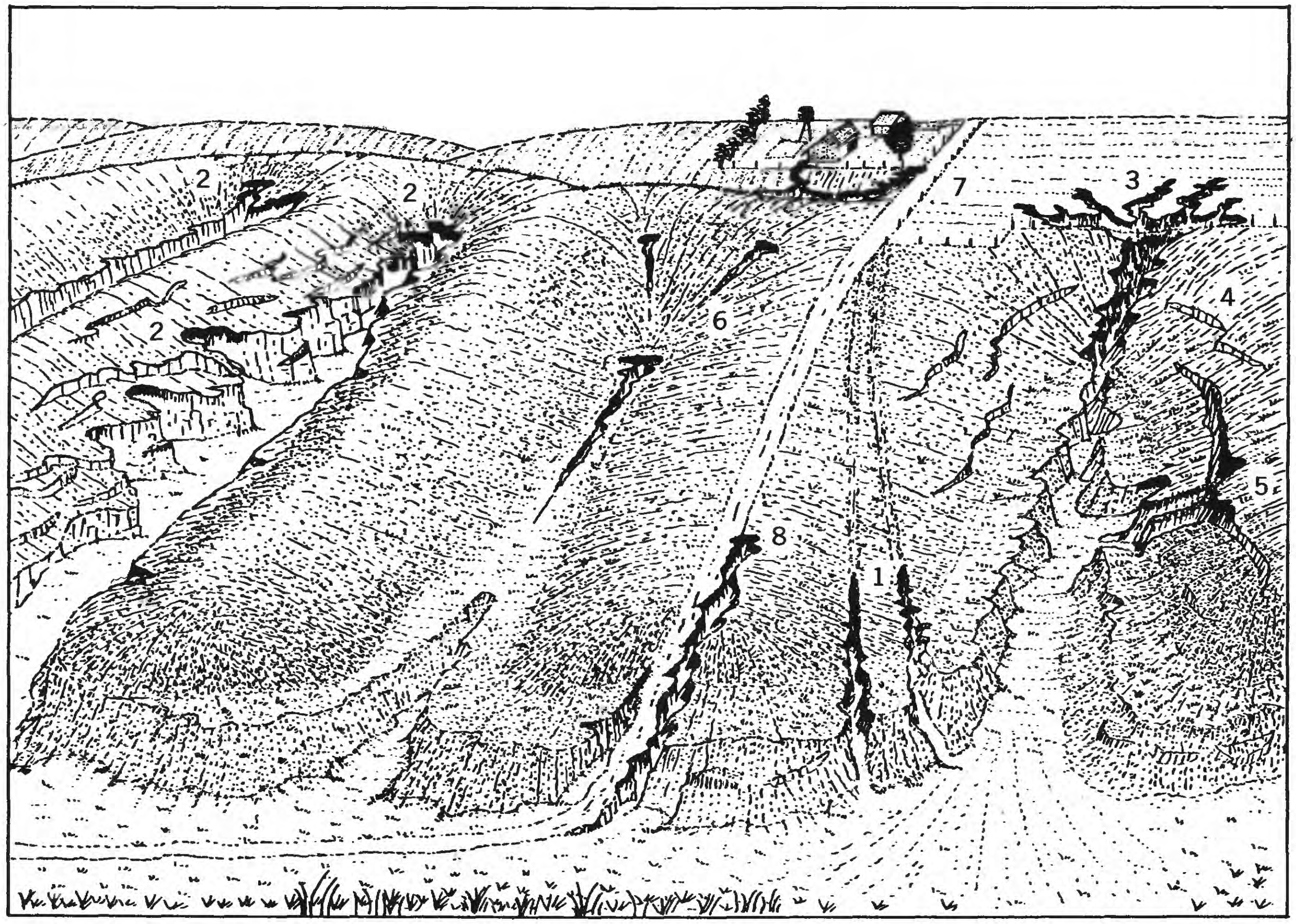


FIGURE 211.—Composite sketch, based on field sketches and photographs, showing different varieties of valley-head and valley-side gullies. Actively eroding scarps are indicated by dark shading. Numbered features are described in text.

MEASUREMENT OF VALLEY-HEAD AND VALLEY-SIDE GULLIES ON DRY CREEK

In the summer of 1953 measurement of the volume increase of valley-head and valley-side gullies during the period 1937–52 was made by field surveys and comparison of aerial photographs. On aerial photographs enlarged to a scale of 1 inch to 660 feet, reference lines across or near gully heads were drawn between fixed points, such as trees, fence corners, houses, or other landmarks. The position of gully head in 1937 was marked on a 1952 aerial photograph, which was then taken into the field to facilitate measurement of the volume increase. Changes in gully depth could not be determined from aerial photographs; but this is probably not a significant source of error, inasmuch as neither height of head scarp nor gully depth changes very much during a moderate advance. The horizontal dimensions of gullies were measured by pacing, and the depths were measured with a steel tape. Determination of volume was complicated by the irregular shape of most gullies. No volume increases less than about 30 cubic yards are reported because increases less than this amount are considered to be unrecognizable by comparison of aerial photographs. Volume increases, however, were measured for nearly all the gullies on Dry Creek that seem to be active, and erosion from gullies that seem to be inactive is probably not quantitatively important.

According to these measurements, the enlargement of all active valley-head and valley-side gullies on Dry Creek (216 gullies) for the period 1937–52 totaled 106,500 cubic yards. A plot of the frequency distribution of gully enlargements on logarithmic probability paper indicates a logarithmically normal distribution, and the skewness at the lower end of the curve is attributed to the omission of perhaps 10 gully enlargements less than 30 cubic yards. (See fig. 213.) The median enlargement is about

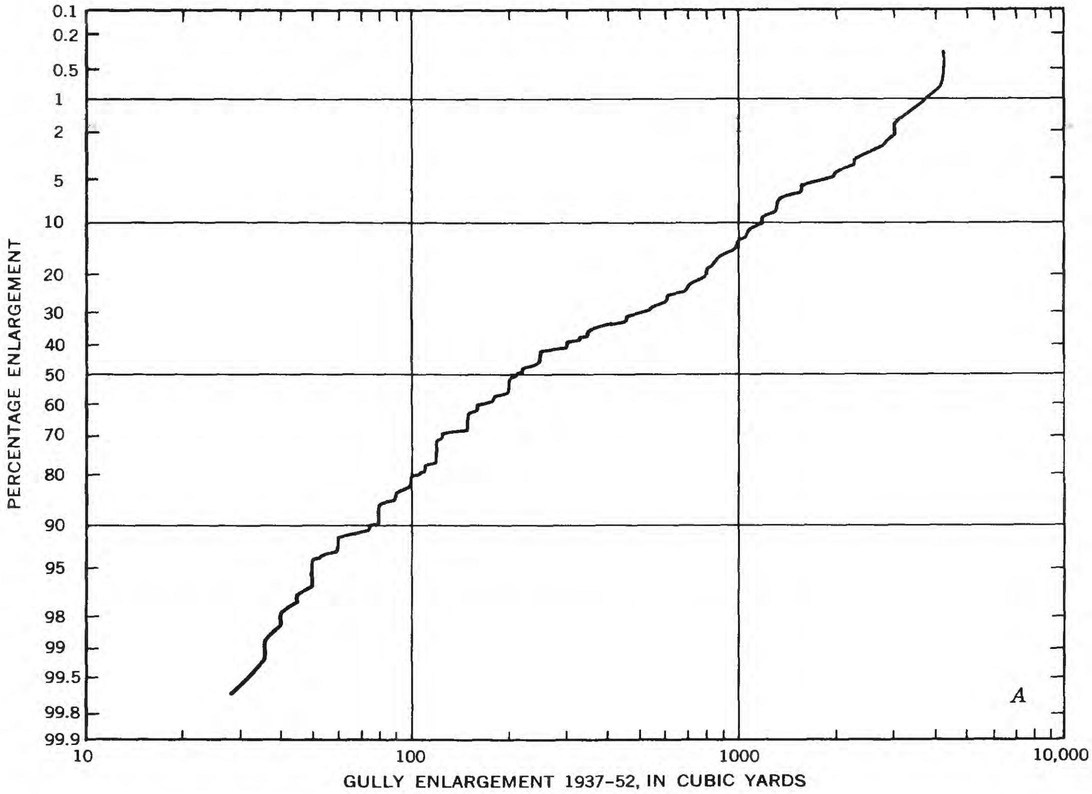
FIGURE 212.—Valley-head and valley-side gullies. *Upper left,* Center, large valley-head gully in Curtis Creek subbasin, NE¼ sec. 10, T. 8 N., R. 28 W. Oblique aerial view, September 4, 1965. *Lower left,* Valley-head gully in Dry Creek subbasin, center sec. 33, T. 9 N., R. 27 W., September, 1953. *Upper right,* Large valley-head gullies and smaller valley-side gullies in Curtis Creek subbasin, SW ¼ sec. 30, T. 10 N., R. 27 W. Oblique aerial view, September 4, 1965. *Lower right,* Valley-side gullies in Well Canyon subbasin, SW ¼ sec. 13, T. 9 N., R. 29 W.

200 cubic yards, and the range is from 28 to about 4,200 cubic yards.

A satisfactory approximation to the measured gully enlargement was reached by another method, which is based on the premise that active gullies can be recognized on aerial photographs and also on the premise that small gullies have small volume increases and large gullies have large volume increases. Several years after the gully measurements were made on Dry Creek, active gullies in the Medicine Creek basin were studied on aerial photographs and ranked into four categories according to size (not according to enlargement). On the basis of the measured gully enlargements on Dry Creek, each size category was assigned an enlargement range, according to the following scheme:

Gully size	*Enlargement range, 1937–52 (cu yd)*	*Geometric mean of enlargement range (cu yd)*
Small	50–100	63
Medium	100–600	245
Large	600–3,600	1,470
Very large	3,600–7,200	5,100

The number of gullies in each category on Dry Creek is shown in table 6. By multiplying the number of gullies in each category by the geometric mean of the enlargement, a total enlargement of 97,300 cubic yards was obtained, which is a reasonable approximation to the measured enlargement. Although this method is obviously subjective, no means of applying rigorously objective sampling methods to such irregular objects as gullies is



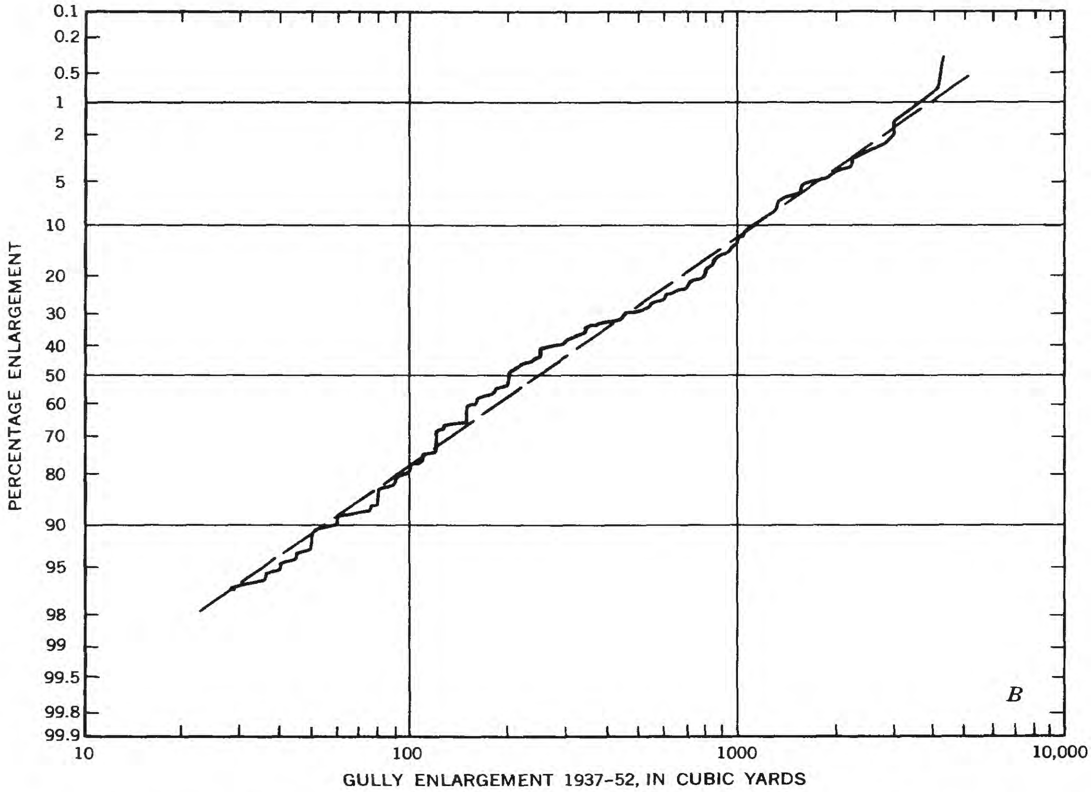


FIGURE 213.—Cumulative frequency distribution of 216 measured enlargements of valley-head and valley-side gullies on Dry Creek. *A*, Curve of 216 measured enlargements. *B*, Curve of 216 measured enlargements plus 7 hypothetical enlargements of less than 28 cubic yards.

TABLE 6.—*Number of gullies according to type and size in the Medicine Creek basin and in major subbasins*

Gully type	Size	Width of gully head (range in feet)	Number of gullies				
			Mitchell (subbasin C)	Dry (subbasin I)	Fox (subbasin K)	Brushy (subbasin N)	Medicine (subbasins A–O)
Valley head	Small	1–15	47	70	39	36	417
	Medium	16–60	99	110	90	302	1,357
	Large	61–180	28	35	16	90	360
	Very large	>180	1	2	----	3	20
Valley side	Small	1–10	22	3	7	10	112
	Medium	11–25	21	14	17	66	279
	Large	26–50	6	2	2	7	44
	Very large	>50	----	----	----	----	----
Valley bottom	Small	1–10	56	38	11	24	563
	Medium	11–25	33	27	23	82	477
	Large	26–50	} 10	10	9	19	152
	Very large	>50					

apparent. In the ranking of gullies into categories, a particularly difficult subjective decision lies in deciding whether the complex branches of a severely eroded valley head should be regarded as one gully or several. In the Dry Creek measurements, most of the branching valley heads were divided into several gullies, whereas in the later ranking of gullies according to size, the branching valley heads were regarded as one gully. For this reason the geometric mean of the largest size category (5,100 cu yd) is larger than the largest measurement reported (4,200 cu yd).

The topographic situations of gullies, as well as most of the topographic features characteristic of the Medicine Creek basin, are illustrated by the vertical aerial photograph reproduced as figure 214. Sec. 17, T. 9 N., R. 27 W., is approximately in the center of the area, and the valley of Dry Creek crosses it from left to right. Gullies numbered 3 and 5 on the photograph are in the very large category and have complexly branching heads. Total enlargement of all branches amounted to about 6,950 cubic yards for gully 3 during the period 1937–52 and about 5,610 cubic yards for gully 5. Figure 204 (*upper right*) is a view of gully 3 as seen from the air. Gullies 1 and 4 are in the large category, and the lobed shape of their heads indicates that they have not advanced beyond the steeper parts of the valley heads, although the head of gully 4 is beginning to branch. Enlargement during the period 1937–52 was 1,320 cubic yards for gully 1 and 2,250 cubic yards for gully 4. The group of four gullies indicated by the numeral 2 are in the medium category, and their enlargements ranged from 107 to 225 cubic yards.

Discontinuous valley-bottom gullies of small size are indicated by the two arrows at left of the numeral 4, and others of medium size are indicated by arrows in the lower left corner of the photograph. Small discontinuous valley-bottom gullies are also indicated by arrows on the valley flat of Dry Creek. The major valley-bottom gully on Dry Creek begins about 1 mile downstream (to the right) from this locality. A valley-side gully of medium size, which is advancing along a fence, is indicated by the numeral 6.

Among the notable relief features shown on the photograph are the differences among valleys in flatness of bottom and steepness of side. The valleys at right of numeral 4 have flat bottoms and steep sides because post-Stockville trenching extended to the valley heads; the valleys at left and below numeral 4 have narrow bottoms and gentle sides because their trenching was incomplete. Also notable, in the field at right center on the photograph, is a dark round spot that indicates a depression. Depressions of this sort, sometimes called buffalo wallows, are common on the Great Plains. Many hypotheses have been proposed as to their origin, but they probably originate in more than one way, and no hypothesis has been established as generally valid. In the Medicine Creek basin, many of the depressions probably mark the positions of sinkholes in the underlying Ogallala Formation.

AREAL DISTRIBUTION OF GULLIES

Experience in the recognition of Dry Creek gullies on aerial photographs and in the estimation of their size and activity was used in the collection of information on the distribution of gullies in the Medicine

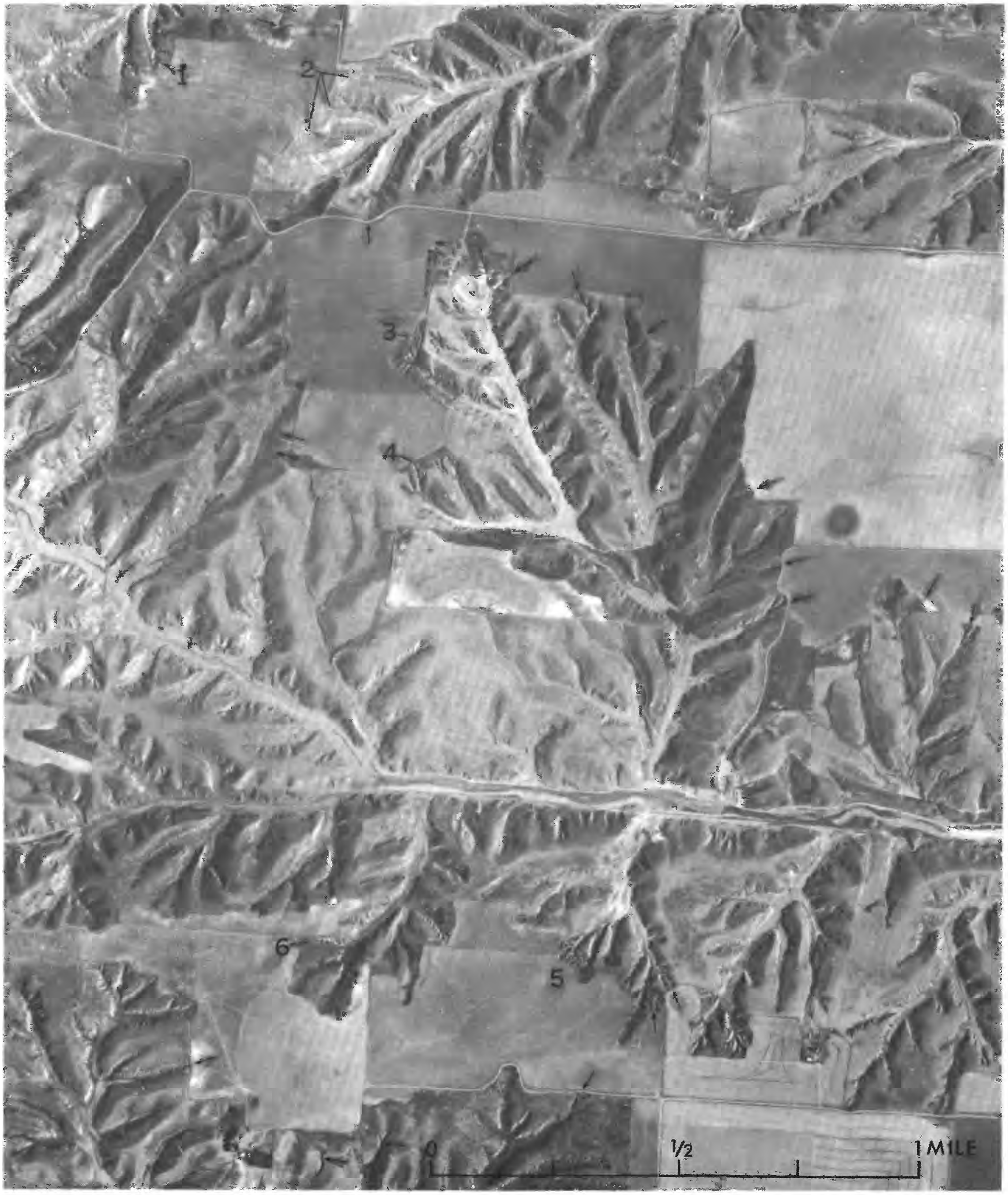


FIGURE 214.—Vertical aerial photograph of a severely gullied area on upper Dry Creek. Numbers indicate gullies described in text. Arrows indicate small- and medium-size discontinuous valley-bottom gullies described in text. Photograph by U.S. Commodity Stabilization Service.

Creek basin as a whole. Aerial photographs of the whole basin were studied stereoscopically, and all gullies in the basin that seemed to be active were plotted on topographic maps. Decisions as to the activity of a gully were checked by reference to 1937 aerial photographs. The gullies were grouped according to type (valley head, valley side, or valley bottom) and according to size (small, medium, large, very large). (See table 6.)

A map showing the frequency distribution of gullies according to subbasin was prepared (fig. 215). The basin was divided into 24 subbasins, corresponding generally to subbasins used by the Agricultural Research Service in their land-use tabulations, that are reasonably homogeneous in texture of relief. The frequencies of valley-head, valley-side, and valley-bottom gullies (excepting large and very large valley-bottom gullies) in each subbasin are given in table 7. Gully frequency refers to number of gullies per square mile of valley system rather than to number per square mile of drainage area. Gullies are directly related to the valley system and are not present in the upland except at its edges. Area of upland and characteristics of the valley system should be regarded as independent variables in their relation to gullying.

The frequency of active valley-head and valley-side gullies is low in the lower and upper part of the basin and ranges from moderate to high in the central part (fig. 215). The frequency ratio of valley-head and valley-side gullies to valley-bottom gullies ranges from about 0.6 in the lower part of the basin (subbasin A) to about 6 in the central part of the basin (subbasin 0–4). The distribution of gullies according to type and frequency is controlled mainly by the steepness of valley heads, the narrowness of valley bottoms, and the amount of upland drained by a valley head. In general, the steepness of valley heads is directly proportional, and the narrowness of valley bottoms is inversely proportional, to first-order-channel frequency.

TABLE 7.—*Gully frequencies and related data for subbasins of the Medicine Creek basin*

Subbasin	Drainage area (sq mi)	Area in upland (percent)	Area of valley system (sq mi)	Frequency of first-order channels	Frequency of valley-head and valley-side gullies	Frequency of valley-bottom gullies
A	27.2	45	15.0	113	3.2	5.3
B–1	43.4	38	26.4	150	2.9	4.2
B–2	11.6	37	7.3	140	3.7	5.5
C–1	22.3	50	10.8	190	16.0	4.3
C–2	29.8	52	14.4	150	3.5	3.4
D	74.4	45	40.9	160	5.7	2.6
E	10.9	42	6.3	165	5.2	6.1
F	58.9	34	35.3	170	6.9	4.1
G	23.2	42	13.4	195	12.4	5.0
H	16.5	48	7.4	185	11.7	4.2
I–1	12.6	40	9.5	214	18.5	5.1
I–2	8.5	49	4.3	185	14.2	5.3
J–1	17.6	12	15.5	275	3.3	3.0
J–2	22.6	45	12.6	200	16.4	4.6
K–1	57.0	12	49.8	260	1.5	4.2
K–2	15.5	30	10.8	200	9.1	1.6
L–1	22.7	12	19.9	260	.5	.2
L–2	30.6	26	22.5	220	5.2	.9
M	27.5	30	19.3	180	6.8	1.6
N	73.8	26	52.4	260	10.0	2.3
O–1	14.6	----	----	----	----	----
O–2	15.0	10	13.5	450	.7	.4
O–3	35.4	12	31.1	350	2.1	.4
O–4	22.0	55	9.9	350	10.8	1.8

Gully frequency in relation to percentage of area in upland and to adjusted frequency of first-order channels is shown in a semiquantitative way in figure 216. Moderate to high frequencies of valley-head and valley-side gullies are associated with values of first-order-channel frequency and percentage of area in upland that plot to the right of the dashed line. On the other hand, values that plot to the left of the dashed line tend to have a higher frequency of small and medium valley-bottom gullies.

Points representing high gully frequency would probably be more widely separated from points representing low gully frequency were it not for the fact that the subbasins are not entirely homogeneous in topographic character. The severity of post-Stockville trenching not only varies from the upper to the lower part of the basin, but also from one minor side tributary to the next (fig. 214). The point indicated by a gully frequency of 10.8 and representing subbasin 0–4, at upper right in figure 216, is most anomalous. In spite of the relatively low gully frequency in this subbasin, it includes an area of exceptionally severe erosion that is about 3 miles northeast of Maywood. This area is also exceptional in that its drainage was greatly extended by post-Stockville erosion. Several large gullies there made advances ranging from 60 to 180 feet during the period 1937–52.

FORMATION OF VALLEY-HEAD AND VALLEY-SIDE GULLIES

The head scarps of many valley-head gullies originate on the steep upper part of the valley head and advance toward the upland. This is indicated by the position of short gullies and by the shape in plan view of long gullies. The width of many large valley-head gullies decreases sharply toward the lower part of the valley head, and the gullies are connected to the valley flat by a narrow trench. (See fig. 217 and gully 5 in fig. 214.) Gully 5 narrowed downvalley (in 1956) to a particularly deep trench about 25 feet deep, 15 feet wide at the top, and 5 feet wide

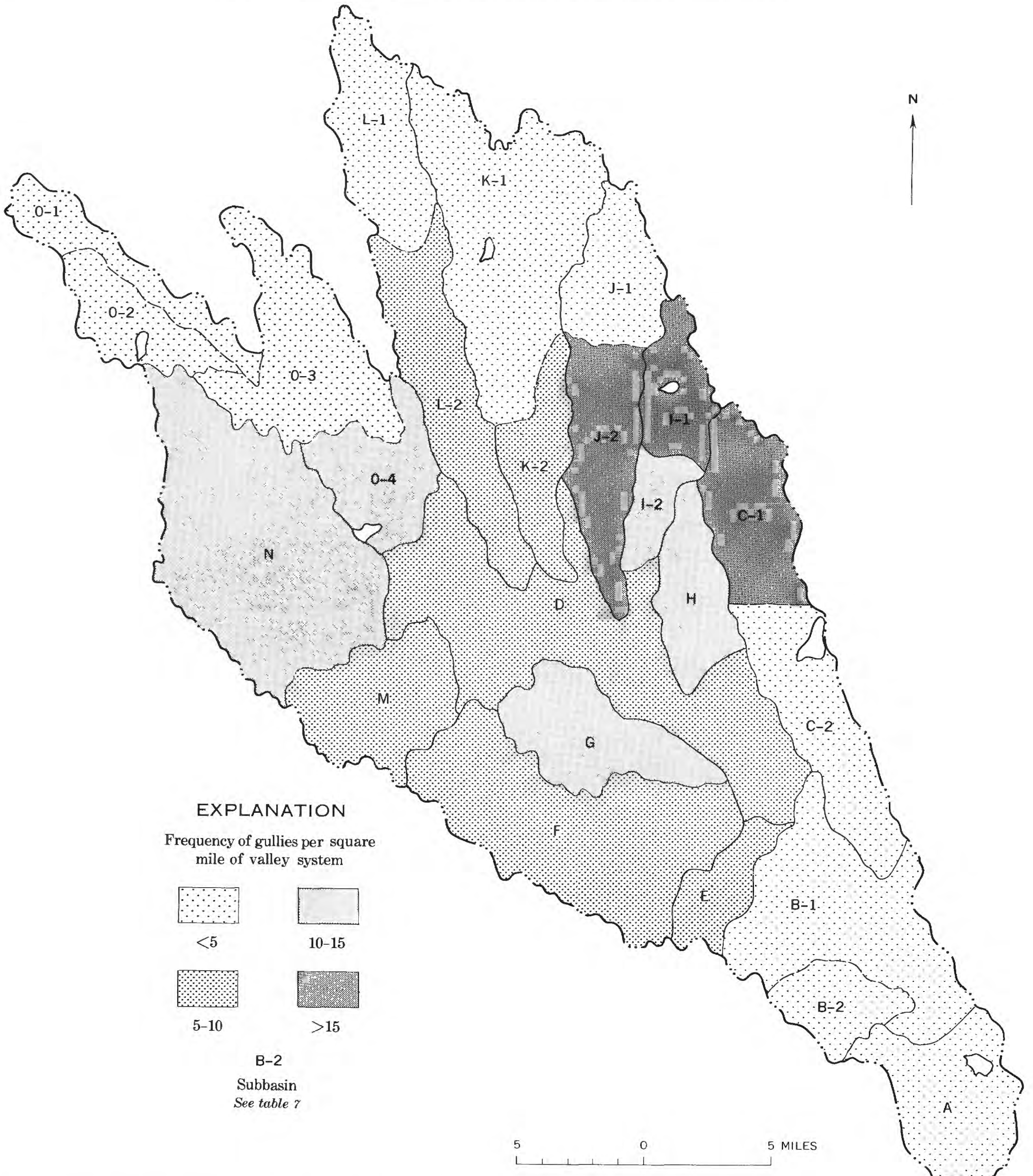


FIGURE 215.—Areal frequency distribution of active valley-head and valley-side gullies in the Medicine Creek basin. Subbasins illustrated in figure 197 are shown by heavy outlines. See table 7.

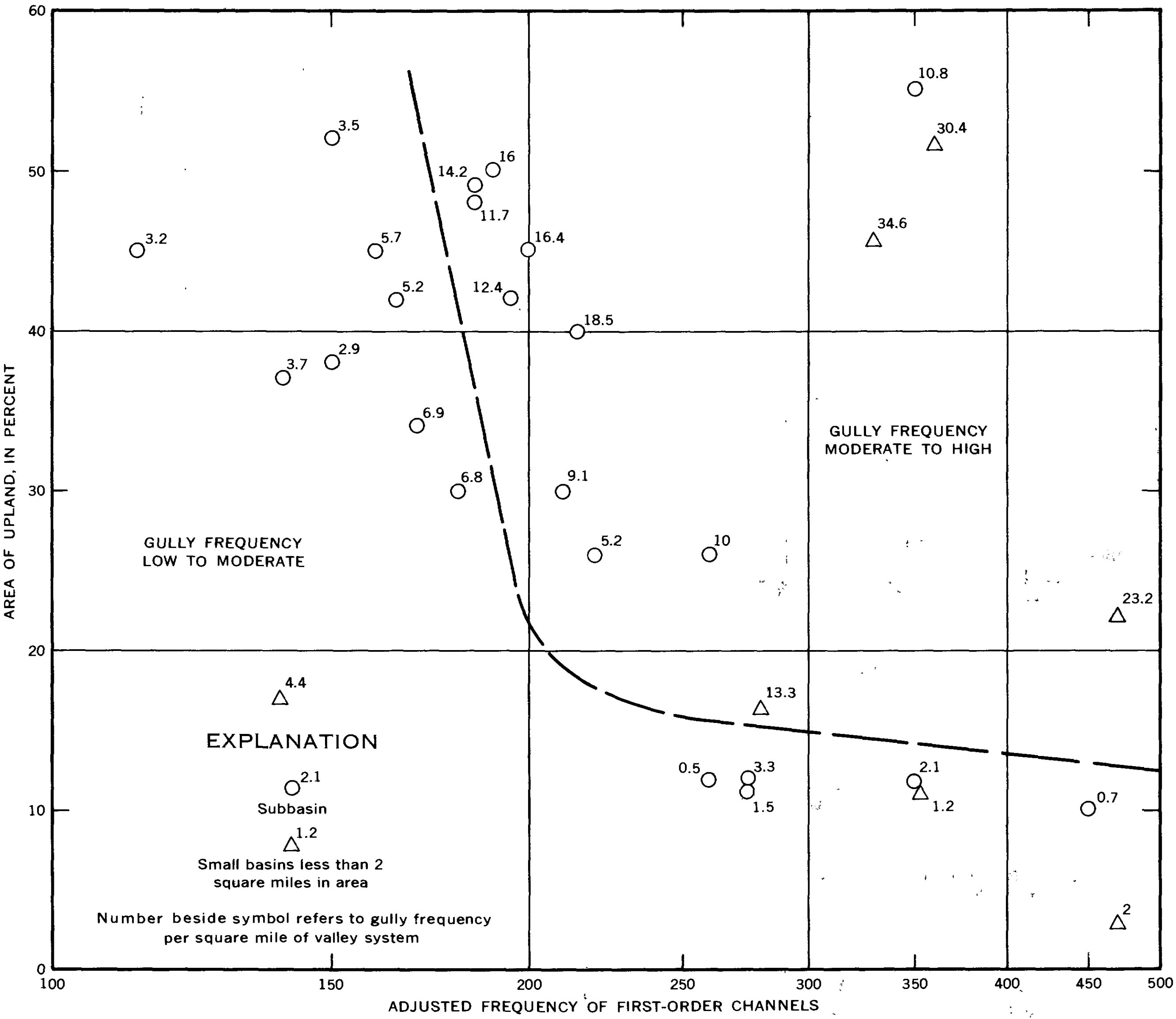


FIGURE 216.—Frequency of active valley-head and valley-side gullies in relation to area of upland and adjusted frequency of first-order channels.

at the bottom. Set in the bottom of this trench was a winding notch, sections of which passed underground.

Other valley-head gullies begin at an upvalley riser of the Stockville terrace, such as the one shown in the valley at center in figure 211, or as discontinuous valley-bottom gullies, such as the ones shown in the valley at upper left in figure 200. In the tabulation of all active gullies in the basin, valley-head gullies that are connected by a continuous, rather wide trench to the valley flat were given a separate designation because they probably began on the valley bottom rather than in the valley head. The percentages of valley-head gullies that fall in this category are as follows for several subbasins: Dry Creek, 7 percent; Brushy Creek, 22 percent; Mitchell Creek, 9 percent; Fox Creek, 6 percent; Lime Creek, 45 percent; and subbasin A, 65 percent. Thus, in the narrow valleys of the lower part of the basin, a greater percentage of valley-head gullies begins on the valley bottoms.

The head scarps of valley-head gullies reach a maximum height of about 35 feet, a value about 10 feet higher than the maximum height of head scarp measured for large valley-bottom gullies. This greater height is evidently related to the steeper slopes into which the valley-head and valley-side gullies are advancing and to the correspondingly steeper slopes at the base of their head scarps. (See figs. 217 and 218.) Material does not tend to accumulate at the base of the head scarp as it does in large valley-bottom gullies. In long profile, the head

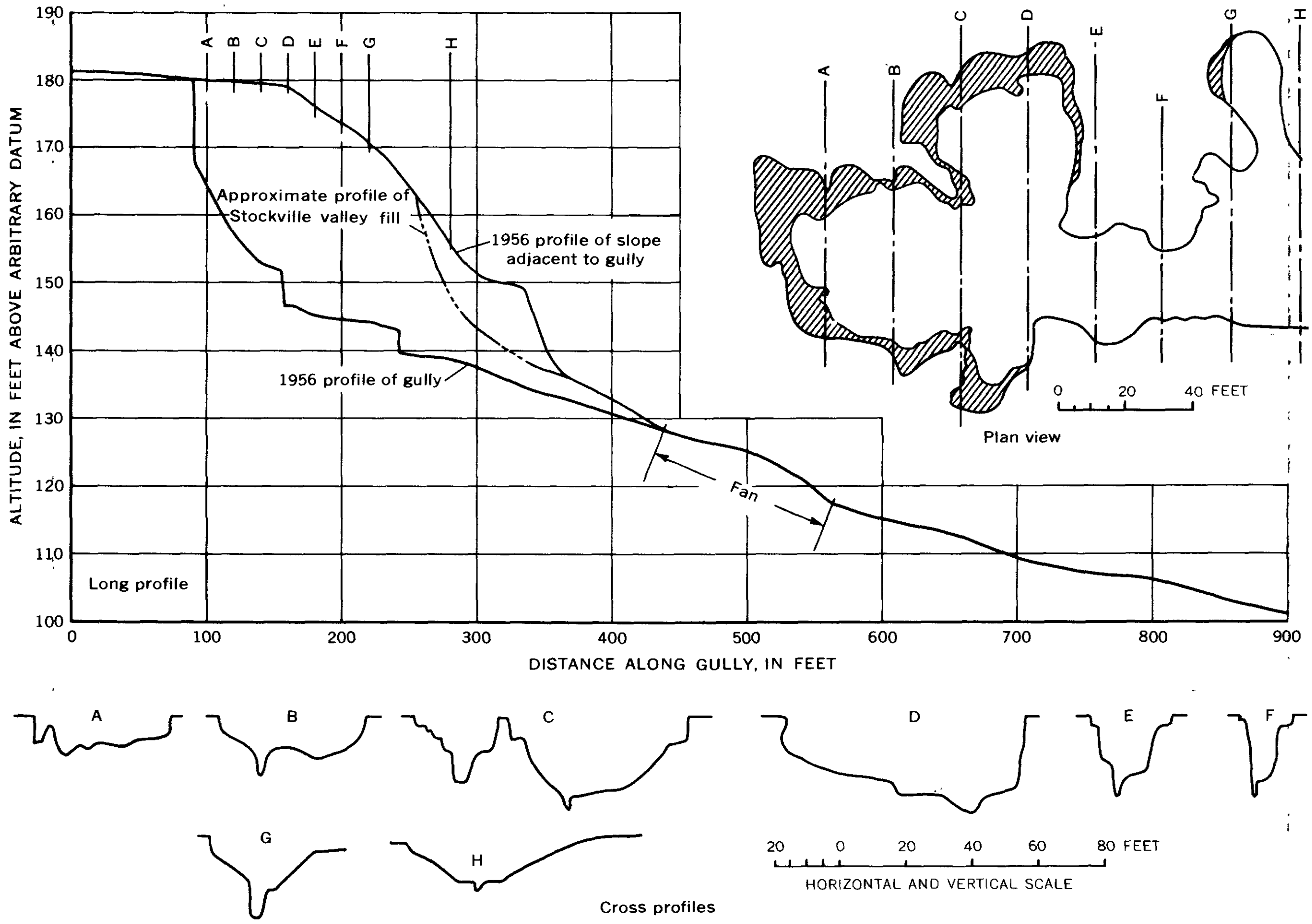


FIGURE 217.—Long profile, plan view, and cross profiles of a large valley-head gully, designated gully 4 in figure 214. Shaded area on plan view indicates enlargement during the period 1954–57. Based of field surveys. Location of cross profile H is beyond limit of area shown in plan view.

scarps are nearly vertical or even overhanging at the rim, and the channel profile downstream from the head scarp is typically broken by several channel scarps. The channel scarps deepen the gully as they advance and probably increase the height of the head scarp by merging with it. The modal value for height of head scarps of active valley-head and valley-side gullies on Dry Creek is about 10 feet.

The mechanism of head-scarp advance is not identical with that described for large valley-bottom gullies. Most valley-head gullies are advancing into surfaces underlain by a well-developed soil profile and, except for gullies advancing into cultivated upland, protected by a sod cover. The rills or trenches that lead to the gully head have not been incised through this profile; hence, the head scarp has a resistant rim. On the other hand, plunge pools are not conspicuous at the base of the head scarps, and saturation of the massive silt by plunge pool action is less important than that for large valley-bottom gullies. The water flowing over the rim of the head scarp has relatively small volume and velocity, and silt beneath the resistant rim is disintegrated by back trickle of water. Underground drainage, which probably enters the ground through rodent burrows upslope from the head scarp, is conveyed into the gully head at some point below the resistant rim. The abundance of rodent burrows intersected by some head scarps, as well as the overhanging of the resistant rim, is shown in figure 219. Head scarps less than 4 feet high do not advance rapidly because the resistance of the soil profile and the sod cover extend to about this depth.

Material that slumps from the head scarps and side scarps accumulates on the gully floor and is gradually removed by runoff. Deposition is uncommon in the trench that drains the gully head, but much deposition takes place where this trench enters the valley flat. The number of valley-head and valley-side gullies that discharge directly into the channels of major tributaries is insignificant, and

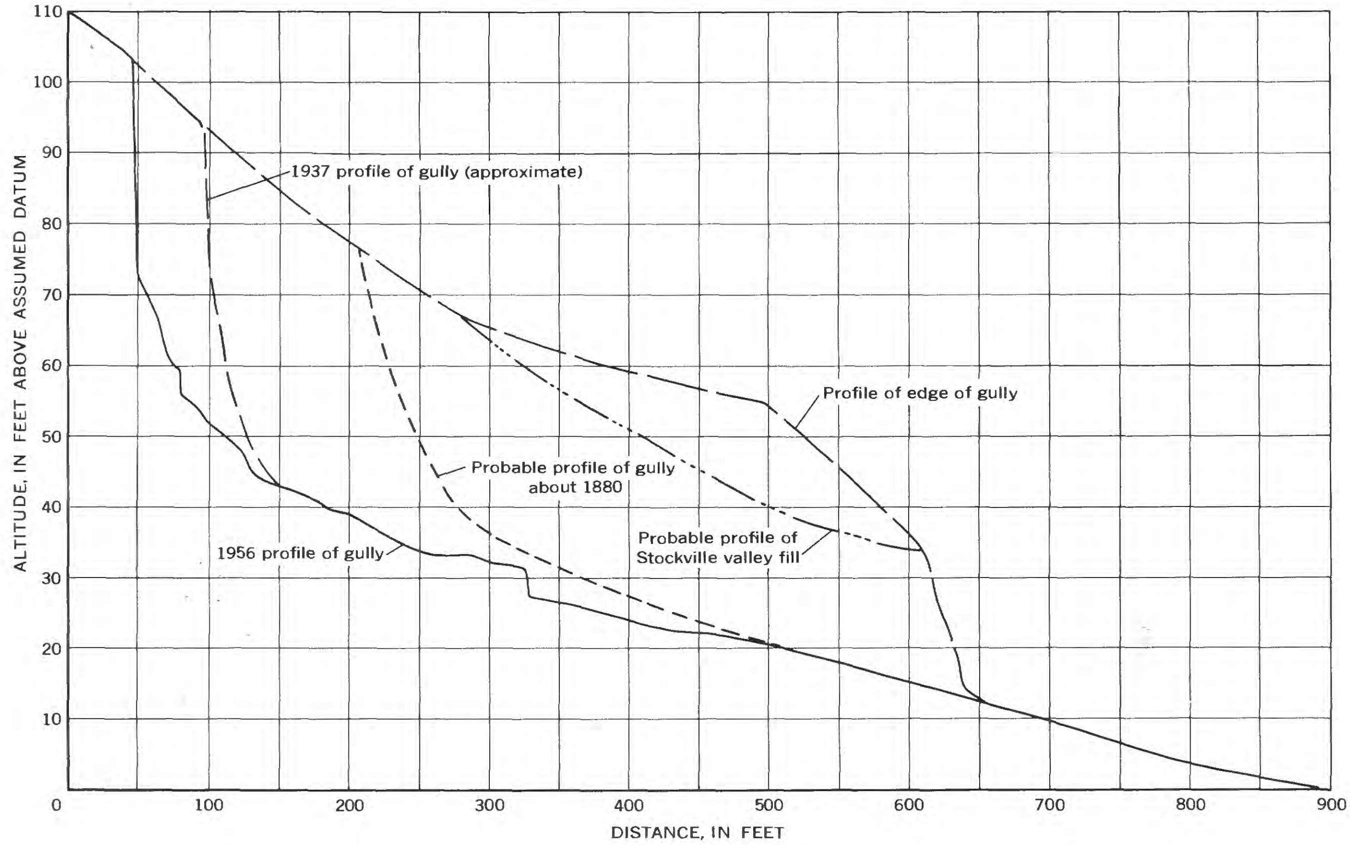


FIGURE 218.—Long profile of a large valley-head gully, designated gully 1 in figure 214.

most of the material eroded is probably deposited on valley flats.

Although the general conditions of topography and vegetation that are conducive to the formation of valley-head gullies can be stipulated, the localization of a gully in a particular valley head rather than in an adjoining valley head depends on events that cannot be reconstructed. Such events include the past methods of cultivation of the upland and the past land use of the valley head, as well as such fortuitous events as the digging of burrows by animals. Moreover, no correlation whatever is apparent between the size of a gully and its topographic situation. Study of the topography of seven of the largest valley-head gullies in the basin showed that the drainage areas ranged from 4 to 37 acres and that the slope of the upland draining into the valley head ranged from 0.02 to 0.06 foot per foot. The slope of the valley heads could not be accurately reconstructed, but all appeared to have been relatively steep. Other valley heads, similar in drainage area and steepness to the severely gullied valley heads, contain small gullies or none.

GULLYING AND LAND USE

That most of the active valley-head and valley-side gullies in the Medicine Creek basin are man induced is highly probable. Many of the valley-side gullies are directly associated with cultural features—such as roads, buildings, and fences—and nearly all the valley-head gullies have begun in valley heads that drain areas of cultivated upland. During past naturally induced episodes of erosion, gullying does not seem to have begun in valley heads. The two post-Stockville episodes of trenching stopped short of the valley heads or else progressed from downvalley to the valley heads. The drainage system is presently extending itself beyond the valley heads and into the upland, a process that last took place before accumulation of the Stockville terrace deposits. The lack of gullying in two tributary heads on Dry Creek, densely vegetated because of protection by fences, indicates that land use has caused gullying elsewhere. (See fig. 182.)

The role of land use in the initiation and growth of large valley-bottom gullies is uncertain. Geologic evidence indicates that valley-bottom gullying has taken place on Elkhorn Canyon and probably on

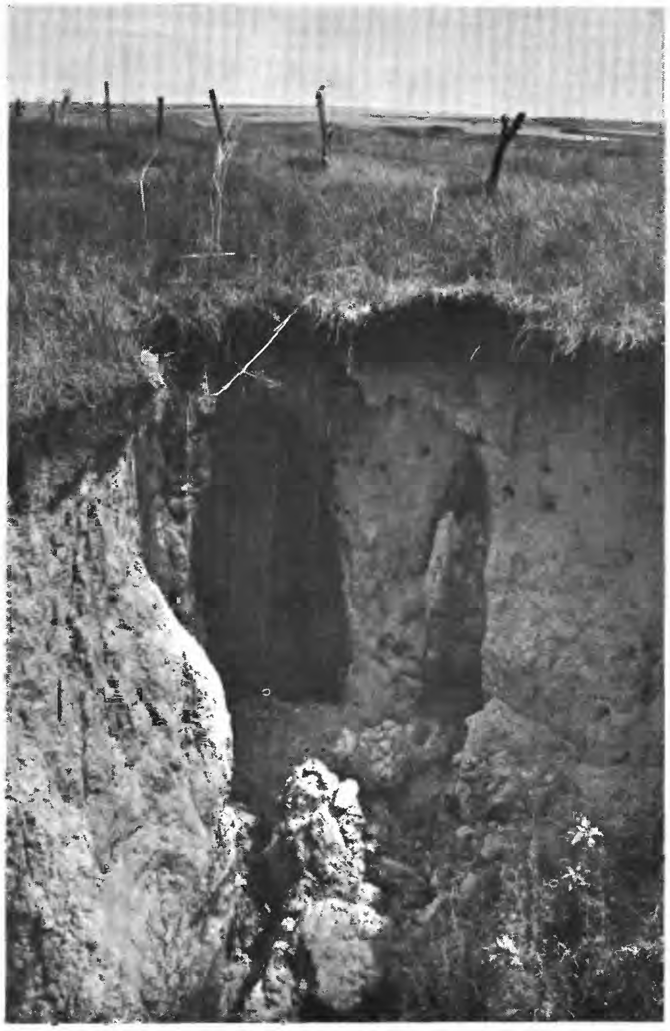


FIGURE 219.—Head scarp of a small valley-head gully on Dry Creek. Note animal burrows and overhanging rim of head scarp.

Dry Creek within the past 350 years and before the arrival of settlers. There is no evidence of late Recent valley-bottom gullying elsewhere in the basin, except that valley-bottom gullies, probably formed since settlement, are advancing rapidly at one or more localities in the valleys of major tributaries to Medicine Creek. The formation of these large valley-bottom gullies entirely from natural causes is improbable. The condition of the vegetal cover in relatively undisturbed areas indicates that the climate since settlement has not been particularly conducive to the formation of gullies.

Antevs (1952) concludes that arroyo cutting and filling in the semiarid southwest are controlled mainly by vegetation, which is in turn controlled naturally by climate. Channeling is a result of drought; filling takes place during climatic transitions; and soil development takes place during relatively moist periods. Arroyo cutting was caused mainly by drought in the past and by overgrazing since 1875. Bryan (1941) also concludes that a slight change in climate from the dry toward the less dry is adequate to convert ephemeral streams from a condition of erosion to alluviation.

These conclusions are reasonable, although the specific climatic conditions that prevailed during past episodes of cutting and filling cannot be reconstructed by any presently known method. During dry years in the Medicine Creek basin, gully advance has been negligible and alluviation has taken place in large valley-bottom gullies. Gullying does not literally take place during dry years, but rather during the wet years that occur from time to time during a general period of drought. A temporary effect of drought may be an increase in the rate of accumulation of valley fill, as is suggested by the character of the terrace deposits on Elkhorn Canyon; but valley fill accumulated during drought is subject to almost immediate incision. As to the climatic conditions that prevailed during episodes of filling, good faunal evidence indicates that the Stockville terrace deposits accumulated during a climatic regime very similar to the present climate. Past episodes of cutting are probably due to a series of droughts more rigorous than any recorded since white settlement.

CONTROL OF GULLIES

Valley-head gullies of moderate to large size have been stabilized in some parts of the basin. The most effective methods of stabilization have involved the construction of an arcuate ditch above the gully head and the diversion of drainage along grassed waterways on either side of the gully. As is true of gully control structures generally, these must be maintained; and lack of maintenance has resulted either in renewed activity of the gully head scarp or in trenching of the grassed waterways.

A heavy vegetal cover in a valley head inhibits formation of new gullies because gullies begin on the valley head rather than on the upland. The cultivation of upland to the very edges of valley heads has been unfortunate. Restoration of native vegetation in the valley heads and in the area of upland adjoining the valley head would probably be effective in preventing new gullies and in stabilizing gullies of small to moderate size.

No large valley-bottom gully in the Medicine Creek basin has been effectively controlled, and only one effort toward control was noted. Concrete blocks were placed in the head of the main gully on Dry Creek, but these had no apparent effect. The control problem is complicated by the fact that a given head scarp may have in its wake a series of channel scarps, all of which must be controlled. A reduction of runoff on the valley bottom is the only apparent solution to the problem, and this can probably be achieved by construction of terraces on the upland, restoration of native vegetation of some parts of the valley bottoms, and more moderate grazing.

SUSPENDED SEDIMENT AND THE HYDRAULIC GEOMETRY OF CHANNELS

By Cloyd H. Scott

Medicine Creek has a well-sustained low flow. Fox Creek and Brushy Creek also receive groundwater inflow, although the volume is not so great as the volume received by Medicine Creek. Fox Creek has a well-sustained low flow, but Brushy Creek usually stops flowing for some time during the summer months. The other gaged tributaries, Dry Creek and Mitchell Creek, and most of the ungaged streams in the basin flow only after rainfall. Typical hydrographs of large flows are shown in figure 220. The magnitude of these flows was such that the daily mean discharge was equaled or exceeded about 1 percent of the time. Medicine Creek at Maywood rises and falls more slowly than the others because of reservoir regulation upstream.

Medicine Creek and its tributaries tend to be "flashy" streams; that is, the discharges increase rapidly in response to rainfall, and peaks are of short duration. This flashy condition is probably the result of several factors, the most important of which is the intensity of thunderstorms. One storm produced 1.70 inches of rain in 45 minutes at Tobiassen gage. Such intense storms do not occur often, but storms that produce as much as three-fourths of an inch of precipitation in an hour or less are common.

The thunderstorms result in runoff having moderately high suspended-sediment concentrations. The maximum observed concentration in the basin during the approximately 37 years of combined station record was 192,000 ppm (parts per million), and the maximum observed suspended-sediment concentration was more than 100,000 ppm in 5 of the 37 years of combined station record. All the annual maximum observed concentrations were in excess of 10,000 ppm for the period of record. Maximum concentrations in excess of those observed undoubtedly occurred during most years. Because concentrations do not remain high for very long, the maximum daily suspended-sediment concentrations are much less than the maximum observed concentrations. The maximum daily concentration during the period of record was 37,600 ppm at the Fox Creek station, but the maximum exceeded 20,000 ppm during only 3 years of combined station record. The maximum daily concentrations were larger than about 1,000 ppm for the combined record, and about one-third were between 10,000 and 20,000 ppm.

The material that makes up suspended sediment is relatively fine because of the general lack of sources of coarse material in the basin. The percentages of clay (finer than 0.004 mm) and silt (0.004 to 0.062 mm) are variable, but clay and silt together make up 90 percent or more of the suspended sediment. Ten percent or less of sand (0.062 to 2.00 mm) is generally finer than 0.125 mm except at the two stations on Medicine Creek, where a few samples contain 1 or 2 percent of sand ranging from 0.125 to 0.250 mm.

Stream-channel cross-sectional shapes are rather diverse within the basin, particularly the shapes of channels of ephemeral streams. In cross section, the channels of ephemeral streams range from shallow swales on the valley floor to deeply incised trenches, either wide or narrow. Figure 210 (*upper left*) illustrates a broad valley floor in which a narrow channel is forming. In figure 204 (*upper left*) a narrow trench is shown upstream from the head of a gully, and this trench is being widened and deepened by the advance of the gully head scarp. The broad trench formed by advance of the head scarp is only about twice as deep as the narrow trench, but a short distance downstream from the head scarp the width of the broad trench is several times that of the narrow trench. Head scarps are advancing in some valley floors where narrow channels are poorly defined or do not exist at all. As a result of the advance of these head scarps, the shape of the channel is changed from broad and shallow to broad and deep.

Dry Creek (fig. 210, *upper right*) and Brushy Creek both have broadly incised channels at the gaging stations, and Brushy Creek has a poorly defined low-flow channel in the broadly incised channel. Medicine Creek and Fox Creek, which are perennial streams, have well-defined low-flow channels at the gaging station.

HYDRAULIC RELATIONS AT A SECTION AND IN A DOWNSTREAM DIRECTION

As the discharge at a particular cross section (called "at a station" by Leopold and Maddock, 1953, p. 4) in a stream increases, the width, depth, and velocity increase. Previous investigators (Leopold and Maddock, 1953; Wolman, 1955; and Leopold and Miller, 1956) have shown that, within limits of

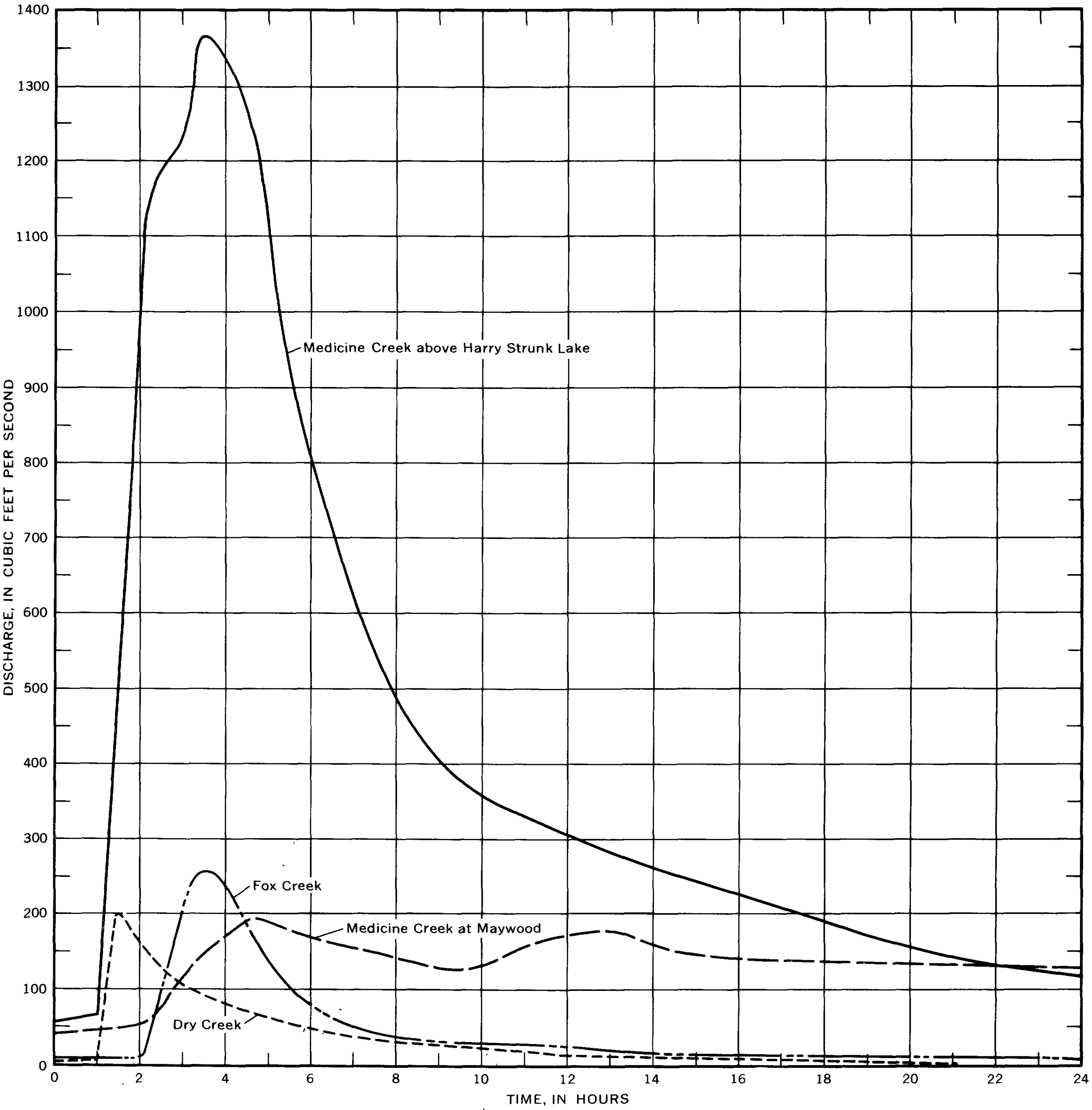


FIGURE 220.—Typical hydrographs of large flows.

bankfull discharge, these variables are simple power functions of the water discharge of the form

$$\bar{u} \alpha Q^m$$
$$d \alpha Q^f$$
$$w \alpha Q^b$$

where $\bar{u}$ is mean velocity (fps),
d is mean depth (ft),
w is width (ft), and
Q is water discharge (cfs).

The product of mean velocity, width, and mean depth must equal discharge; therefore, the sum of the exponents b, f, and m must equal 1.00.

Points on graphs of width, depth, and velocity versus discharge for the gaging stations in the Medicine Creek basin scatter rather widely from the mean, particularly for Brushy, Dry (fig. 221), and Mitchell Creeks. Scatter at the lower values of discharge is caused, in part, by natural variations

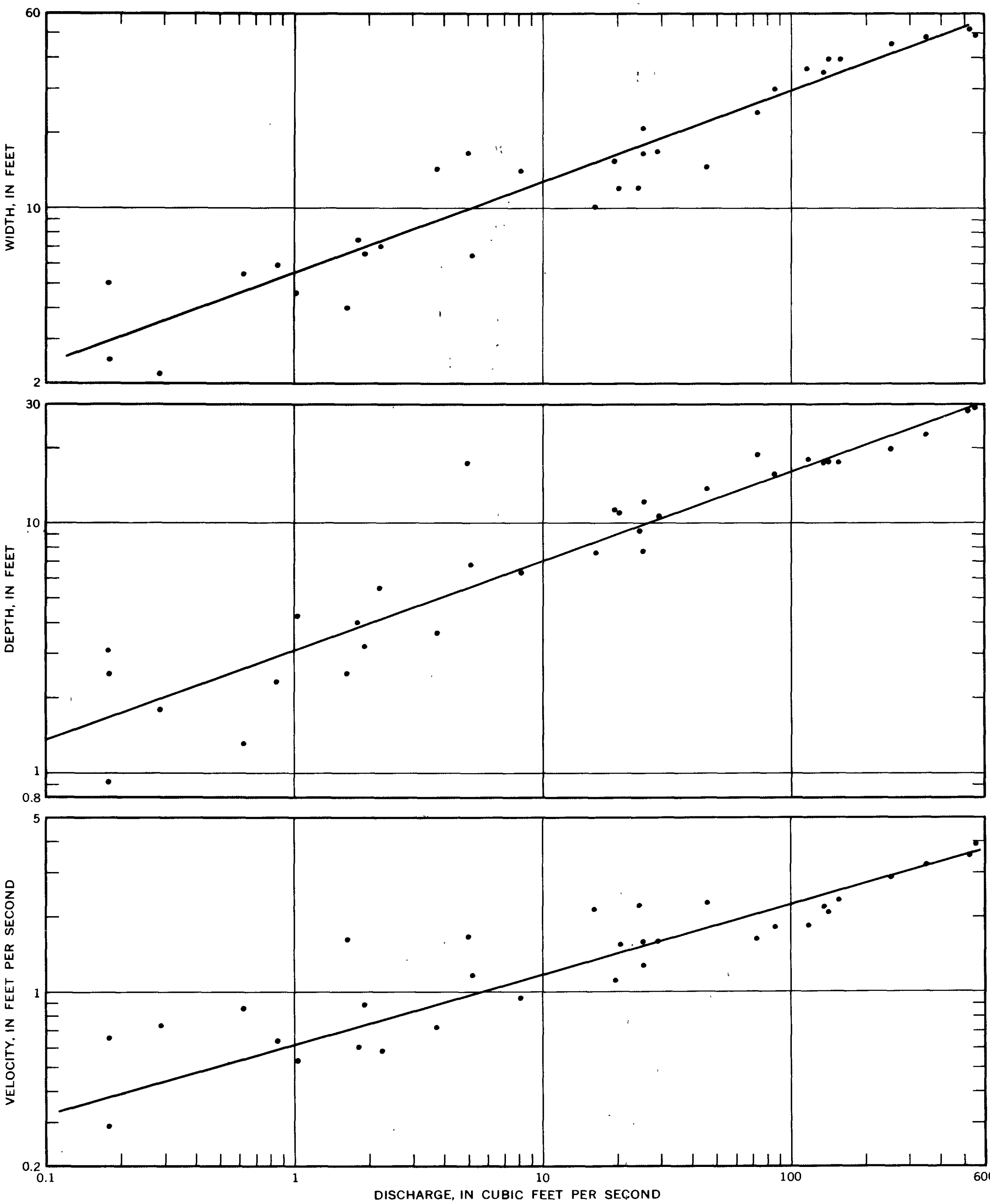


FIGURE 221.—Change of width, depth, and velocity with increasing discharge at a section, Dry Creek near Curtis.

in channel shape at the different sections used for making discharge measurements by wading. Flows too deep to be waded were measured at a single section at each of the stations, and the scatter on the plots is somewhat reduced at the higher discharges. There would be some scatter on the plots even if all measurements were made at a single cross section.

The slopes of curves relating width, depth, and velocity to discharge at each gaging station were fitted by eye and adjusted so that the values of *b*, *f*, and *m* summed to 1.00. The adjustments were small for all sections. The relations of width, depth, and velocity to water discharge at the individual sections have little meaning; therefore, the curves, without the defining points, were placed on one graph, and the discharges that were equaled or exceeded 1, 2, and 25 percent of the time were indicated on each of the curves. Discharges equaled or exceeded 1, 2, and 25 percent of the time were selected because the 1-percent discharge represents approximately bankfull flow at the Fox Creek station but less than bankfull flow for the other stations. The 25-percent discharge is approximately the modal discharge for the Fox Creek and both Medicine Creek stations, and the 2-percent discharge is about the lower limit for which reliable measurements of width, depth, and velocity are available for the Dry, Brushy, and Mitchell Creek stations.

The slopes of width-discharge relations for Dry and Brushy Creeks are greater than those for the other sections, and lines joining points of equal-discharge frequency indicate that the sections should be divided into two groups (figs. 222 and 223). The fact that Mitchell Creek does not fit with either group is attributed to the presence of a concrete control at the section and to a low-water road crossing a short distance downstream, which causes backwater at the section. Therefore, the Mitchell Creek section will not be considered further.

Lines that join points of equal frequency of discharge on the curves of the at-a-station relations represent the downstream relations of width, depth, and velocity to discharge, if the assumption is made that the relation at sections not on the same stream is representative of relations at different sections on the same stream. This assumption may be justified for two reasons. First, the discharges of equal frequency for the two Medicine Creek stations and the Fox Creek station plot about on a straight line even though the uppermost section on Medicine Creek, at Maywood, is somewhat affected by reservoir regulation. Second, the gaging sections are on reaches where flows are over loess, which covers much of the basin. The assumption implies that the channels of two streams are similar at the points along their lengths where the discharges are the same at equal frequencies of occurrence.

The values of *b*, *f*, and *m* for changes of width, depth, and velocity in a downstream direction obtained from figures 222 and 223 cannot be considered reliable because too few stations are available to establish averages. The values can be used to show general differences between the types of streams represented by the two groups.

The downstream relations of width, depth, and velocity to discharge could best be defined by measurements along a stream at several stations for which at-a-station relations of width, depth, and velocity to water discharge and flow-duration curves are available. However, gaging stations of the number required for such a study are found on few if any streams. When better data are lacking, discharge measurements might be made at several sections in a downstream direction at discharges of unknown frequency at each of the sections. Even though the frequency of the discharges were the same at all the sections measured, the plot of width, depth, and velocity against discharge would scatter from the average line because of variations in shape that exist from place to place in a natural channel. Of course, it would not be possible to obtain measurements of discharges of the same frequency at all sections, especially for channels of ephemeral streams.

Assume that a series of measurements are to be made in a downstream direction on Dry Creek at discharges that are equaled or exceeded about 2 percent of the time at each of the sections. Further assume that the downstream relation of width to discharge for Dry Creek is the same as that shown on figure 223 for discharges equaled or exceeded 2 percent of the time. If a measurement is made at the gaging station at a discharge assumed to be equaled or exceeded 2 percent of the time, but the discharge is actually the one equaled or exceeded 1 percent of the time, then the width will be greater than that indicated by the downstream relation at discharges equaled or exceeded 2 percent of the time by about 40 percent plus or minus the deviation from the at-a-station relation (fig. 221). About two-thirds of the points that defined the at-a-station relation for the Dry Creek station were within plus 35 and minus 35 percent of the mean line. As the difference between the slopes of the lines for the at-a-station relations and the downstream relations of width, depth, and velocity to discharge becomes less, the scatter from the average line attributable to differ-

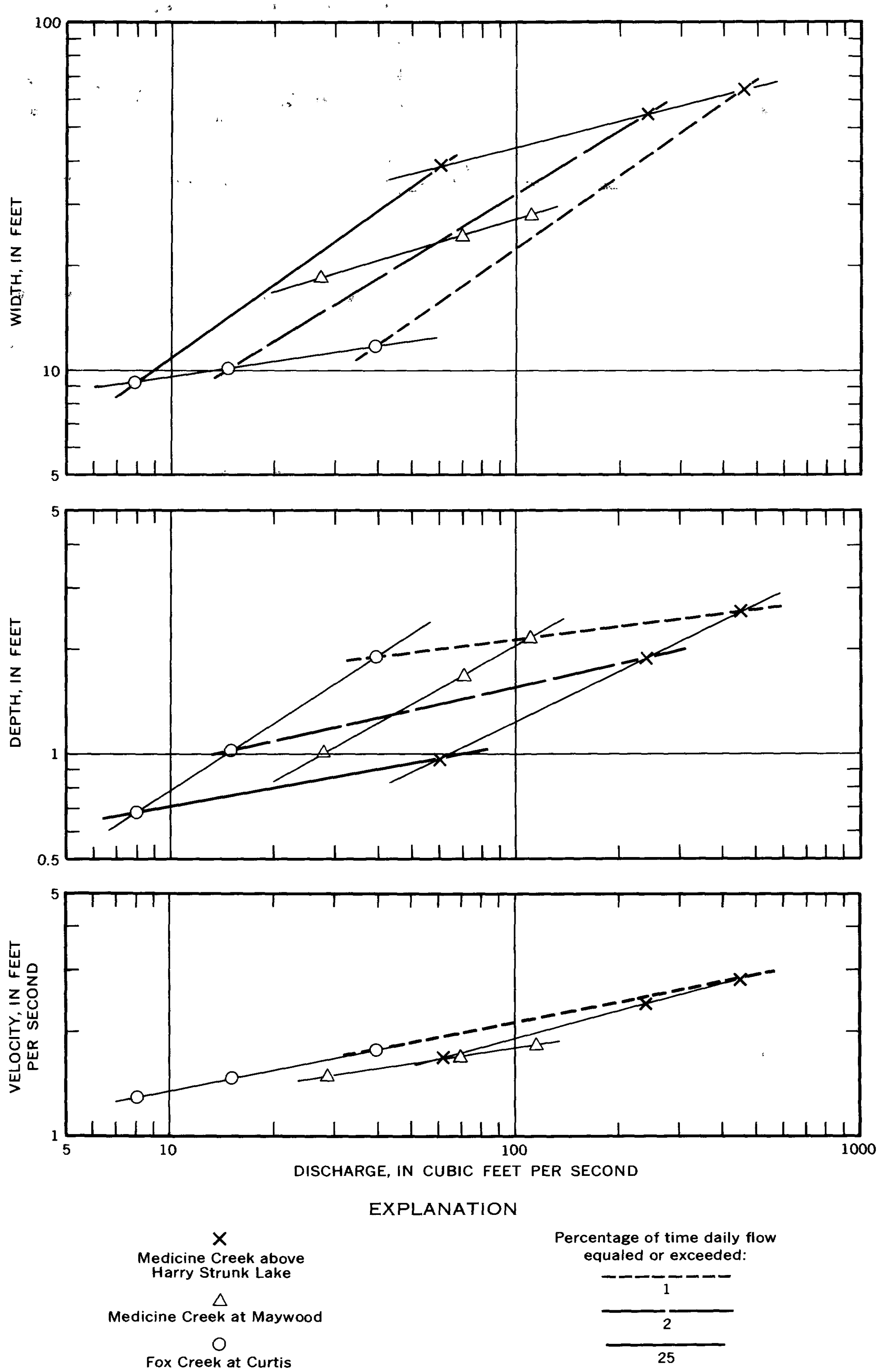


FIGURE 222.—Change, of width, depth, and velocity in a downstream direction for channels of perennial streams.

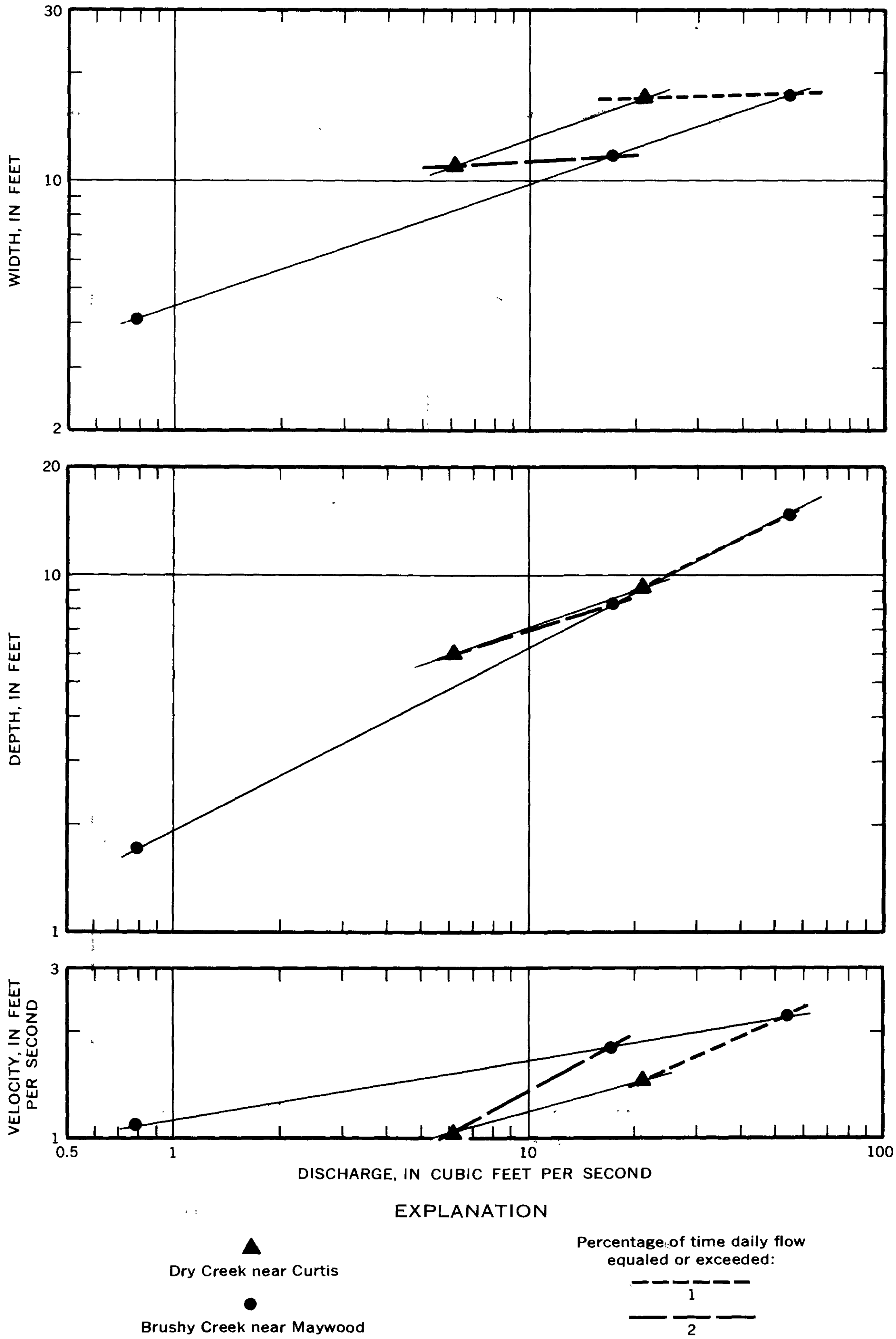


FIGURE 223.—Change of width, depth, and velocity in a downstream direction for channels of ephemeral streams.

ences in frequency of discharge at the various stations becomes less. Establishing fairly reliable downstream relations of width, depth, and velocity to discharge is possible if a sufficient number of sections are selected to provide a reliable average and if measurements of extremely high or low discharges are avoided.

The slopes of the relations of width, depth, and velocity to discharge (table 8) indicate differences

TABLE 8.—*Values of* b, f, *and* m *for streams in Medicine Creek basin*

	Perennial streams		Ephemeral streams	
	At a station [1]	Downstream [2]	At a station [1]	Downstream [2]
b	0.24	0.69	0.35	0.03
f	.56	.12	.43	.48
m	.20	.19	.22	.45

[1] Unweighted average.
[2] At discharge equaled or exceeded 1 percent of time.

between the perennial and ephemeral streams in the Medicine Creek basin. The at-a-station slope values may be considered reliable, but slopes for the downstream relations probably only indicate the correct order of magnitude. The differences between the at-a-station relations for the perennial and ephemeral streams reflect the differences in channel shapes. The channels of the perennial streams have fairly steep banks, and the width does not increase as rapidly as the depth. The channels of the ephemeral streams also have steep banks; but the bottoms of the channels are somewhat parabolic, and the width can increase rapidly as discharge increases until the limits of the steep confining banks is reached. However, a relatively large discharge is required for the width of water surface to reach the confining limits of the steep banks in the broadly incised channels of ephemeral streams. The changes of velocity with increasing discharge are about the same for perennial and ephemeral streams; therefore, the change of width is less and the change of depth is greater with increasing discharge for perennial streams than for the broadly incised ephemeral streams.

Depths of water in a channel normally do not increase very rapidly in a downstream direction. That is, it would not be expected that the depth at a cross section on a stream would be much greater than the depth at another section several tens of miles upstream. The downstream change in depth for perennial streams in Medicine Creek basin is relatively small, and the downstream change in velocity is about the same as the change in velocity at a station. Because the discharge at a constant frequency increases downstream, the width must increase rapidly. However, the width for the broadly incised ephemeral streams increases very little downstream. The increase in discharge is accommodated by relatively large changes in both depth and velocity in a downstream direction. The downstream change in width of the broadly incised ephemeral streams may be greater than that indicated on figure 223, but the change still would not be so large as the change of the perennial streams. Figure 204 (*upper left*) shows the main-stem channel of Dry Creek just below the gully scarp that forms the end of the broadly incised channel, and figure 210 (*upper right*) shows the main-stem channel at the gaging section. The top widths of the channel just below the gully scarp and in the vicinity of the gaging section are 40 to 50 feet. The distance is too short and the measurements are too rough to indicate the change in width along the Dry Creek channel; but if the width increased as rapidly as the indicated change of about 5 percent per mile on Medicine Creek between Maywood and the gage above Harry Strunk Lake, the width at the gage on Dry Creek should be more than 10 feet wider than the width in the vicinity of the head scarp.

SUSPENDED-SEDIMENT DISCHARGE RELATIONS

The curves relating suspended-sediment load to water discharge for the perennial streams (fig. 224) have breaks in slope at water discharges that are higher than normal but below bankfull stage. The curves applying to ephemeral streams show no corresponding breaks in slope (fig. 225), and in value of slope they are generally similar to the upper part of the curves applying to perennial streams. The breaks in the suspended-sediment rating curves result from a rather complex and uncertain set of conditions. The concentrations, peak and mean, for runoff periods are highly variable. Even two events, which may be very similar with respect to peak discharge and total discharge, may have very differpeak suspended-sediment concentrations and mean concentrations. The peak concentration generally occurs before the peak water discharge for stations in the Medicine Creek basin, but the length of lead is variable. The length of lead may be from 1 to 3 or or more for the perennial streams and is generally an hour or less for the ephemeral streams. The shorter lead time, in general, occurs with a small peak discharge. The variability in concentration of suspended sediment and in length of lead results because the suspended-sediment load is made up principally of fine material derived from sources other than the streambed. The amount of fine material that is transported by the streams during a given storm depends on intensity and duration of rainfall, soil conditions at the time of the storm, and other factors. The leading concentration indicates that the sediment rating curve should describe a loop, but because of the variability of concentration from storm to storm and the variability of the lead time of concentration, the loop would not be defined by an average of many measurements for many storms. Instead, the points defined by the measurements would scatter with increasing discharge. (See fig. 224.) The measurements that define the points of figures 224 and 225 are somewhat biased, however, because only a few measurements were obtained before peak water discharge and practically none were obtained near peak sediment concentration. The generally rapid rises and mud roads prevented arrival of workers at the stations much before the occurrence of the peak water discharge, particularly on the ephemeral streams. Nearly all the measurements at those stations were obtained after the peak water discharge; therefore, the scatter of points is fairly uniform throughout the range of water discharge.

The lower part of the curves for the perennial streams is represented mostly by measurements made during small rises. A small increase in water discharge is accompanied by a relatively large increase in sediment concentration, and the lead time for smaller rises is generally short. As a result, the slope of the relation of water discharge to sediment discharge increases more rapidly for low water discharges than for the high water discharges.

The fact that the slope of the water-sediment discharge relation is slightly less than unity for the ephemeral streams indicates that the concentration remains about the same or decreases slightly in a downstream direction, but the fact that the slope of the water-sediment discharge relation is slightly greater than unity for perennial streams indicates that the concentration increases in a downstream direction. Because so few records are available to establish good average downstream relations, it is not possible to state that an actual difference exists between the slopes of the water-sediment discharge relations in a downstream direction for perennial and ephemeral streams.

PARTICLE-SIZE DISTRIBUTIONS OF SUSPENDED SEDIMENT AND BED MATERIAL

Average particle-size distributions of suspended sediment were obtained from unweighted averages of all size analyses at each of the stations. The size analyses were not weighted because a plot of water discharge against percentage of suspended sediment finer than 0.004 mm and coarser than 0.062 mm indicated no relation between instantaneous water discharge and particle-size distribution. The average size distributions for each year for each of the stations did show an inverse relation to annual water discharge; that is, the percentage finer than a given size decreased as water discharge increased. The relation was not very well defined, and the indicated change was not large; but the relation of annual water discharge to the average percentage finer than a given size does indicate the possibility of a relation between the percentage finer than a given size and instantaneous water discharge. The large variability of particle-size distributions for a given water discharge, however, prevent detection of a relation.

Average particle-size distributions of suspended sediment and bed material (figs. 226 and 227) indicate little difference between size distributions of suspended sediment and a large difference between size distributions of bed material for Medicine Creek at Maywood and Medicine Creek above Harry Strunk Lake. Medicine Creek above Harry Strunk Lake has a small percentage of material in the 0.125- to 0.250-mm range in suspension; such material is normally not in suspension at Maywood. Although the size distributions of suspended sediment are similar at the Medicine Creek stations, the distributions of bed material are very different. The bed material at Maywood has 36 percent of the material finer than 0.062 mm, 44 percent between 0.062 and 2.0 mm, and 20 percent coarser than 2.0 mm; at the station above Harry Strunk Lake only 8 percent is finer than 0.062 mm, 80 percent is between 0.062 and 2.0 mm, and only 12 percent is coarser than 2 mm. The increase of material in the 0.062- to 2.0-mm range is probably from the tributaries draining the area to the southwest of Medicine Creek. There are, however, no analyses of bed-material samples from any of these tributaries. The average distribution of only three samples, each of bed material from the low-flow channels of Brushy and Fox Creeks (fig. 50), indicates that the bed material at those stations is similar to bed material at Medicine Creek at Maywood, especially for the sizes finer than about 1.0 mm. Suspended-sediment size distributions for Brushy, Fox, Dry, and Mitchell Creeks (fig. 226) show that there is an apparent increase in fine material available for transport as suspended sediment from the west to the east side of the basin. Brushy Creek, on the west side of the basin, has a median suspended-sediment particle size of about 0.014 mm, whereas Mitchell Creek, on the east side

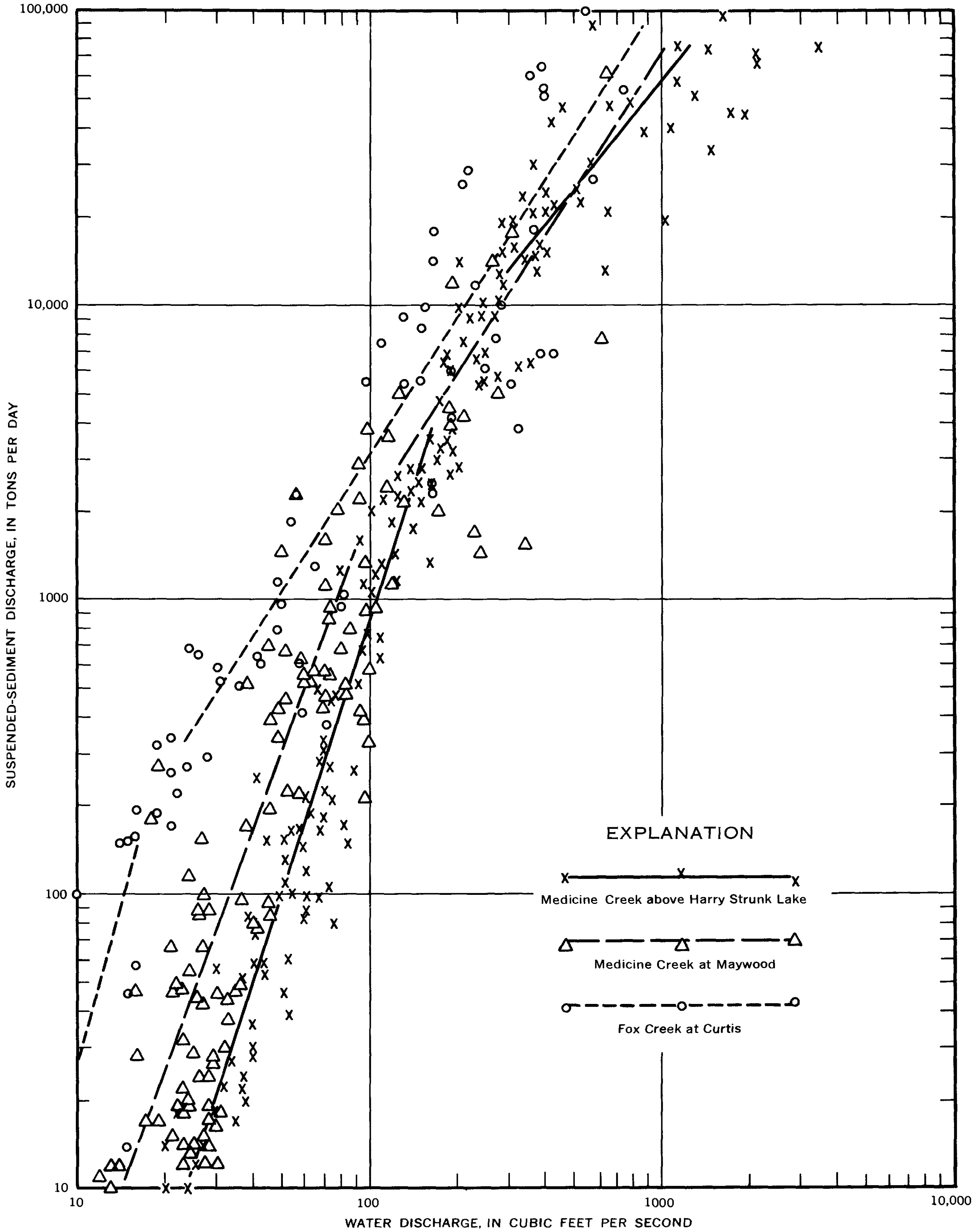


FIGURE 224.—Change of suspended-sediment load with increasing discharge at a section, perennial streams.

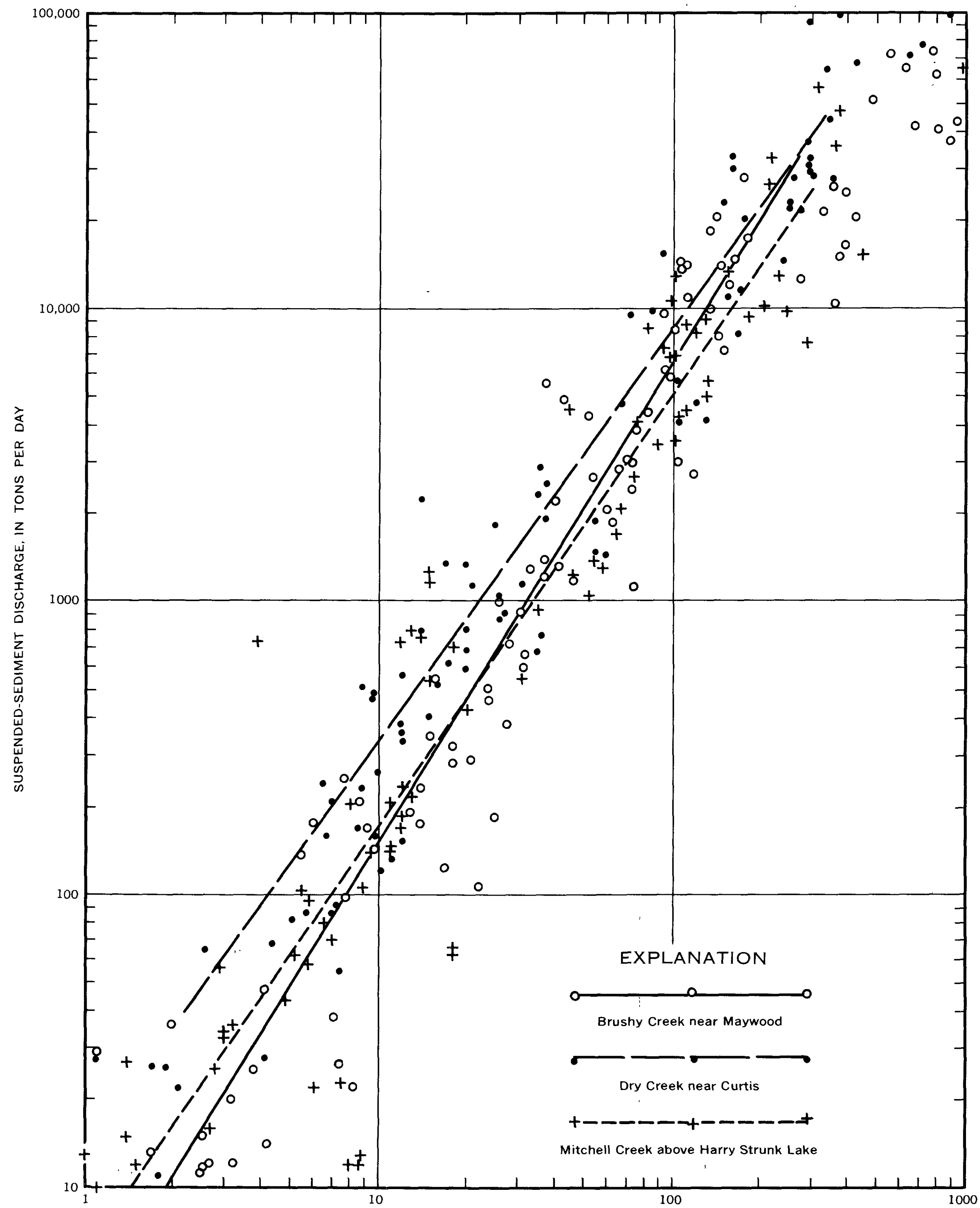


FIGURE 225.—Change of suspended-sediment load with increasing discharge at a section, ephemeral streams.

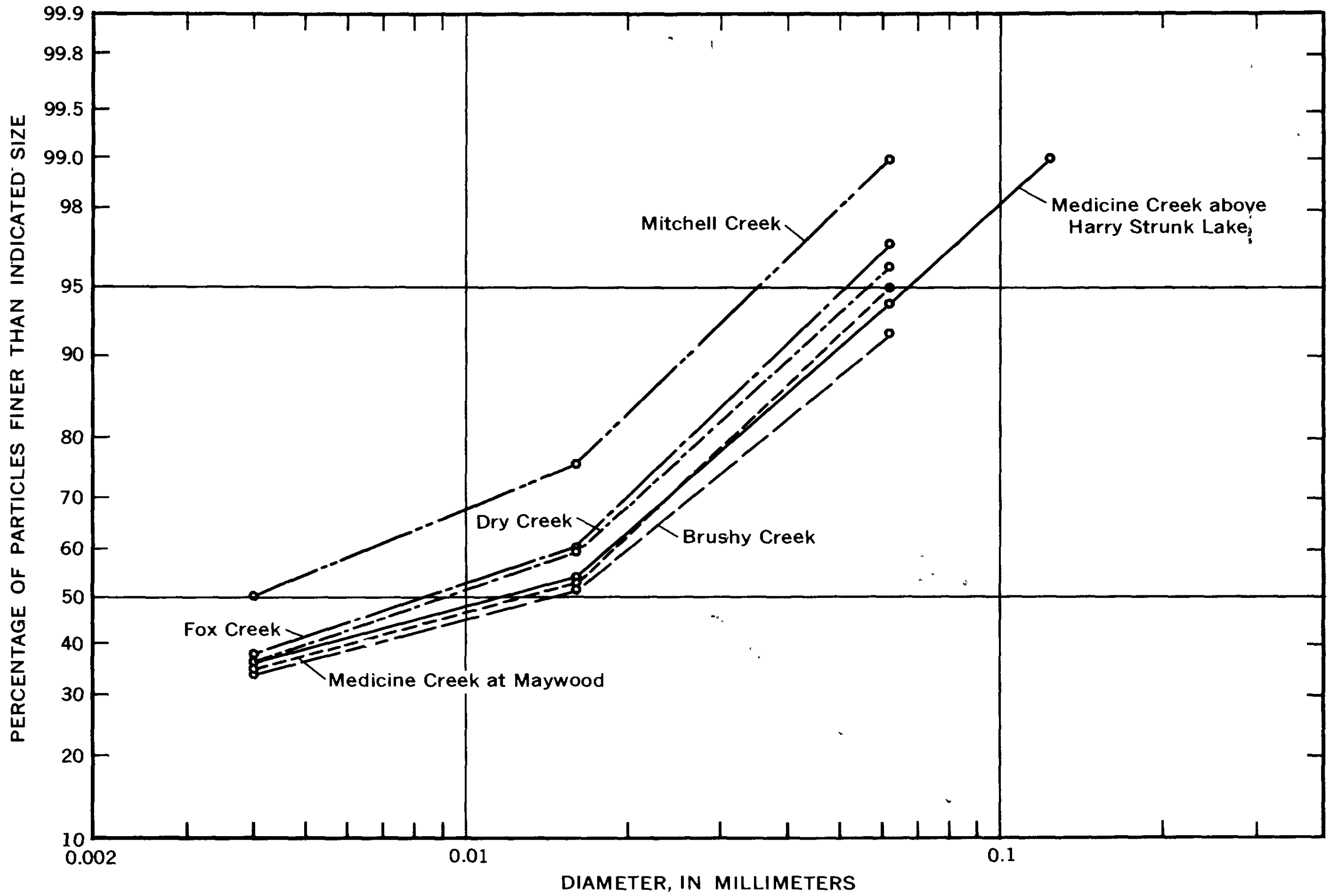


FIGURE 226.—Size distribution of suspended sediment at gaging stations in Medicine Creek basin.

of the basin, has a median particle size of about 0.004 mm. The decrease in median particle size from west to east reflects the increasing distance from the sand-dune area of the extreme western and northwestern parts of the basin.

The measured loads for all the stations are nearly the total loads because the suspended sediment contains little sand and the fine suspended sediment should have fairly uniform distribution in the vertical. Computations of total load were made by the Colby method (Colby, 1957) for the two stations on Medicine Creek, both of which have sand beds. Not many sets of data are available for computation of total loads, but the average percentage of measured load to total load is indicated. At low flow the measured load amounts to about 90 percent of the total load, but at high flow it amounts to more than 95 percent. Because all the suspended sediment at the Dry Creek gage results from storm runoff and a large part of the suspended sediment at the Brushy and Fox Creek gages results from storm runoff, the measured suspended sediment for those stations probably represents 95 percent or more of the total load for the period of record.

RELATIVE SEDIMENT CONTRIBUTIONS OF THE MAJOR TRIBUTARIES

In any basin or subbasin, erosion and deposition are taking place simultaneously, and sediment data collected at any point along a stream represent the net of erosion and deposition upstream from that point.

A measure of the net erosion and deposition in a basin is the discharge-weighted mean concentration of suspended sediment. This is the concentration that would result if all the water passing a point during some period of time were mixed with the suspended sediment passing during the same period. If the cumulative water volume is plotted against cumulative weight of sediment, the slope of a line that joins points of the graph defines the discharge-weighted mean concentration for the period of time for which the data are cumulated. The annual sediment loads and storm runoff for the station were reduced to a per-square-mile basis and are shown

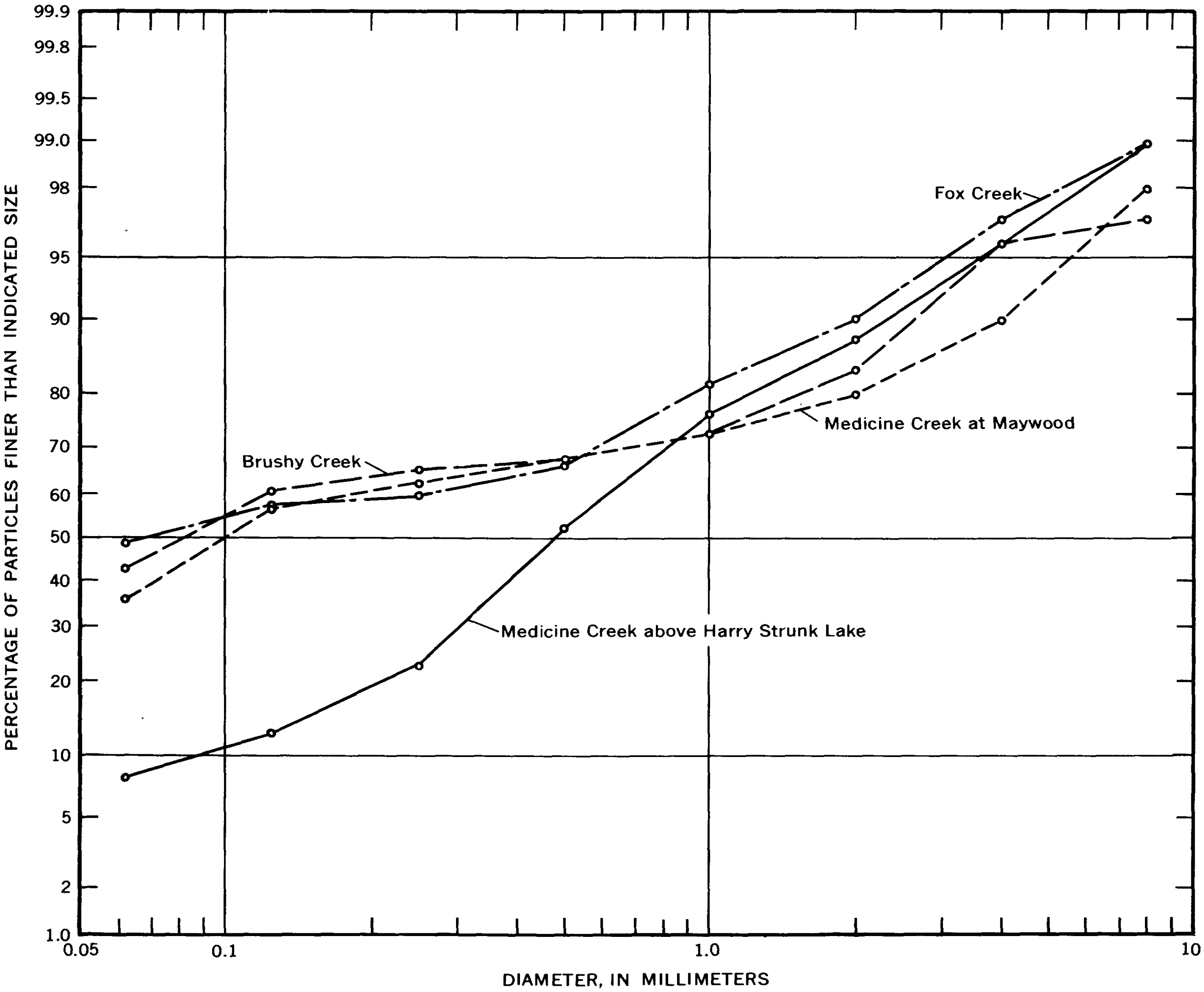


FIGURE 227.—Size distribution of bed material at gaging stations in Medicine Creek basin.

on figure 228. Reducing the values to a per-square-mile basis does not change the constant of proportionality and presents a comparison of storm runoff and sediment yields. Such a comparison is valid if precipitation over the entire basin is assumed to be uniform in amount. Because of the relatively small size of the basin and the low relief, the assumption of uniform precipitation probably is valid if several years record are considered. The differences in total precipitation for the years 1951–58 recorded at the Wellfleet, Curtis, and Stockville rain gages were less than 10 percent. As the time period is shortened, however, the probability of uniform precipitation becomes less.

Each of the stations shows a definite break in slope following the 1951 water year. The break in the curve probably occurs because the ratio between the variables is not constant at all rates of cumulation. If the ratio were constant at all rates of cumulation, the break would have to be explained by a physical change that would cause a greater reduction in sediment yield than in water yield (Searcy and Hardison, 1960). A break in the curve is drawn at the 1956 water year for the Dry Creek data; and breaks at the same year are indicative for Fox and Mitchell Creeks, but they are not drawn. For hydrologic data plotted in this manner, breaks that persist for less than about 5 years should be attributed to chance and ignored unless there is definite reason for believing that such a break should occur. The high rainfall and runoff during the 1951 water year explains the break at the end of that

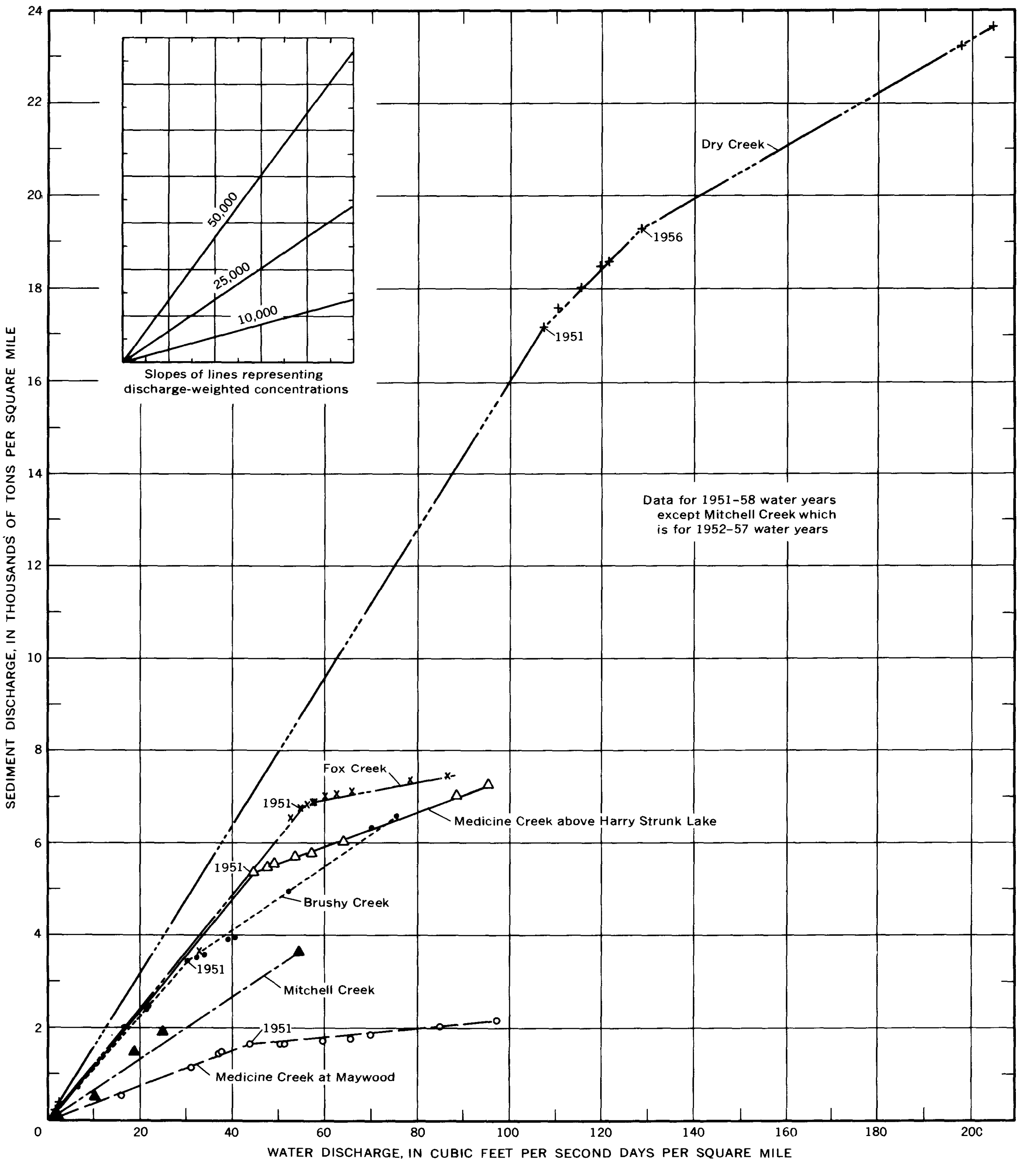


FIGURE 228.—Cumulative water discharge and sediment discharge per square mile at gaging stations in Medicine Creek basin. Year at which a curve changes in slope is indicated.

year. Data are available for only the part of the year when rainfall was extremely heavy. The reason for the break at the end of the 1956 water year is obscure. Runoff for the 1957 water year was generally greater than normal, but the break is in the wrong direction on the basis of the experience for the 1951 water year. Land-conservation work was being actively carried on during the period of the investigation, but there are too few data to evaluate the significance of the break.

The ephemeral streams—Brushy, Dry, and Mitchell Creeks—have higher discharge-weighted mean concentrations and generally yield larger amounts of sediment per square mile for storm runoff than the perennial streams.

GEOMORPHIC PROPERTIES IN RELATION TO WATER AND SEDIMENT DISCHARGE

One major objective of quantitative geomorphic measurements is to select drainage-basin properties that have the highest possible degree of correlation with runoff and sediment yield. If runoff and sediment yield are known for a large number of drainage basins in the same region, statistical methods can be used to evaluate the significance of different drainage-basin properties. If, as in the Medicine Creek basin, runoff and sediment yield are known for only five subbasins, evaluation of the properties cannot be made rigorously by statistical methods. Ideally, the properties selected should be independent of one another, unambiguous, and not unduly time consuming to obtain. For the Medicine Creek basin, properties that meet these qualifications and offer promise of good correlation with runoff and sediment yield are relief ratio, adjusted frequency of first-order streams, and percentage of area in upland.

Relief ratio was shown to correlate with mean annual sediment accumulation for small drainage basins in the upper Cheyenne River basin by Hadley and Schumm (1961, p. 173). Maner (1958) reports that relief ratio correlated more closely with sediment delivery rates than did size of sediment contributing area, drainage density, basin shape, or weighted-average land slopes. The drainage basins studied by Maner, which are in the Red Hills area of Oklahoma and Texas, range from 332 to 0.036 square miles. For these basins, relief ratio showed a correlation, as based on inspection of scatter diagrams, with basin size, basin shape, average land slopes, and drainage density. Maner concludes that sediment delivery rate in the Red Hills area is a function of several drainage-basin properties that evidently are expressed adequately by relief ratio.

For drainage basins that are incised in a level or gently sloping upland surface to approximately the same local relief, a correlation of relief ratio with size and shape properties is apparent. Basin relief increases at a much slower rate than basin length; therefore, relief ratio is reduced both by increase in basin size and by increase in basin length. Because of the decrease in valley-side slope with increasing channel order, the lower relief ratio of high-order basins is accompanied by a lower mean value of side slope. Similarly, because of the decrease in channel slope with channel order (fig. 229), the lower relief ratio of higher order basins is accompanied by a lower mean channel gradient. However, the relation of channel slope to channel order may not be consistent; therefore, relief ratio may not express adequately the slopes of low-order channels.

In a discussion of the interrelations of drainage-basin characteristics, Gray (1961) presents evidence to show that, for small basins, the properties of area, length of main stream, and length to center of area are highly correlated. In a region of homogeneous relief, a correlation also exists between these properties and the slope of the main stream. Although not discussed by Gray, relief ratio probably will express adequately all the above interrelated properties for some regions. In addition, relief ratio will express differences in relief between basins of about the same size. The effectiveness of relief ratio as a property probably depends on, among other things, the constancy in shape of long profile among the basins being compared. A basin whose main

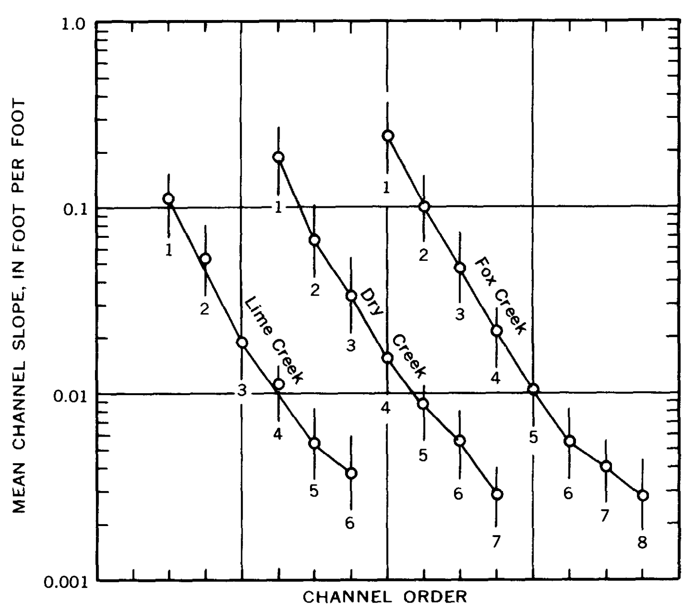


FIGURE 229.—Mean channel slope in relation to channel order for Lime, Dry, and Fox Creek subbasins.

stream is strongly concave upwards in long profile may have the same relief ratio as another basin, of equal size, whose main stream is nearly straight in long profile. However, such differences in long profile surely affect runoff and sediment yield.

Frequency of first-order streams was found by Morisawa (1959) to give a high correlation with peak intensity of runoff for drainage basins in the Appalachian Plateaus. The properties used by Morisawa in multiple regression analysis were relief ratio, basin circularity, and first-order channel frequency. She considers that these three properties express the shape, relief, and network composition of a drainage basin, that they vary independently of each other and of area, and that they do not duplicate any other geomorphic factor. For the Medicine Creek basin, relief ratio is considered to be an adequate expression of basin shape, but first-order channel frequency is an important property not only in relation to runoff and sediment yield but also in relation to gully erosion.

Frequency of first-order channels expresses the small-scale properties of a drainage basin and thereby complements relief ratio, which expresses the larger scale properties. Channel frequency must be adjusted for immature basins according to their differing percentages of upland area. In figure 230 scatter diagrams show the relation of adjusted frequency of first-order channels to mean valley-side slope, slope of first-order channels, and mean length of first-order channels. The number of points is too small to warrant the calculation of correlation coefficients, but the existence of a relation is apparent not only from the scatter diagrams but also from examination of the topographic maps. In addition, the reason for the correlation is apparent from geomorphic history. In subbasins where post-Peorian dissection was most intense, first-order channels are shorter, steeper, and more numerous. Much of the scatter of points in figure 230 is due to the fact that some of the subbasins are less homogeneous than others in texture of drainage.

The relation of length to channel slope for first-order channels in the lower part of Dry Creek is shown in figure 231. Each point represents the mean slope and mean length of 10 channels in a particular length group. Noteworthy is the fact that the shorter channels have relatively steeper slopes than the longer channels. In addition, the shorter channels have steeper valley heads and more concave profiles. This is of particular importance in gully erosion because steep valley heads promote the formation of new gullies.

In combination, relief ratio and frequency of first-

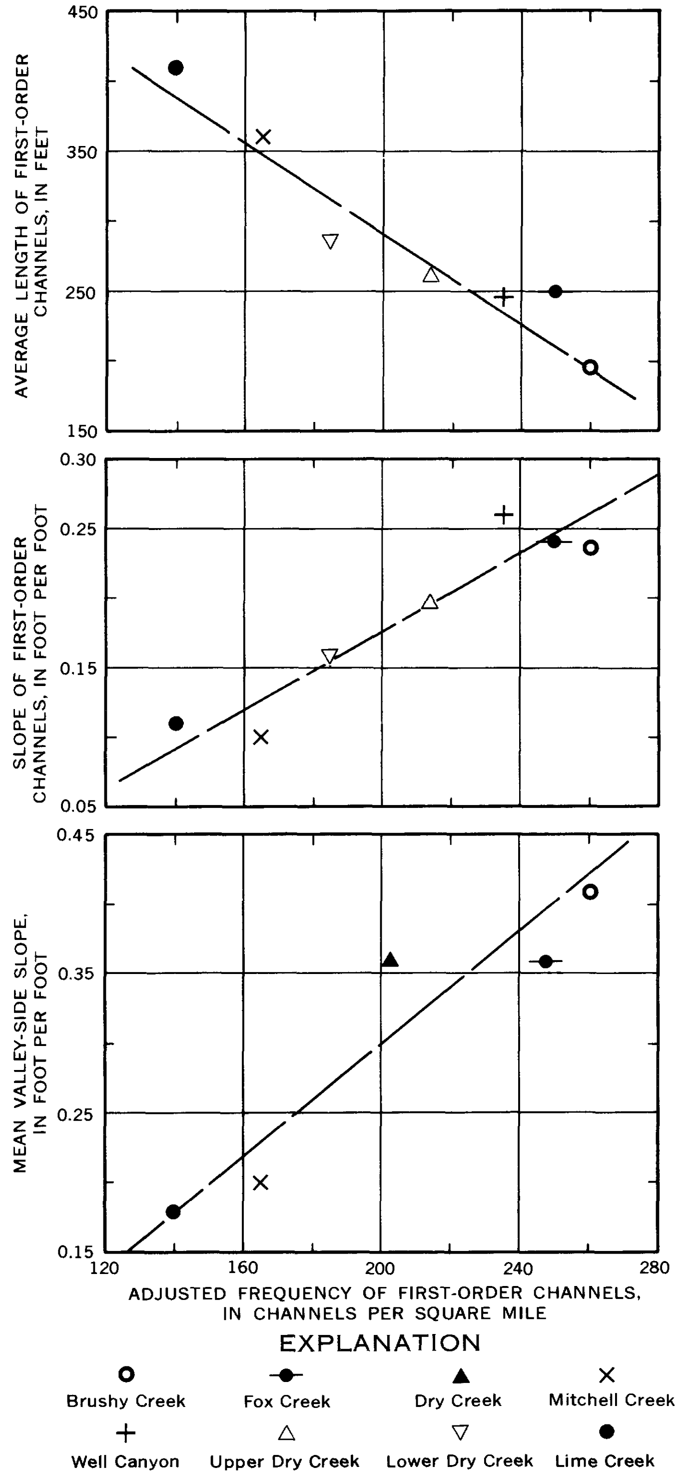


FIGURE 230.—Adjusted frequency of first-order channels in relation to mean valley-side slope, mean slope of first-order channels, and mean length of first-order channels.

order streams should give indirect expression to another important variable—the percentage of area in valley flat. An unusual geomorphic feature of the Great Plains generally is the flatness of valley

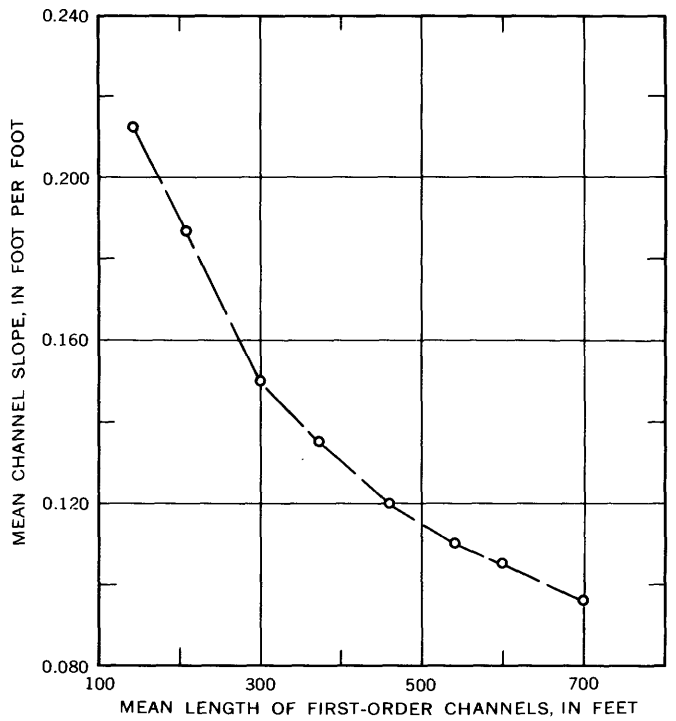


FIGURE 231.—Slope of first-order channels in lower Dry Creek subbasin in relation to length.

bottoms along channels of both low and high order. The percentage of area in valley flat for each channel order in each major subbasin has been calculated from the product of average width of valley flat and average length of channel. (See table 4.) The percentage distribution of valley flat according to channel order differs considerably from one subbasin to the next and depends mainly on the distribution of channel length according to order. In Well Canyon subbasin, for example, about 18 percent of the total area of valley flat is in the wide bottom along the main channel, whereas in Dry Creek subbasin only 8 percent is along the main channel. The probability of deposition of sediment on the main valley flat seems greater for Well Canyon than for Dry Creek, and the probability of rapid runoff is less because of the lower slope angle of the Well Canyon valley. The relief ratio gives an indication of the percentage of valley flat along channels of fourth and higher order, whereas the frequency of first-order channels gives an indication of the percentage along channels of first, second, and third orders. (See fig. 198, in which the slope of the curve relating channel length to channel order changes at about third order.)

Because of the immaturity of drainage in the Medicine Creek basin, a variable is needed to express the difference among subbasins in percentage of upland. The slope of the upland, which shows variation from one subbasin to the next, is related to the slope of channels. In general, the slope of the upland is less than the slope of first- and second-order channels, about equal to the slope of third-order channels, and greater than the slope of fourth-order and higher order channels. (See tables 3 and 4.) The percentage of upland gives a reasonably good indication of land use. (See table 9.) Similarly, the percentage of area in side slope and valley flat shows a correspondence with the percentage of area used for hay and pasture.

The probable effect of the selected properties (relief ratio, frequency of first-order streams, and percentage of area in upland) on runoff and sediment yield can be inferred. On the premise that lower slopes, wider valley flats, and larger (or longer) drainage basins all tend toward reduction of runoff and sediment yield because of greater opportunity for infiltration and for deposition of sediment, runoff and sediment yield should be positive functions of relief ratio. According to the graphs of Hadley and Schumm (1961), the function is exponential where mean annual sediment accumulation in reservoirs is the dependent variable. According to the graph of Maner (1958, fig. 3), the function is exponential where sediment delivery rate is the dependent variable. Sediment delivery rate is the ratio, expressed as a percentage, between annual rate of sediment yield and annual gross erosion rate.

An increase in frequency of first-order channels is associated with an increase in both valley slope and side slope for lower order channels; therefore, increase in water and sediment discharge should be a positive function of frequency of first-order channels. For drainage basins whose main channel is very long and bordered by wide valley flats, a high yield of water and sediment from lower order channels may be largely dissipated along the main channel.

TABLE 9.—*Areas in upland and valley flat in comparison with areas in two categories of land use*

[Land-use percentages are mean values from inventories taken in 1954, 1955, and 1957]

Subbasin	Area in side slope and valley flat (percent)	Area in hay and pasture (percent)	Area in upland (percent)	Area in row crops, small grain, and fallow (percent)	Ratio of row crops to small grain
Mitchell Creek	48.2	51.3	51.8	46.6	1.72
Dry Creek	65.2	69.7	34.8	28.7	1.43
Well Canyon	79.6	83.4	20.4	15.6	1.34
Fox Creek	83.5	86.2	16.5	12.7	1.57
Brushy Creek	74.1	77.7	25.9	21.7	.98

The effect of percentage of area in upland depends on the land use of the upland. If the upland is used mainly for row crops, runoff and sediment yield probably would be a positive function of percentage of area in upland. If, on the other hand, the upland were thickly sodded, the function probably would be negative. A positive function would be expected for the Medicine Creek basin.

The preceding inferences as to the geomorphic properties most highly correlated with runoff and sediment yield cannot, unfortunately, be rigorously tested for Medicine Creek because of the small number of subbasins for which data are available. Nevertheless, a trial multiple linear regression of sediment discharge in relation to the three selected variables (fig. 232) is given in order to illustrate the numerical effects of these variables. The trial regression is based on data in table 3 and figure 228. The uncertainties involved in correlation are apparent from the graphs in figure 232, and clearly no quantitative significance can be attached to the results.

In figure 232 the assumption is made that the sediment discharge of each subbasin for the period 1952–58 is correctly represented by the data. Data for 1951 were not used because no measurements for Mitchell Creek were made during that year. The 1958 suspended sediment for Mitchell Creek is estimated. Relief ratio is plotted against sediment discharge on semilogarithmic paper because previous work has indicated that this relation is exponential. Percentage of upland and adjusted frequency of first-order streams are plotted against sediment discharge on rectangular coordinate paper. When only relief ratio is considered (top graph, fig. 232), the sediment discharge of Fox Creek is very low and that of Mitchell Creek is high relative to the trial curve. This is perhaps accounted for by the fact that the percentage of upland on Fox Creek is lower than the average, and the percentage on Mitchell Creek is higher. When relief ratio and percentage of upland are held constant (bottom graph), a reasonably good correlation with adjusted frequency of first-order channels can be obtained for all the subbasins except Medicine Creek above Harry Strunk Lake, which shows a high sediment discharge not only for this trial regression curve but for the other two as well.

The relatively high sediment discharge of Medicine Creek above Harry Strunk Lake is attributed to yet another factor—the presence of raw vertical banks along a continuous incised channel for a distance of several miles upstream from the gaging station. In general, the banks along Mitchell, Fox,

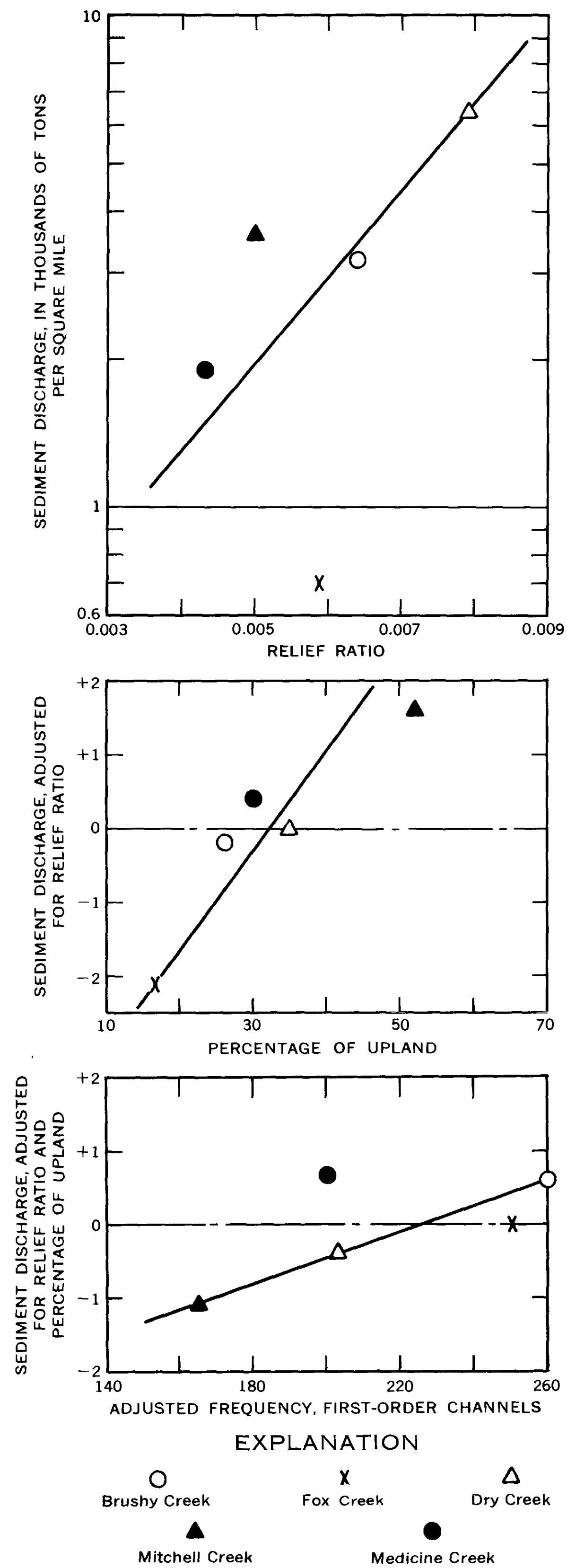


FIGURE 232.—Trial graphic multiple linear regression of sediment discharge in relation to relief ratio, percentage of upland, and adjusted frequency of first-order channels.

and Brushy Creeks upstream from the gaging stations are more sloping and more protected by vegetation than the banks along Dry and Medicine Creeks. But Dry Creek is ephemeral, whereas the continuous flow along Medicine Creek obtains a continuous supply of sediment from bank erosion.

A trial graphical linear regression, in which water discharge was plotted as a dependent variable against the three geomorphic factors used in the sediment discharge regression, yielded results similar to those of the sediment yield regression. As with the sediment discharge, the water discharge of Medicine Creek above Harry Strunk Lake is much higher than expected. Probably, Medicine Creek receives a larger proportion of its water discharge from ground water than do Fox and Brushy Creeks. In addition, the assumption of uniform distribution of rainfall over the various subbasins during the period 1952–58 may be incorrect.

SUMMARY AND CONCLUSIONS

Annual precipitation at Curtis for the period 1895–1960 averaged 21.5 inches but ranged from 11 to 38.2 inches. More than half of the precipitation falls during 4 summer months, and much of this is thunderstorm rainfall. The 5-year moving average for Curtis indicates a long-term trend toward decreasing annual precipitation. Rainfall intensity-duration-frequency curves indicate that the rainfall regimen was satisfactorily represented at Curtis during the years 1951–58, although precipitation was lower than the long-term average. Potential evaporation is about three times average annual precipitation. The Medicine Creek basin lies in a transitional zone between prairie and plains grassland; the climax plant community consists of a dominance of midgrasses and an understory of short grasses.

The immediate effects of drought, as during the years 1933–40, are to reduce the grass cover in such a way as to leave bare patches of ground, but grasses are rapidly replaced by weeds. As a result of a secular climatic shift toward dryness, a climax community of short grasses would become established. Climatic change since the arrival of settlers has had little effect on the climax community, as indicated by the character and abundance of vegetation in areas that are neither grazed nor cultivated.

Geomorphic and stratigraphic evidence indicates that the drainage system grew to approximately its present pattern and extent during the episode of erosion (tentatively assigned to the interval 12,000 to 11,000 years B.P.) that followed deposition of the Peorian Loess. During the subsequent episode of deposition (about 11,000 to 5,000 years B.P.), deposits of the Stockville terrace accumulated in the valleys and the valley sides were graded. The deposits were incised (about 5,000 to 4,000 years B.P.) to form the Stockville terrace, and the deposits that subsequently accumulated in the valleys (4,000 to 1,000 years B.P.) were later incised (about 1,000 to 900 years B.P.) to form the Mousel terrace. Mousel terracing was followed by accumulation of the upper Recent alluvium that underlies the present valley flats. In some valleys the late Recent alluvium has been incised intermittently during the past 350 years. Thus, within the past 12,000 years, the valleys were trenched three times prior to the trenching that is taking place in some valleys at present. No clear evidence was obtained as to the causes of past episodes of erosion or of deposition. However, snails from the Stockville terrace deposits probably lived under climatic conditions similar to the present, and the terracing of the Stockville terrace corresponds approximately with the Altithermal, a well-established dry climatic period that lasted from about 6,000 to 4,000 years B.P.

Morphometric analysis of the drainage system shows that the slope of the exponential curves relating mean channel length to channel order changes at the lower channel orders, whereas the curves relating number of channels to channel order have a nearly uniform slope. This change in slope of the curve relating channel length to channel order is attributed to post-Peorian drainage transformation in which the lengths of first- and second-order channels were reduced relative to third-order channels. In order to compare the channel frequencies of immature drainage systems whose drainage basins differ in percentage of undissected upland, drainage basin area is adjusted by subtracting the area of upland. Channel frequency, expressed as number of channels per square mile of area actually occupied by the valley system, is called adjusted channel frequency.

Erosion by scarp retreat takes many forms in the basin, and gullies are regarded as a type of scarp erosion. Gullies are defined and are classified as valley-bottom, valley-side, and valley-head gullies. Many large valley-bottom gullies apparently originate on valley reaches that are locally steepened at the entrance of a major tributary. However, the ratio of local slope to drainage area that is critical for the initiation of a gully is not sharply defined because other factors (such as width of valley bottom) are important. In general, trenching of a valley reach to bedrock does not take place by the coalescence of two discontinuous gullies, but by the passage of several channel scarps in succession. Saturation of massive silt at the edges of a plunge pool is the most important factor in the advance of channel scarps.

Steep-sided valleys that drain areas of cultivated upland are most susceptible to valley-head and valley-side gullying. The most significant geomorphic factors in the areal frequency distribution of valley-head and valley-side gullies are percentage of area in upland and adjusted frequency of first-order channels.

Generalizations regarding suspended sediment and the hydraulic geometry of channels are based on data from six gaging stations, two of which are on the main channel of Medicine Creek and four on tributaries. At the gaging stations on Dry, Mitchell, and Brushy Creeks the flow is categorized as ephemeral; at the others, as perennial. Water discharge tends to increase rapidly in response to rainfall, much of which falls during summer thunderstorms; and the discharge peaks are of short duration.

Hydraulic geometry of the channels is expressed by the slope of curves relating width, depth, and velocity to discharges equaled or exceeded 1, 2, and 25 percent of the time. At a station, the low-flow channels of perennial streams are well defined and have steep banks; with increasing discharge, width does not increase as rapidly as depth. By contrast, the low-flow channels of ephemeral streams are shallow and transient, and width increases rapidly with discharge until the steep sides of the incised trench are reached. In a downstream direction, the incised trenches of ephemeral streams do not widen appreciably, and increase in discharge is accommodated by relatively large changes in depth and velocity. The increase in discharge of perennial streams is accommodated by relatively rapid increase in width and by a slow increase in depth and velocity.

Curves relating suspended-sediment load to water discharge for the perennial streams are characterized by a break in slope at water discharges above normal but below the bankfull stage; curves for the ephemeral streams show no corresponding break. Peak sediment concentrations usually occur before peak water discharge, but the length of lead is variable and is generally shorter for smaller discharge events. In general, 90 percent or more of the suspended sediment is silt and clay, and the measured (suspended) load represents 90 to 95 percent of the total load. No relation was discerned between instantaneous water discharge and particle-size distribution. In general, the concentration of measured suspended sediment is higher in wet years than in dry, and the ephemeral streams have higher concentrations than the perennial streams.

An evaluation of geomorphic properties indicates that relief ratio, adjusted frequency of first-order channels, and the percentage of area in upland would be expected to have the highest correlation with runoff and sediment discharge. No rigorous statistical correlation can be made because of the small number of subbasins for which data are available, but a trial graphic multiple regression indicates that differences in runoff and sediment discharge can be accounted for reasonably well by differences in these three properties. They are not only important in themselves, but they also give indirect expression to other important properties. For example, the percentage of area in upland is related to area in row crops, small grain, and fallow.

Active valley-head and valley-side gullies, and all but a few of the active valley-bottom gullies, are attributed to land use since settlement. During the past two naturally induced episodes of erosion, gullying was mainly confined to valley bottoms. Although some valley incision has taken place within the past 500 years and before settlement, major episodes of the past are probably associated with droughts more severe than any since settlement. Restoration of native vegetation to the heads of valleys, together with conservation measures on the upland, would be effective in the control and prevention of valley-head gullies, which are the most numerous in the basin. These steps, if accompanied by more moderate grazing in the valleys, would probably prevent the initiation of new valley-bottom gullies; but no economically feasible means for arresting the present large valley-bottom gullies is apparent.

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