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ARROYOS AND THE SEMIARID CYCLE OF EROSION

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ABSTRACT. Longitudinal valley profiles, surveyed in small drainage basins in eastern Wyoming and northern New Mexico, indicate that discontinuous gullies are often developed on areas of local steepening of valley fills.

The large amounts of runoff lost through channel absorption in ephemeral streams cause increased sediment loads downstream. This promotes aggradation within these valleys and eventual dismemberment of the drainage system by the sealing off of tributary channels. Continued aggradation in these valleys steepens the gradients, causing the formation of discontinuous gullies and reintegration of the system by arroyo cutting in the fills.

INTRODUCTION

Arroyos or gullies trenching valley fills are common throughout the semiarid regions of the West. The cause of arroyo cutting has interested many investigators, mainly because of the economic losses resulting from their formation.

Current hypotheses of the origin of arroyos have been succinctly summarized by Antevs (1952). Briefly, two schools of thought are dominant: (1) Depletion of vegetative cover by overgrazing is the cause of present arroyo cutting (Bailey, 1935; Thornthwaite, Sharpe, and Dosch, 1942; Antevs, 1952); (2) Overgrazing may be an initiating factor, but the chief cause is a climatic change (a) to the drier (Bryan, 1925), (b) to the more humid (Dutton, 1882; Barrell, 1908; Huntington, 1914; Gregory, 1915, 1917; Bryan, 1922, p. 85), (c) either a change to the drier or to the more humid (Richardson, 1945), or (d) a change in rainfall intensities (Leopold, 1951).

It is generally agreed that the introduction of large numbers of cattle began about 1870 and that arroyo cutting became serious beginning about 1880 (Antevs, 1952). Arroyo cutting following overgrazing seems a logical conclusion.

It is difficult to evaluate the possibility of a change in climate because of the few meteorological records available. Trends have been found in some data, but even a proved trend in 50 to 100 years of record may be little more than a temporary fluctuation from wet to dry conditions during that period. This is amply demonstrated by the results of tree-ring analysis. Analysis of many hundreds of years of tree-ring variations, although in themselves revealing little about long-term climatic change, indicate that a rainfall record of 100 years duration cannot be cited as evidence for a climatic change (Schulman, 1954).

Schulman's studies of tree-ring chronologies for the Upper Colorado River (1945), Mesa Verde, Gila, and southern Arizona regions (1942), as well as the correlation of tree growth with known rainfall and runoff records, afford information on fluctuations in tree growth and rainfall for a period

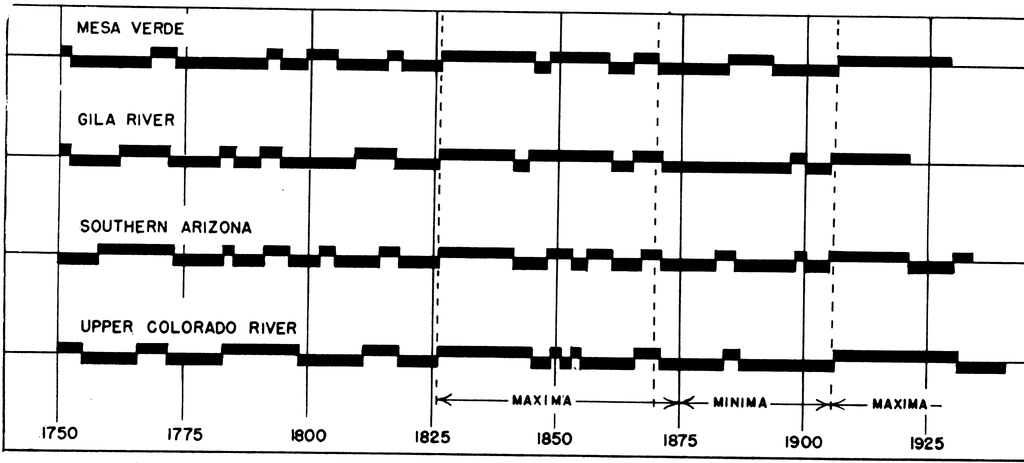

Fig. 1. Periods of maximum and minimum tree growth. The portion of each graph above the mean line indicates years of maximum tree growth, whereas that portion below the mean line indicates years of minimum growth.

from A. D. 1298 to 1940. Schulman has prepared tables indicating periods of maximum and minimum tree growth. For the purposes of this paper, Schulman's data for the period 1750 to the present have been plotted in figure 1. The periods of maximum and minimum tree growth as plotted do not indicate the severity of each period, but as Schulman suggests the relationship of tree growth to precipitation indicates that in a general way these periods are closely related to maxima and minima of winter precipitation. It may be that the years of maximum tree growth are also years of good grass cover.

The plots of figure 1 may be divided into four segments: the period from 1750 to 1826 is in general a period in which minimum growth exceeds growth above normal; the period from 1826 to 1870 is clearly a period of maximum growth, except in the upper Colorado River region where the period is shorter, ending about 1855. The period 1870 to 1906 is a period of marked minimum growth, whereas after 1906 a period of maximum growth is maintained until between 1921 and 1931.

The importance of these periods is obvious, for the lush vegetation in many valleys, described by the early travelers in the Southwest, may be correlated with the period of maximum tree growth of 1826 to 1870. Coincident with the introduction of large numbers of cattle in the Southwest in 1870 a period of minimum growth began, interrupted by short periods of higher rainfall from 1881 to 1884 (Peterson, 1950) and higher intensity rains (Leopold, 1951).

It seems, then, that each of the hypotheses listed above has some validity, for if vegetation was depleted it was depleted both by the cattle and by dry conditions associated with a period of minimum tree growth. To add to the complexity of the problem, arroyo cutting began in some areas before they were grazed, and in other heavily grazed areas no arroyos have developed (Peterson, 1950, p. 421).

It is the purpose of this paper to present data, collected in small drainage areas, suggesting the origin and location of discontinuous gullies within these valleys may be dependent on the gradient of the valley fill, and that any hypothesis of arroyo cutting must take into consideration the character of the drainage basin itself.

The writers' observations in the Cheyenne River basin above Angostura Reservoir, Wyoming, South Dakota, and Nebraska and in Sandoval and San Juan Counties, New Mexico, are the basis of the following discussion. Because the studies were made in small valleys tributary to Lightning Creek (Cheyenne River basin), Arroyo Torreon (Rio Puerco drainage system) and the Mancos River a direct comparison should not be made between the present studies and longer arroyos typified by the Rio Puerco.

THE ORIGIN OF DISCONTINUOUS GULLIES AND ARROYOS

Observation in Wyoming and New Mexico.—In order to obtain quantitative information on the characteristics of a drainage system that might influence arroyo cutting, longitudinal profiles of several trenched valleys were surveyed.

Because alluviation within a valley steepens its gradient, it was assumed that the alluvial fill might be built up to a critical angle and then trenched. To determine if this were true, it was necessary to survey the profiles of both the present channel and the surface of valley fill adjacent to the trench.

Trenched reaches of several small valleys were surveyed in Wyoming and New Mexico. In each case the valley contained what appeared to be a modern alluvial fill, for although vegetation was present no distinct soil profile had developed on the fill surface, and recent artifacts were found in two of the fills. The alluvium generally was derived from one gently dipping lithologic unit, and, therefore, was of nearly uniform texture and composition where sampled within the valleys.

In none of the surveyed gullies did bedrock influence the profiles to any noticeable extent. None of the headcuts or breaks in gradient were caused by the appearance of bedrock in the channel. In some cases, bedrock was exposed in the gully floors, but its effect was probably limited to a retardation of incision or a tendency toward lateral planation. No evidence of either was observed.

The profile shown in figure 2 is that of a portion of Manning Draw located in sec. 36, T. 35 N., R. 67 W., Niobrara County, Wyo. The drainage area above the surveyed reach is 1.7 square miles. The valley fill, derived from the Paleocene Fort Union formation is composed of 45 percent clay-size particles, 34 percent silt, and 21 percent sand.

A marked convexity exists on the fill surface above the lower gully in figure 2. The convexity is not as obvious near the mouth of the upper gully, but the gradient of the fill is definitely steeper at the lower end. At the mouth of the lower trench the gradient of the valley fill is 0.027 while the floor of the trench has a gradient of only 0.017. Upstream from the mouth of the trench the gradient of the fill increases to 0.036 and then gradually decreases to 0.009 at the upper extremity. The presence of both of these gullies appears

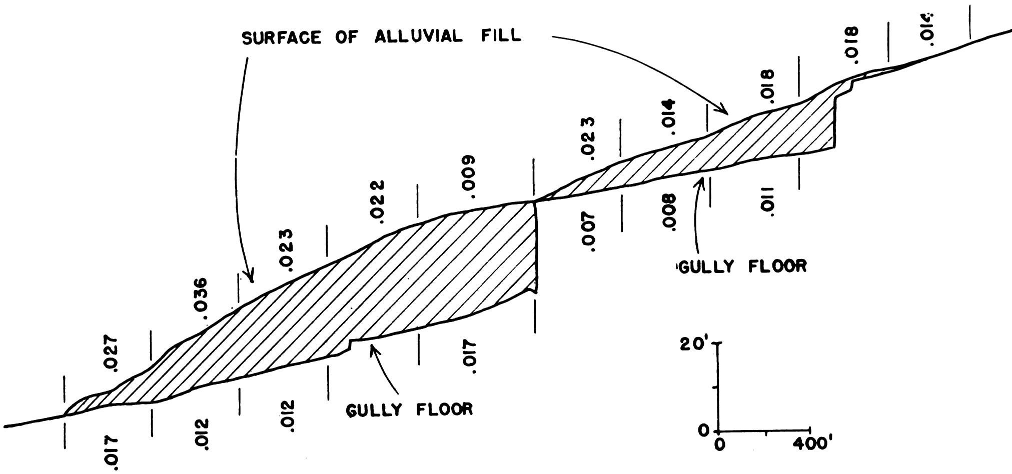

Fig. 2. Profile of discontinuous gullies in Manning Draw, Niobrara County, Wyo. Figures are gradient for each section of the profile in ft./ft.

to be due to a localized steepening of the alluvial fill. Trenching was probably initiated on the steeper sections of the fill, 0.036 on the lower and 0.023 on the upper gully.

If trenching began on the section with a gradient of 0.036 at the lower end of the fill, then the gully has apparently extended itself some distance downstream from the point of initial trenching, contemporaneous with upstream headcut migration. Further headward development of the lower gully will undoubtedly cause integration of the two trenches.

Harney Creek Draw, with a drainage area of about 1.25 square miles, located in sec. 22, T. 34 N., R. 67 W., is another example of a trenched valley, developed in alluvium derived from the Fort Union formation, showing relationships similar to those on Manning Draw (fig. 3A). Only one gully is present in the valley, but again the steepest part of the alluvial fill surface, in the lower reach of the valley, is located just above the mouth of the gully, suggesting that it was the point of initial cutting. Upstream from this point the gradient on the fill is 0.008 and downstream it is 0.004. Farther upstream both the gradient of the gully and the fill surface increase toward the drainage divide.

Joe Warren Draw, located in sec. 34, T. 35 N., R. 67 W., on the Fort Union formation, contains three discontinuous gullies within a drainage area of 0.6 square miles (fig. 3B). The mouth of each is located at a change in gradient of the fill surface. The gradient of the fill at the downstream end of the lower trench is 0.015 which decreases to 0.009 upstream until the second trench appears where the gradient is 0.013. At the upper end of the valley a small trench has begun to cut in a reach where the gradient steepens to 0.016. The middle of the three trenches shows two sections of steeper gradient, marked by a convexity of the fill surface at each point. The presence of a knickpoint in the profile of the trench suggests that two discontinuous gullies

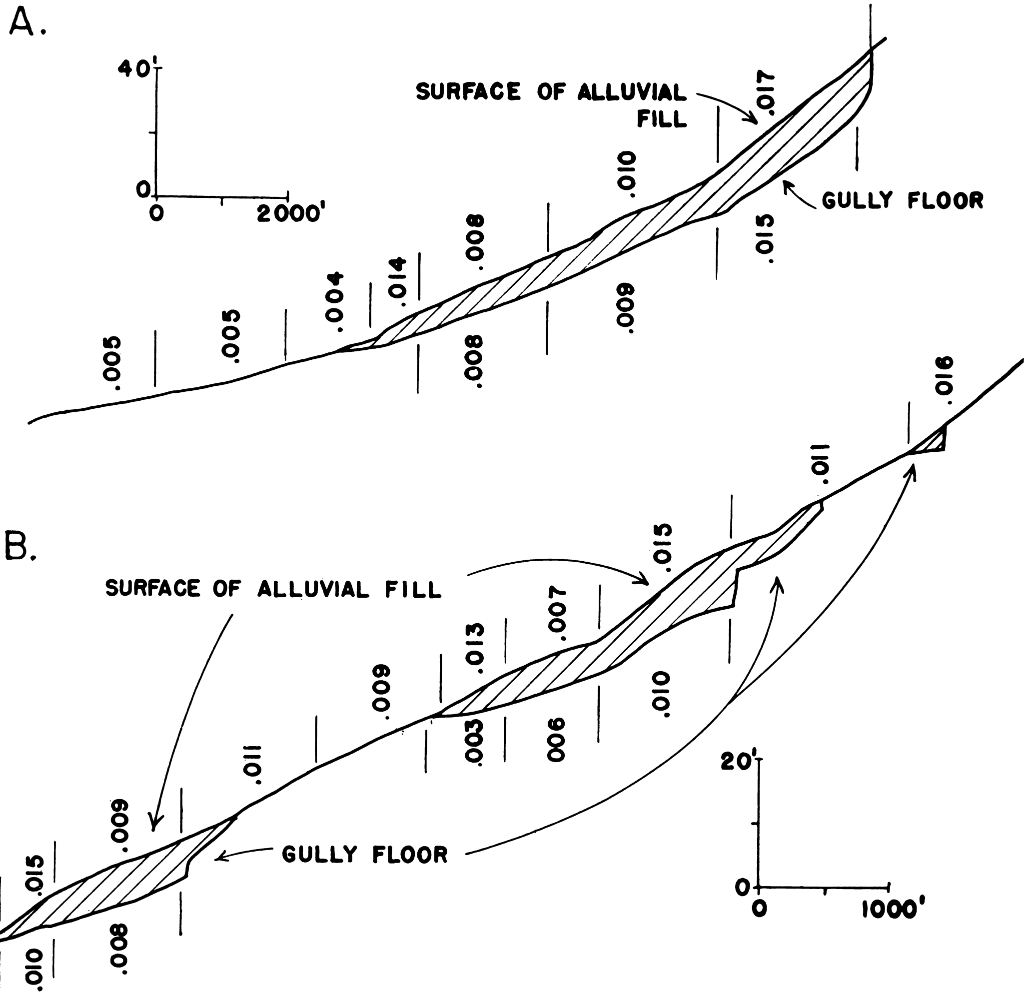

Fig. 3. Profiles of discontinuous gullies, Niobrara County, Wyo. Figures are gradient for each section of the profile in ft./ft.

A. Harney Creek Draw

B. Joe Warren Draw

developed on the steeper segments of the fill, which were united by the headward growth of the lower trench.

Traphagen Draw is located in sec. 5, T. 37 N., R. 64 W., Niobrara County, in alluvium derived from the Upper Cretaceous Lance formation. Profiles A and B of figure 4 reveal the abrupt changes in gradient and a reversal of gradient at the mouth of two gullies due to deposition and the formation of an alluvial fan. The integration of the headward eroding down-valley arroyos with the upper gullies is hindered by the high rates of deposition between the two. It is possible that the mouth of the upper gullies will migrate

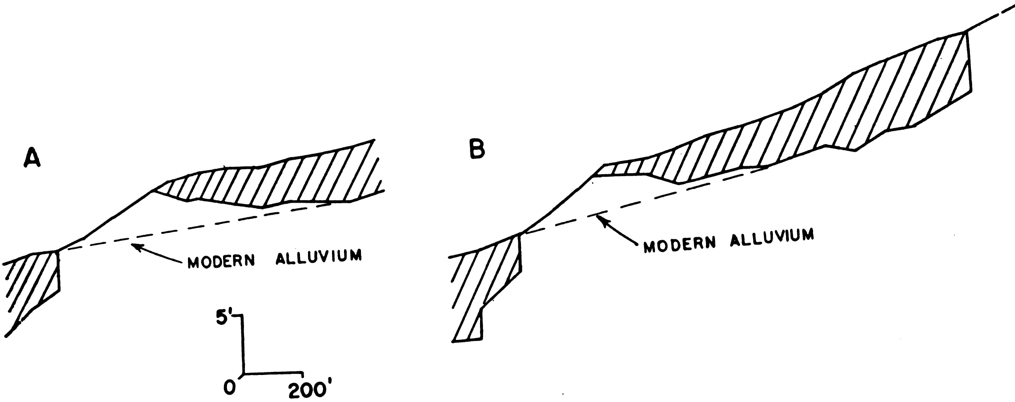

Fig. 4. Alluviation in the lower reach of small discontinuous gullies in Traphagen Draw, Niobrara County, Wyo., hindering integration of the upper and lower gully and causing reversal of gradient.

upstream as the lower reaches of the gully are buried by deposition, maintaining their distance between the lower headcuts. This recent deposition has obscured the point of origin of the upper gullies. It has been noted in the field that the fill surface, adjacent to the longer arroyos, shows many such areas of recent overbank deposition, which obscure the history of the arroyo by burying points of probable origin of discontinuous gullies or creating other areas of steepening on the fill.

A small, well-vegetated valley underlain by Pierre shale of Late Cretaceous age in sec. 15, T. 36 N., R. 63 W., Niobrara County, contains three discontinuous gullies and intervening fans (fig. 5). The entire sequence is only 1,200 feet in length and the drainage area above the upper gully is less than 0.5 square mile, yet similar slope conditions prevail as were found in larger valleys. The headcuts occur on slopes ranging from 2.5 to 3.5 percent and the average slope between gullies is only 1.5 percent. The measurements were made using a hand level, but they do demonstrate the clarity of the relationships between steep gradients and trenching even in the smallest of valleys.

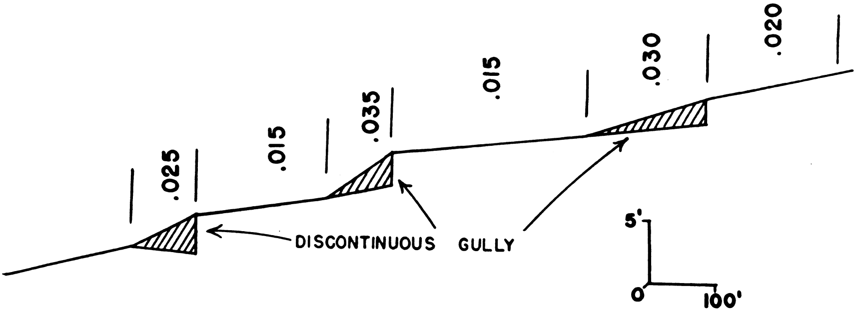

Fig. 5. Discontinuous gullies in a small well-vegetated valley in Niobrara County, Wyo. Figures are gradient of profiles in ft./ft.

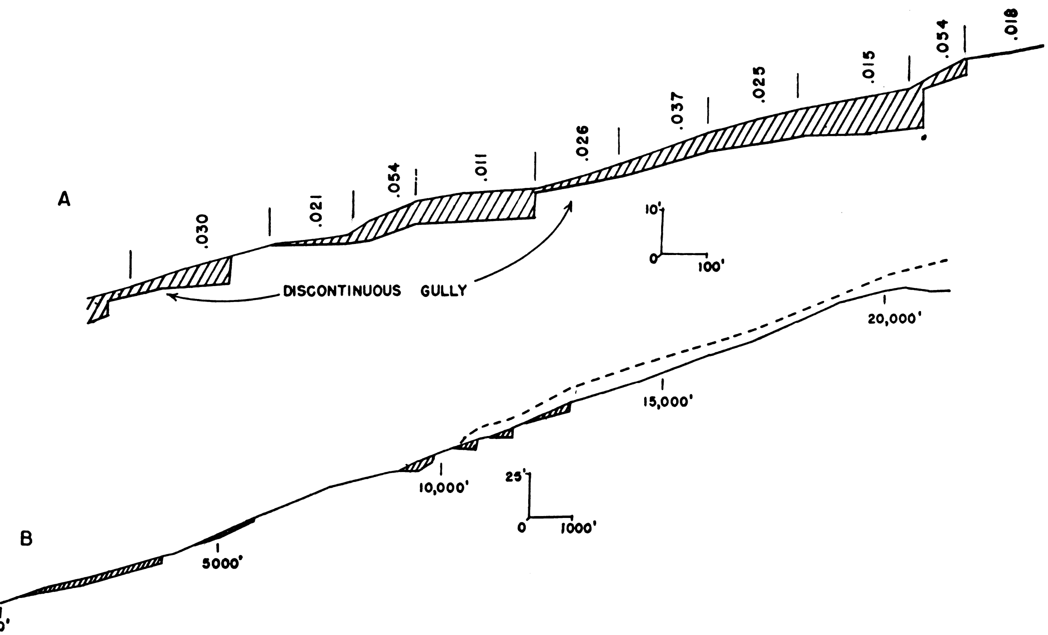

Fig. 6. A. Discontinuous gullies in Dam 17 Wash near Cuba, N. Mex. Figures are gradient of profile in ft./ft.

B. Longitudinal profile of tributary to the Mancos River, San Juan County, N. Mex. Dotted line is profile of older terrace surface. Hatched areas are discontinuous gullies.

Figure 6A shows a reach of channel surveyed in Cornfield Wash near Cuba, New Mex. in a drainage area of about 0.5 square mile. Two discontinuous gullies trench the alluvium, which is derived from a predominantly shale member of the Mesa Verde formation of Late Cretaceous age. Grain-size analysis of a composite sample of the fill shows: 30 percent clay-size material, 54 percent silt, 12 percent sand, and a 4 percent fine to medium gravel. The relationships in the gully farthest downstream on this profile are obscured by overbank deposition caused by a small dam near its mouth. However, each of the gullies appear to be formed by the union of two smaller discontinuous trenches. Where irregularities on the valley fills are closely spaced the integration of small gullies may be common, forming larger more efficient channels. In addition, the profile shows that the relationships observed in Wyoming are similar to those in New Mexico with the steepest parts of the profiles occupied by discontinuous gullies.

To study the relationships in larger valleys an area in New Mexico just south of the Colorado State line was visited, and a reach in a tributary to the Mancos River with a drainage area of about 19 square miles was surveyed. The valley-fill was derived predominantly from the Mancos shale of Late Cretaceous age. A mean of ten samples of the fill indicate that it is composed of 27 percent clay-size particles, 57 percent silt, and 16 percent sand. The sand fraction may be derived in part from outcrops of the Mesa Verde formation. The essential features of the profile are shown in figure 6B. The profile was begun at the head of a gully integrated with the Mancos River. Above this headcut the valley is filled by a broad alluvial fan. Two small discontinuous gullies are present on this fan. At 9,000 feet on the profile the fill surface steepens markedly and a small discontinuous gully trenches the fill there. At 10,400 feet an older terrace surface rises from the fill forming a continuous trench in the valley ranging from 100 to 200 feet wide. Three small discontinuous gullies lie within this wide flat-floored trench in areas where the alluvial fill steepens. The height of the banks above the valley floor in this reach is 10 feet. At 19,000 feet on the profile this height has decreased to 5 feet due to recent deposition in the trench. At 19,500 feet the upper surface steepens and the height of the terrace increases to 10 feet again at 20,500 feet. At 20,500 feet the channel slope is reversed due to recent deposition at that point, which is downstream from a recent trench actively eroding in the upper surface.

Here again the cutting begins where a steepening of gradient occurs whether on the valley floor composed of recent alluvium or on the older fill rising above the recent deposits.

In summary, in each of the valleys surveyed, the trenching of the fill is associated with a steepening of the gradient on the valley fill (see also Ireland, Sharpe, and Eargle, 1939, fig. 63, p. 100, and Leopold and Miller, 1954, fig. 25, p. 81). In some cases the cutting appears to have originated on these steeper reaches and the channel has eroded up-valley with little down-valley development (figs. 2 and 5). In other areas the gullies have extended themselves down-valley also (figs. 3 and 6A). In some valleys deposition at the lower end of the trenches appears to prohibit integration with other gullies (fig. 4) whereas in other valleys integration has apparently occurred or will occur (figs. 2, 3B, and 6A).

In the larger valleys studied in eastern Wyoming and New Mexico, ranging in size from 0.6 to 19 square miles cutting is begun on slopes of from 1.5 to 2.5 percent, whereas in smaller valleys ranging in size from 0.05 to 0.5 square mile the steeper portion of the fill is 2.5 to 5.4 percent.

The increase of the angle at which trenching occurs with decreasing size of the drainage basin strongly suggests an inverse correlation of angle at which the fill will be trenched or instability of the fill with discharge; i. e., for a given storm, discharge will be less from the small drainage systems and cutting will not occur on a slope as flat as it will in a neighboring larger basin with greater discharge. This may also explain the ease of recognition of steepened portions of fills in the smaller valleys.

The decreasing stability of the fill during alluviation, caused by increased gradient, may be expressed graphically as done by Terzaghi (1950) for earth slopes prior to failure (fig. 7). Superimposed on a descending curve of decreasing stability are many minor fluctuations caused by high intensity rains, floods, or depletion of vegetation. The effect of these fluctuations on the fill is minor until the factor of safety or stability of the fill has been so reduced by oversteepening that during one fluctuation the arroyo cutting begins. It is

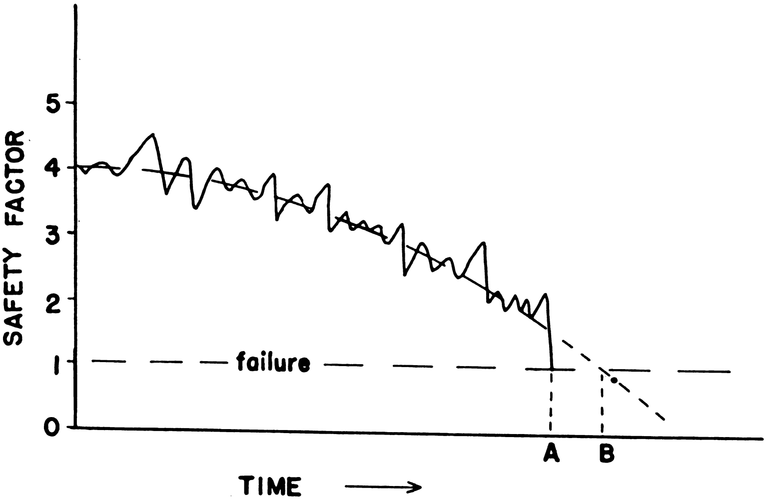

Fig. 7. Possible changes in the safety factor of a valley fill prior to trenching (after Terzaghi).

important to note that the cause of the fluctuation, be it a large flood or overgrazing, is not necessarily the primary cause of the valley trenching; it may be only the most obvious cause.

Restated in another fashion, on a slope of a certain inclination trenching will not occur at a given discharge, Q_1, until additional deposition steepens the fill. If floods of discharge Q_1 were of the greatest magnitude possible, then trenching would be delayed until time B (fig. 7). However, if a flood of doubled discharge occurs, Q_2, due perhaps to a storm of high intensity then cutting might occur at time A, for the increased mass of water and velocity due to the greater discharge (Q_2) will initiate cutting where it could not occur under the conditions of discharge Q_1. This concept appears to agree with the field observations of a steeper angle at which cutting begins in the smaller valleys.

Observation made by other writers.—Some examples of similar cyclic alternation of erosion and sedimentation in stream valleys have been observed which illustrate that these alternations may be a natural part of the cycle of erosion. These are enumerated below.

Thornthwaite, Sharpe, and Dosch (1942, p. 89) clearly suggest this possibility in the Polacca Wash:

> ". . . . it is believed that the explanation of successive deposition and removal of fill lies in sedimentary processes and irregular occurrence of heavy storms rather than change of climate."

McGee (1891, p. 261), referring to work in Iowa, stated:

> "One who lives in a region of delicate adjustment between water work and configuration, such as the driftless area, cannot fail to observe the alternate formation and destruction of miniature terraces in every minor valley or ravine within a period ranging from a year to a generation."

According to McGee, the valleys are plugged by tributaries building fans or deltas into the main valley or the dropping of stream load for any reason.

Deposition continues in the channel above the plugged zone and works headward, resulting in an alluviated channel above the original point of deposition. Trenching of this deposit occurs when sufficient water is available and the gradient is steep enough, causing terraces to be formed along the valley sides. In this region, more humid than those cited in the previous sections, the walls of the trench are rapidly weathered back, destroying their arroyo-like apperance until only small remnants remain. McGee says (1891, p. 262):

> "In some quite small periodic streams the cycle is completed in five or ten years, and the birth, development, decadence, and final dissolution of the successive straths and their resulting terraces have been observed in the same valley. In the larger periodic and smaller permanent streams the stages of half a cycle have been noted, progressing at such a rate as to require quarter or half of a century for its completion; in mill-streams single stages (but all stages in various streams) have been observed during such period as to indicate a cycle of some hundreds of years; while in still larger streams the stages are obscure, and the alternation during a score of years is too inconspicuous to attract attention."

In the Cheyenne River basin (Sioux County, Nebr.) a cottonwood tree approximately 60 years old was found partly buried by 8 feet of alluvium within a valley draining about 20 square miles. The depth of burial was revealed by a retrenching of the fill adjacent to the tree. Therefore, in the past 60 years the channel was filled by 8 feet of alluvium and then cut again to its present depth slightly below the roots of the tree. Renewed deposition is occurring at present some distance downstream from the tree. This example suggests that in small valleys the process occurs as visualized by McGee and at rates more rapid than generally believed possible.

SOME ASPECTS OF THE CYCLE OF SEMIARID EROSION

The presence of oversteepened reaches within an alluviated valley, and the appearance of discontinuous gullies on these over-steepenings suggest that some natural cycle of alluviation and erosion is operative in semiarid valleys. The problem still remains as to the reason for alluviation or valley filling. Apparently, it is due to a deficiency of water in relation to sediment.

Hydrologic considerations are, therefore, of major importance in any consideration of stream action in areas of low rainfall. It has been shown (Leopold and Miller, 1956) that sediment load in the arroyos of New Mexico increases faster than discharge. Hadley reports three occurrences of floods in Wyoming in which the discharge was greatly reduced in a downstream direction due to channel absorption in the stream beds (see table 1). In addition, recent hydrologic studies in the Cheyenne River basin have shown that a large percentage of runoff from headwater areas is lost in the channels before reaching a master stream, (Culler, 1956). Sediment being transported in this type of channel must be deposited as the flow is dissipated.

TABLE 1

Downstream Decrease in Discharge Due to Channel Absorption

Date of observation	Creek	Q upstream (est.)	Q downstream (est.)	Distance between points (miles)
July 18, 1953	Twentymile	40 cfs	0	6
Aug. 3, 1953	Twentymile	450 cfs	42 cfs	7
Aug. 16, 1953	Lightning	100 cfs	40 cfs	5

Observations in Wyoming and elsewhere reveal that one other important characteristic of a semiarid drainage system is the lack of accordance of tributary and main channel, that is, the tributaries may or may not be graded to the main channel. As an example of this, the Twentymile Creek drainage basin may be cited where one-third of the tributaries are graded to the surface of a terrace above the main channel (Hadley, 1953). This lack of integration in certain channels is due to the filling of the lower parts of the tributary valleys with sediment, causing spreading of water and sediment over the terraces and flood plain adjacent to the main channels. In any larger drainage system the tributaries may be found in all stages of integration with the main channel, suggesting that each tributary has its own history of alluviation and dissection which may not be contemporaneous with that of its neighbors.

With the above two main characteristics of a semiarid drainage network in mind, it may be possible to hypothesize a cycle of semiarid erosion based on field observations within the Twentymile Creek drainage basin, Wyoming. Twentymile Creek drains an area of about 200 square miles underlain by the Fort Union formation in which mean annual rainfall is about 14 inches. The main channel of Twentymile Creek is tributary to Lightning Creek, and throughout its length has a well-defined channel, i. e., aggradation is minor within the channel.

Field examination of a number of tributaries to Twentymile Creek show in general two cases: (1) actively eroding headwater channels and filled or alluviated lower valley reaches and (2) moderate erosion in headwater channels and gullies trenching the lower valley fill. These two seemingly distinct examples appear to be the two components of the semiarid cycle of valley development. This cycle may be outlined as follows: An alluviated tributary valley is united with the major drainage channel by the development of a trench in the recent alluvium clogging the tributary channel. The gully is extended headward by upstream headcut migration. Figure 8A shows the channel at the beginning of this rejuvenation. As the headcut migrates up channel the lower section of the tributary drainage (sec. 1, fig. 8A) becomes very efficient for sediment transport, for the runoff is concentrated in a clearly defined channel. The headcut continues to work up channel, passing tributaries 2 and 4 and rejuvenating them in turn (fig. 8B). Runoff increases and time of concentration is much shorter, but the volume of sediment moved is greatly

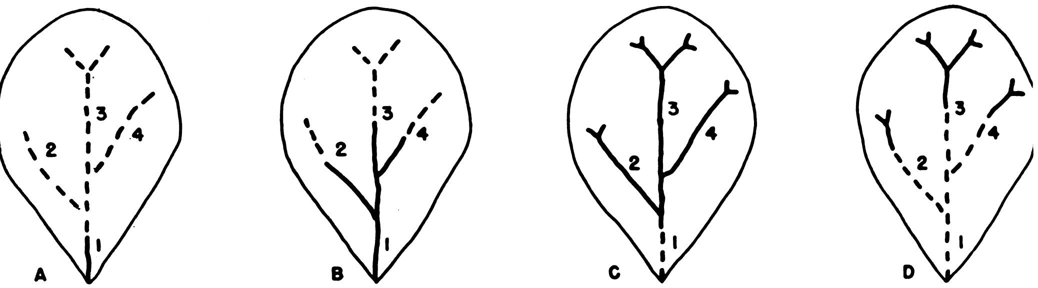

Fig. 8. The cycle of trenching and alluviation in a semiarid valley. Dotted line indicates alluviation within a channel. Solid line indicates trenching or a through channel.

increased by the rejuvenation of tributaries 2 and 4. With the rejuvenation of tributaries the upland slopes may be steepened and they in turn may supply more sediment to the channels. Thus, as the headward cutting continues, up-channel sediment delivered to section 1 of this basin is greatly increased as is the velocity of flow but with perhaps only minor increase in runoff. Sections 2, 3, and 4 now are supplying much sediment, but section 1 has a gradient formed when the supply of sediment was lower and aggradation begins in section 1, perhaps due also to widening of the channel (Leopold and Miller, 1956), or deposition may begin at the junction of tributary with master stream (fig. 8C). Thus, aggradation begins as discontinuous deposits in reaches of the valley with either the least slope or greatest width or both. Alluviation once begun promotes more alluviation until the channel is filled and is no longer smoothly graded to the main drainage channel. The area of maximum channel deposition then migrates upstream. As it passes the mouths of tributaries they begin filling their valleys, for the local base level is raised. The area supplying sediment to the main channel decreases in size (fig. 8D) and the rate of alluviation undoubtedly decreases. The gradient of the filling valley becomes steeper until discontinuous gullies begin to form in stretches of channel where the gradient is steepest. These discontinuous gullies shift the alluvium down channel by building fans in the valley which are in turn trenched when the gradient steepens. Finally the shifting of sediment down-channel forms a fan near the tributary mouth. This fan is in turn trenched, integrating the tributary drainage with that of the master stream, and so the cycle begins again.

This hypothetical cycle explains many of the relationships observed in small valleys in Wyoming, and is a partial development of McGee's statements (1891). Probably this proposed cycle or some modification of it is typical of semiarid channels and even intermittent channels in more humid regions (Happ, Rittenhouse, and Dobson, 1940).

CONCLUSIONS

The profiles of valley fills and discontinuous gullies surveyed in Wyoming and New Mexico strongly suggest that discontinuous gullies form on reaches of steeper gradient within a valley. The angle at which the fill will be trenched is probably dependent on discharge. In two similar valleys, trenching will occur soonest in the valley with the highest frequency of large floods.

Semiarid and probably arid regions are distinguished from the more humid by lack of accordance of many stream junctions and high rates of water loss due to channel absorption, which cause an increase in sediment concentration downstream.

The cycle of erosion within a large drainage system may be made up of major cycles of arroyo cutting on the main channel, but within these major cycles are a number of epicycles in which alluviation and erosion alternate in the smaller valleys, making them temporarily independent of the main drainage channels. The inception of cutting within the smaller valley appears to be dependent on the angle to which the fill has been steepened and the incidence of high intensity precipitation. Since the smaller valleys are found in all stages of the cycle of aggradation and trenching, these epicycles are probably dependent mainly on local factors.

The possibility that cutting is started on steeper reaches of even the largest valleys might be difficult to prove, although it may be that principles of gully formation discovered in small valleys are applicable to the larger ones.

The minor fluctuations within the cycle then do not markedly affect the major landforms but will cause the development of valley-plug deposits or the formation of terraces (arroyo cutting) in smaller valleys. The epicycles become more prominent in arid and semiarid regions as the readjustment, owing to the deficiency of water, will not occur as rapidly. These epicycles are then minor parts of the main erosion cycle, but they exert a great influence on the economy of semiarid areas.

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