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Climate and Accelerated Erosion in the Arid and Semi-Arid Southwest, With Special Reference to the Polacca Wash Drainage Basin, Arizona

By

C. WARREN THORNTHWAITE
Chief

C. F. STEWART SHARPE
Associate Soil Conservationist

and

EARL F. DOSCH
Assistant Soil Conservationist
Climatic and Physiographic Division
Office of Research
Soil Conservation Service

UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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SINCE this bulletin was written and started through the press, we have become a Nation at war. Peacetime pursuits have been set aside, and new and vital needs have come to the forefront. Prepared originally to help clarify the relations of the arid and semiarid climates of the Southwest to soil conservation, the detailed climatic analysis presented in this bulletin can be of immediate use in two other ways. With the cutting off of our major source of rubber we have turned to the production of guayule as a possible substitute. It is a plant native to the semiarid Mexican Plateau but has been grown experimentally with success in the semiarid coastal valleys of California. The information contained in this bulletin will be of assistance to ecologists and botanists charged with finding the most suitable sites for the production of this vital war material. Analysis of the dry climates of our country finds further use in the insight it gives to comparable climates in Australia and other theaters of the present war. Through full understanding of the variability of these climates, our troops can be properly equipped and trained to cope with the weather conditions they will encounter.

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Climate and Accelerated Erosion in the Arid and Semi-Arid Southwest With Special Reference to the Polacca Wash Drainage Basin, Arizona[1]

By C. WARREN THORNTHWAITE, *chief*, C. F. STEWART SHARPE, *associate soil conservationist*, *and* EARL F. DOSCH, *assistant soil conservationist, Climatic and Physiographic Division, Office of Research, Soil Conservation Service*

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INTRODUCTION

Accelerated stream trenching or arroyo cutting in the Southwest has been noticed for more than 50 years. In that time the gullying of channels in flat-floored valleys with the consequent dissection of bottom land, lowering of the water table, and loss of palatable grasses have become increasingly apparent. Wind action has removed soil from tilled fields and other areas where the vegetal cover has been depleted and has deposited the debris in the form

[1] Submitted for publication June 21, 1941.

Longitudinal dunes (*76, p. 121*), oriented in a general southwesterly direction parallel to the prevailing winds (figs. 25 and 40), are the dominant type on the valley bottom. Dunes are especially abundant in the Tusayan Washes section, where sand storms are said to have increased in frequency during recent years.

Wherever wind-blown sand is found as a continuous surface mantle, it is effective in preventing erosion by running water. Parts of the Polacca drainage are almost immune to sheet wash and serious gullying because of absorption of the flowing waters by sand and because of the obstruction offered by drifting sand to the formation and maintenance of channels. By reason of their retention of water these sand areas are favorable for vegetative growth and are valuable to the inhabitants of the region as agricultural land.

ACCELERATED EROSION IN THE SOUTHWEST

Recent acceleration of erosion in the Polacca drainage and in the Southwest as a whole is now generally recognized. There is as yet, however, no general agreement as to the cause of that acceleration. Any valid explanation of this recent trenching must recognize that a large part of the region is affected by it and that in some localities it began as much as 80 to 100 years ago, though in most areas it had its start more recently.

Date of Acceleration of Erosion

THE SOUTHWEST

Rich, Gregory, Bryan, and others have gathered many records of the beginning of accelerated erosion in the Southwest. The dates vary from valley to valley as do also the nature of the terrain, time of settlement, type of land use, climate, and reliability of the information. Hough, in 1906, made a general statement for the entire region that acceleration of erosion began 30 years earlier or about 1875 (*64*). Bryan considers this too early and places the beginning of cutting about 1885 (*23*).[18]

Most accounts by early travelers in the Southwest indicate that acceleration of erosion did not begin until after the establishment of settlements and the expansion of the cattle industry. Local exceptions may be noted. Explorers and military parties that crossed the Rio Puerco of the Rio Grande drainage in New Mexico between 1846 and 1877 report banks 10 to 30 feet high and a channel as much as 100 feet wide (*10 pp. 466–467; 23, p. 339; 71, p. 432; 95, p. 71*). This would suggest that channeling had set in far earlier than the late eighties, the date given for it by local inhabitants (*23, p. 339*). The explanation of apparent disagreement of the two accounts may lie in the development of discontinuous channels, which eventually joined to form one great continuous gully (pp. 92–95). Albert, Simpson, and Jackson, whose journals tell of the early condition of this river, may have crossed some of the earlier channeled reaches. Later, as gullying spread up and down the valley, subdraining the bottom lands

[18] Bryan, Kirk. Pre-Columbian agriculture in relation to periods of alluviation in the Southwest. Paper presented before Anthrop. Sec., 8th Amer. Sci. Cong., May 16, 1940. Washington, D. C.

and impeding the diversion of water for irrigation, the population was more seriously affected. At least three river towns were abandoned (*22, p. 80*).

Judging from an early account by Simpson (*95, p. 78*), Chaco Canyon, a tributary of the San Juan River in northwestern New Mexico, had no gully in 1849. Jackson, in 1877, found an arroyo 16 feet deep and 40 to 60 feet wide (*71, pp. 431–450*), and by 1924 this channel had enlarged to 30 by 200 to 300 feet in section (*23, p. 340*).

Agricultural land along the Rio Salado, tributary to the Rio Grande at San Acacia, N. Mex., was settled in 1880. According to local inhabitants, an exceptional rain and flood in 1883 cut a new channel for the stream along the course of an old road. Most of the farming land of the valley has since been destroyed by further cutting that between 1882 and 1918 increased the width of the Rio Salado 10 to 40 times (*26*).

The channel that occupies what was once the main street of Silver City, in southwestern New Mexico, was cut largely in the years 1895 to 1905 (*32; 31, p. 11*). Intense rains fell in this area in July and September 1875, and July and August 1881 but it was not until the 6-inch rain of July 21, 1895, that the major excavation began. August 1903 had two more disastrous floods on successive afternoons. In 1917 the channel was over 100 feet wide and 37 feet deep (*79, pp. 24–25*), and by 1934 the depth was reported to have increased to at least 54 feet (*31, p. 41*).

Acceleration of erosion on the Gila River in southern Arizona and on various of its tributaries took place between 1870 and 1900 (*104; 113*). Rillito Creek, a tributary of the Santa Cruz River, began cutting a few miles northeast of Tucson after the opening of a United States Army post on the Rillito at Fort Lowell in 1872. Pantano Wash, entering the Rillito from the south, eroded rapidly during floods in 1881 and in the nineties (*96, p. 98*).

In 1870, the valley of the San Pedro, a long tributary of the Gila in southeastern Arizona, had a shallow grassy bed and banks covered with luxuriant vegetation. Willow, cottonwood, sycamore, and mesquite timber were abundant, and there were large beds of saccaton and grama grasses and sagebrush. By 1900, the river had cut 10 to 40 feet below its former banks. Trees and underbrush were gone, and cattle and horses trailing between feed and water had cut many small waterways from the hills to the river (*53, p. 12*).

Another account of the lower San Pedro says that until about 1888 the Valley consisted of a narrow strip of very fertile subirrigated fields. Beaver dams retarded the flow and prevented channel cutting. Trapping of the beavers and removal of grass from the hillsides allowed such an increase in erosion that by 1892 or 1893 a channel 3 to 20 feet deep had been cut almost the whole length of the river. Freshets each year carried away more of the bottom lands, and in addition to curtailing the area of good land, the deep channel drained the bottoms, killing the native grass and making irrigation more difficult (*53, pp. 13–14*). Bryan points to the change in plant associations in the San Pedro Valley as characteristic of the recently dissected valleys of the Southwest. Within the memory of men now living the *phreatophytes*, or shallow ground-water plants, have disappeared and have been replaced only by groves of mesquite (*27, pp. 475–476*).

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The Gila itself has cut away much of the former flood plain in its upper course, but below the mouth of the Santa Cruz River it has deposited enough sediment to fill the old deep channel and form a sandy plain a quarter of a mile to half a mile wide (*23, pp. 342–343*).

Floods that have carved a large channel in the floor of Blue River Canyon in the Gila River drainage began in 1900. Between 1900 and 1921 the number of ranches in this basin decreased from 45 to 21 and the population from 300 to 95 (*23, p. 342; 74*).

The present channel of San Simon Creek, which enters the Gila River from the south about 4 miles east of Safford, is 10 to 30 feet deep, 600 to 800 feet wide, and 60 miles long. Olmstead reports that it developed after the cutting of a small floodway by settlers in 1883 (*23, p. 342; 79, p. 79*).

Arroyo cutting in streams tributary to the Mangas River, and so indirectly to the Gila, began between 1881 and 1891 (*86*).

In northern Arizona and southern Utah much of the channeling of flat-floored washes appears to have started between 1880 and 1890. According to Brady (*20*), the Rio de Flag, northwest of Flagstaff, Ariz., formerly flowed through a grassy flood plain but in 1936 was deeply entrenched. Cutting began in 1886–87, when a logging road down the center of the valley was in use. The arroyo enlarged rapidly between 1890 and 1892, and by 1900 it was 15 to 20 feet wide and 10 feet deep. When reported on by Brady in 1936 it was 60 feet wide and 20 feet deep.

Cottam and Stewart (*37, p. 614*) state that Mountain Meadow, in southwestern Utah, was dissected by huge gullies during a protracted period of torrential storms in the spring of 1884.

Davis reports that cutting on Kanab Creek is known to have begun in the flood of July 29, 1883, which was followed in 1884 and 1885 by high waters from unusually heavy snows. In these three years a gully 60 feet deep by about 70 feet wide and 15 miles long was cut in the fill of Kanab Creek (*39, p. 11*). Lakes known to have existed in Bonito Canyon in 1850 (*95, p. 110*), in Tyende Valley in 1880, and in Laguna Canyon in 1882 have been drained and the valleys deeply trenched.

According to Gregory (*51, pp. 130–131*), Navajo legend tells that the Segi region was bewitched in 1884. The lakes vanished and farm lands were cut out.

In 1894 the flat-bottomed alluvial floor of Walker Creek was occupied by Indian farmers, and the bed of the Chinle was cultivated; in 1913 the terraces on Walker Creek were 80 feet above the stream and the Chinle flowed between alluvial banks 100 feet in height. Since the Mormon occupation of Tuba in 1878 the Moenkopi has intrenched itself in alluvium to depths of 15 to 40 feet.

Prospectors, pottery hunters, Government officials, Navajos, and Hopis agree, Gregory says, in placing the formation of terraces 25 to 35 years before he wrote, or between 1882 and 1892. Those on Pueblo Colorado Wash at Ganado were formed about 1890 (*51, p. 131*).

THE POLACCA DRAINAGE BASIN

The beginning of accelerated erosion in the Polacca drainage basin can be dated only approximately, but the several lines of evidence are all in general agreement. Early travelers through the Navajo country appear to have said nothing about the presence of gullied channels.

The first descriptions yet found are by Bourke, who visited the Hopi snake dance in 1881. He noted on August 16 that high wind-rippled sand dunes on the plain south or southwest of the tip of First Mesa provided heavy going for their mules (*17, p. 281*). To the west, in the center of the broad valley separating First and Second Mesas, he says, is a rainy-season stream, apparently Wepo Wash, flowing from the north and joining what is now called the Polacca Wash. Where his party crossed the Wepo it was a brook 20 feet wide and 3 to 6 inches deep, with a swift current. Corn, melons, pumpkins, and squashes were being grown along the valley (*17, pp. 281–282*). As he does not mention any difficulty in crossing it is presumed that the Wepo at the trail between First and Second Mesas was at that time a surface flow with only low banks. The "clay talus" forming the slopes from the base of the mesa cliffs to the plain, Bourke says, was "slashed and wrinkled in all possible directions by ravines and arroyos, ranging from 2 feet to 200 feet in depth, across and between which runs a maze of sheep and goat and donkey trails" (*17, pp. 282–283*). Dissection of these steep infertile slopes is probably almost as old as the congested settlements on the mesa tops above them and must have long preceded the widespread gullying of the wash floors.

On August 19 Bourke's party started southeast from the plain below Mishongnovi at the tip of Second Mesa. When scarcely a mile on their way they ran into an alkali flat full of mud holes, and their mules and wagon became deeply mired. After digging out they proceeded down drainage and succeeded in crossing at a place where the water flowed between vertical banks 10 feet high. The walls, of a crumbling sand and clay mixture, had to be graded down to allow the wagon to pass. Less than 250 yards farther another and more troublesome ravine was crossed in similar manner (*17, pp. 339–342*). The position of these mud flats and the two ravines suggests strongly that the miry area and the arroyo first crossed may have been along the Wepo. The second and larger arroyo or gully may have been the Polacca. From this it would appear that gullying along the Polacca had induced correlative cutting on the tributary Wepo or that both had trenched independently. In any event, cutting on the Wepo did not extend up drainage so far as the boggy area, which may have been on a broad alluvial fan. The place where the Wepo had been crossed 3 days before must have been still farther upstream. These few observations of valley trenching suggest that by 1881 acceleration of erosion had made a start in the central part of the Polacca drainage but that the gullies were not continuous up the washes and had not reached anything like their present width and depth.

The first topographic survey of the Polacca drainage, made in 1883, is shown on the Canyon De Chelly, Marsh Pass, and Tusayan reconnaissance maps of the United States Geological Survey. Because of the small scale (1:250,000) and reconnaissance nature of these old maps it is impossible to be sure that all drainageways were mapped. Permanent and intermittent streams are shown in several of the other valleys, however, and it is unlikely that a well-developed steep-walled gully down the Polacca Wash would have been ignored. Various springs in the Polacca drainage are shown, and the Canyon De Chelly quadrangle indicates a permanent stream about 4 miles long in one of the Polacca headwaters. As near as can be determined

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this channel was in Dripping Springs Canyon (fig. 42), and it may have been a natural feature. These early maps, therefore, suggest that gullying in the Polacca drainage was not well developed until some time after 1883.

According to information obtained from the Hopis, accelerated cutting of the Polacca Wash began in the 1890's at a point several miles below the village of Polacca. The exact location is not known, but field evidence suggests that cutting began about 7 miles down valley from the village (figs. 25 and 26 between *E* and *F*).

On the basis of the positions of longitudinal fans and on comparisons of cross sections of the present gully above and below the fans, the approximate positions of other old gully channels along the course of the present Polacca Gully can be located. One such discontinuous channel is thought to have extended from about a mile southwest of the mouth of Red Canyon (fig. 26 between *A* and *B*) upstream for at least 2 miles; one for a distance of about 3 miles up from the mouth of the Burnt Corn (fig. 26 between *C* and *D*); and one from about 6 miles to 9 miles above the mouth of the Burnt Corn. The longitudinal fans were formed by deposition from discontinuous channels and were later cut through when the channels became incorporated in the continuous gully system.

According to this interpretation, active discontinuous channels were present in four reaches of the main drainage of the Polacca Wash, possibly before the end of the last century. Integration of these channels under the influence of continued accelerated erosion produced the long, continuous Polacca Gully.

Evidence from the major tributaries of the Polacca also indicates that acceleration of erosion began some time after 1890. A land survey made in 1891-92 [19] shows a discontinuous gully in the Wepo Wash, terminating about 5 miles above the present junction of the Wepo with the Polacca—a reach that now contains a continuous gully channel. In Keams Canyon Wash, according to Hoover, writing in 1930 (*62, p. 437*):

> The greatest trenching has taken place within the last 10 or 15 years. Before 1880 there was no serious arroyo wash in Keams Canyon, but later the government experimental farm there was largely washed away and had to be abandoned. The school was moved two miles down the canyon to its present site. The wash is now about 25 feet deep and goes through the middle of the old fields and cemetery.

Gregory, who worked in this area intermittently from 1909 to 1913, said that the deep alluvial fill of Keams Canyon was then being removed so rapidly that location of roads and preservation of buildings was a serious problem (*51, p. 131*).

Cutting of neighboring washes has also taken place largely since 1900. Hoover says of the Oraibi (*62, p. 437*), the next wash west of the Polacca, in 1930:

> The old Oraibi Wash of 30 years ago was no more than five or six feet deep and can still be traced where it was abandoned for the great gash about 35 feet deep and several hundred feet across. Locally it has cut to bed rock, and here there is a constant flow of surface water. It is representative of what has taken place in all the valleys.

[19] U. S. General Land Office. TOWNSHIP NO. 28 NORTH, RANGE NO. 18 EAST, GILA AND SALT RIVER MERIDIAN. Scale, 40 chains to an inch. [Ms. map, United States Department of the Interior.]

Jadito Wash, adjoining the Polacca drainage on the east, has a present channel in some places as much as 100 feet deep. Most of this, according to Hack, has been cut since 1914 (*55, p. 68*).

The weight of evidence indicates that accelerated erosion in the Navajo country began between 1880 and 1885, and gradually spread until by about 1914 all the major drainages and most of the larger tributaries were trenched by a system of continuous gullies. Since then gullies have cut deeper and have joined to form a more complex continuous gully system. Enlargement of channels and extension of the system continues. Parts of some of the larger gullies appear to be less active than they were a few years ago.

Causes of Acceleration of Erosion

DIASTROPHISM

Available information indicates that accelerated erosion in the Southwest was initiated at slightly different times in different areas but that by far the greatest incidence was in the period 1880–1900. In the search for the cause of acceleration of erosion these geologically short time limitations must be kept in mind.

Rejuvenation of stream action would be a possible explanation of the trenching of the valley floors. In individual streams this could be brought about by increase of flow, through capture, or by the cutting through of a resistant barrier such as a massive bed, lava flow, or landslide. More or less synchronous acceleration on streams throughout the Southwest could scarcely result from any such local causes.

A far more widespread cutting of gullies in valley floors could be brought about by steepening of channel gradients through diastrophic action. Any type of doming, warping, or tilting of the earth's crust, however, would involve a directional orientation along which grades would be increased and an orientation in the opposite direction in which grades would be decreased. Warping that would produce increased cutting in southward-flowing streams should produce aggradation in those flowing toward the north in the same area. Vertical uplift or doming would produce a steepening of gradient of streams flowing radially outward from the uplifted area.

No evidence of recent drainage changes of these kinds has been found in the Polacca or elsewhere in the Southwest. Observation of the growth of continuous gullies from short discontinuous ones (p. 92) further suggests that acceleration of erosion has been brought about by changes on and above the earth's surface rather than within the crust.

AGRICULTURE

Where cultivation of the land entails complete removal of natural vegetation and for part of the year leaves the surface entirely bare, the hazard of soil erosion varies with the farm calendar and with the seasonal variations in climate. In the Navajo and Hopi reservations agriculture is well adapted to the climatic conditions and is far less likely to induce serious erosion than are the usual agricultural practices of farmers in somewhat more humid lands.

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Few of the Indian fields of northeastern Arizona are ever plowed. Corn, the major crop, is planted in individual holes made with a planting stick. Most of the fields are in sandy areas which retain much of the scant rainfall and therefore do not wash badly. Sand blowing rather than gullying is the major difficulty to be combatted on these fields, and windbreaks of reed, brush, or stones are commonly used. Fields on alluvial fans or on flood plains of arroyos are more subject to gullying. Even here, however, the usual Indian agriculture does little to increase the hazard. Stewart (*100, p. 329*) reports that flood-water irrigation as practiced by the Hopis and the Zunis today is a highly effective means of preventing gullying. The result of land abandonment may be seen on a field that went out of tribal control when boundaries of the Zuni Reservation were realigned about 35 years ago. The flat-bottomed stream which was formerly used to provide floodwater irrigation for the field has now cut a channel approximately 75 feet wide by 20 to 30 feet deep.

Diversion dams and distribution ditches to irrigate the fields are reported to have been very numerous in the past (*82, 100*), and if properly maintained must have acted to prevent rather than induce accelerated erosion. Abandonment of these works, as Reagan (*82*) has suggested, may have been a contributing factor in starting accelerated channel cutting. Bryan [20] believes there were fewer dams than Reagan indicates and that their effect on alluviation and erosion was small. It seems certain, however, that in the areas most intensively cultivated the water-control structures of these early farmers were highly effective in retarding run-off and in causing alluviation.

Little is known of the number of inhabitants in northeastern Arizona before the coming of the Spaniards. Espejo in 1583 estimated the number of the Moquis at 50,000, but this is thought to have been far too high (*43, p. 15; 48, p. 661*). In 1776 the engineer Miguel Costanso [21] made an estimate of 7,494 (*43, p. 15*). This figure, which is also given by Escalante, agrees well with other estimates of that period. In 1780, however, after 3 years without rain, Governor Anza gave the population as 798 and the deaths as 6,698. Whipple in 1853 noted the population as 6,720 (*111, p. 13*), the Eleventh Census in 1890 as 1,996 (*43, p. 49*), and the Indian Service in 1939 as 3,339, including 114 Hopis residing off of the reservation (*109, table 3*).

Considering that the Hopi population probably has never exceeded 8,000 and that the Navajos have gradually risen to their present 48,235 (*109, table 2*) from a start of about 8,000 in 1868, it is improbable that the Indian lands have ever been much more intensively farmed than they are today.

In recent years only about 38,000 acres on the Navajo and Hopi reservations have been under cultivation, exclusive of a small area around Gallup, N. Mex., and of acreage operated by the Indian Service. The cultivated acreage, less than 60 square miles, is approximately 0.25 percent of the two reservations excluding the Gallup area, or an average of 1.6 cultivated acres per square mile.[22] The

[20] See footnote 18, p. 102.

[21] CONSTANSO, MIGUEL. DICTAMEN . . . SOBRE DISTANCIAS DEL NUEVO MEXICO A SONORA, Y A MONTERREY. [Ms.] Arch. Gen. y Pub. de la Nac., Prov. Int., v. 169, item 2. Mar. 18, 1776. Mexico City.

[22] U. S. SOIL CONSERVATION SERVICE. STATISTICAL SUMMARY HUMAN DEPENDENCY SURVEY, NAVAJO AND HOPI RESERVATIONS. 41 tables and map. Albuquerque, N. Mex. Rev. 1939. [Mimeographed.] (See tables 1 and 24.)

proportion in the Hopi country is higher, 7.6 acres per square mile in 1936, but above and below the Hopi lands on the Polacca and adjoining drainage basins cultivated land falls to less than the average for the reservations. Considering the small amount of land cultivated it seems impossible that agriculture could have been a significant cause of the acceleration of erosion.

CLIMATE

Many of those who have considered the acceleration of erosion in the Southwest have concluded that it has been brought on by a change of climate. The exact mechanism operative or the amount of change necessary to produce the accelerated cutting are not stated, but references to progressive desiccation, decreased rainfall, or greater relative aridity are common. Huntington (*65, 66, 67*), Gregory (*51*), Visher (*110*), and Bryan (*23, 28*) have suggested such a change as the cause of recent channel trenching (pp. 45–46).

RELATION OF CLIMATE TO NORMAL AND ACCELERATED EROSION

The possible effects of change of climate on rate of erosion are many and varied. Increase or decrease of precipitation are the changes most prone to affect run-off and are therefore of greatest significance in the problem.

Decrease of precipitation in an arid or semiarid land reduces the vigor of plant growth. The less hardy specimens die, the survivors are reduced in size or strength, and there is a general shift toward a more xerophytic vegetation. With decreasing precipitation there is also less water to flow off the lands. Three results are possible: (1) If the effect of vegetal depletion is less than that of reduction in precipitation, run-off will be less destructive and the hypothetical change of climate will bring less erosion than formerly; (2) vegetal depletion may balance decrease in precipitation and erosion conditions may remain the same as before; (3) depletion of vegetation may be more effective than the decrease in precipitation and, particularly if individual storm intensity remains the same, run-off and erosion will be accelerated.

Moderate increase of precipitation may have the opposite of any of these three effects. In an arid or semiarid land moderate increase should improve the vegetal cover on slopes. A great increase in precipitation is likely to cause degrading of stream valleys temporarily, until vegetal protection can adjust fully to the new climatic conditions. There is a question, then, in any area whether increase or decrease of annual precipitation would be most likely to cause acceleration of erosion. It has been assumed by most of the proponents of the climatic-change hypothesis, that a decrease in precipitation, by lowering the resistance offered by vegetation to run-off has brought about the increase in erosive activity in the Southwest. Huntington (*66, p. 32*) stresses the complimentary process. He points out that depletion of vegetation because of decreased precipitation so increases the amount of debris removed from the slopes that streams are overloaded and must aggrade rather than degrade their valleys. It must be kept in mind that processes are different in upstream and downstream parts of the same drainageway. In arid drainages that do

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not run through to a major stream all material eroded from the headwaters must be deposited at least temporarily in the lower course. The boundary between the eroding and the depositing zones migrates upstream or downstream with each period of run-off.

Possible results of a lowering of precipitation would depend in large part on the specific meteorological changes. In northern Arizona, for example, a reduction in winter rains would have a different effect from reduction in summer rains. Bailey has pointed out that a change in intensity would be important even if there were no change in total precipitation (*13, p. 337*). A meteorological shift that would lessen the frequency and intensity of summer thundershowers and of the occasional tropical cyclones in the Southwest, while maintaining the same annual total, might increase the protection afforded by the plant cover to the ground surface. A shift that would delay the inception of the summer rains by only a few weeks, however, would seriously damage the vegetation, thus favoring acceleration of erosion.

In a land of abundant rain an increase rather than any slight decrease of precipitation would be needed to cause acceleration of erosion.

It has been pointed out in the discussion of the distribution and intensity of precipitation in the Southwest and in the Polacca drainage in particular that summer conditions are markedly different from those of winter (pp. 8–11, 47–48). The silent differences and their effects on the operation of normal and accelerated erosion are summarized in table 13.

TABLE 13.—*Relation of summer and winter precipitation to normal and accelerated erosion in the Navajo country*

Seasonal elements of erosion	Normal erosion	Accelerated erosion
Summer:		
Vegetal cover at maximum	Natural cover retards run-off and promotes rapid infiltration and transpiration.	Depleted cover of slight effect in retarding run-off and in removing water by transpiration. Infiltration decreased.
Storms of high intensity but small areal extent and short duration.	Owing to natural vegetal protection, new channels can be eroded only in small areas visited by storms of exceptional intensity.	Owing to depletion of vegetal protection, new channels may form from storms of lower intensity, hence more areas are channeled.
No snow	Run-off beyond the storm area rapidly diminished by absorption and evaporation.	Run-off beyond the storm area rapidly diminished by absorption and evaporation.
Low cloudiness; high evaporation rate; rapid surface drying.	Few channels formed, mostly discontinuous.	Many channels formed, mostly discontinuous.
Winter:		
Vegetal cover at minimum	Natural cover offers limited obstruction to run-off; infiltration low; transpiration inoperative.	Depleted cover provides little obstruction to run-off; infiltration decreased; transpiration inoperative.
Storms of low intensity but large areal extent; may be of long duration.	Although natural vegetal protection is low at this season, rains are generally of too low intensity to carve new channels.	Combination of seasonal lowness of vegetal protection and depletion of natural cover may allow carving of new channels locally.
Snow	Run-off beyond the storm area little diminished by absorption and evaporation; flow from protracted storms may travel great distances.	Run-off beyond the storm area little diminished by absorption and evaporation; flow from protracted storms may travel great distances.
High cloudiness; low evaporation rate; slow surface drying.	Few channels formed, some of the existing channels cleared out and enlarged by confined flow.	Limited number of new channels formed; many existing channels cleared out and enlarged by confined flow; extensive continuous gully systems result.

Under normal conditions the vegetal cover of the Navajo country in summer gave adequate protection against all but the most intense rains. Carving of new channels took place largely where storms of unusually high intensity centered over areas where the vegetal cover was locally impoverished or destroyed by fire or other causes or where steep slopes allowed very rapid run-off. Most of the storms covered areas of less than 30 square miles and had low total precipitation and durations of less than an hour. High temperatures and almost continuous wind movement caused rapid evaporation outside the immediate storm area and only slightly slower evaporation within. Infiltration into the soil and transpiration from the natural plant cover were higher than they are today and were at their peak in the summer months.

Outside of the highly localized storm center the run-off rapidly diminished in volume, owing to losses from infiltration and from evaporation and transpiration, usually termed "evapo-transpiration" by hydrologists. Erosion and transporting power decreased as the volume of flow lessened, and the material washed from the storm area was deposited at no great distance.

Summer conditions tend to retard run-off and localize the effect of each storm. As a result the arroyos that were formed in summer under normal conditions were mostly short and unconnected and characteristically terminated in alluvial fans. Longitudinal alluvial fans, representing in part at least deposition at the lower end of discontinuous arroyo channels in the period of normal erosion, are present on the surface of the upper Polacca Wash.

In contrast to the intense summer storms, winter storms are characteristically of low intensity, may last for several days, and are of wide areal extent (table 13). These storms are accompanied by widespread cloudiness and low evaporation; winter vegetal cover is light and transpiration therefore ineffective. Under these conditions the widespread winter storm, although less able to initiate new channels locally, may cause run-off throughout the entire area. Especially if coalescence of tributary drainage brings together considerable flows of water, winter run-off, whether from rain or melting snow, tends to clear out channels and enlarge discontinuous arroyos lying within the drainageways.

With normal plant cover, the lands recovered quickly from the effects of heavy storms. Vegetation crept back into the newly carved channels and aided in trapping sediment. Vegetation on the surrounding area prevented rapid run-off from average rains and permitted healing of the storm-cut channels.

Depleted plant cover is much less effective than the natural cover in retarding run-off and removing water by transpiration. It is also less effective in aiding infiltration. In areas subject to accelerated erosion the effect of depletion is shown in several ways. Summer storms of an intensity of precipitation insufficient to cause cutting of new channels on a landscape clothed with natural vegetal cover can initiate channels in areas of depleted vegetation. Thus in a region having natural cover, only the area affected by the intense central part, or eye, of the typical summer storm would be subject to initiation of new channels, whereas in a region of depleted cover a much larger part of

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the storm might cause destructive erosion. Similarly, where the ground retains its natural cover, a rain of given intensity would carve channels only on steeper slopes and where drainage was concentrated in sags or draws. Where ground cover is depleted, a storm of the same intensity could initiate channeling on gentler slopes and on surfaces outside of draws and sags, hence subjecting a much larger part of the area to accelerated erosion.

Plant cover offers much less protection against erosion in winter than in summer. Mechanical obstruction to run-off is slight, especially where the cover has been depleted, and transpiration in winter is essentially inoperative. It is fortunate indeed that rains in the Southwest are characteristically of low intensity during this season of poorest vegetal protection.

Channel initiation is inactive in the winter months except along some of the major drainageways. Instead, the run-off from the slow, protracted, widespread rains and melting snows increases the size of channels already formed. Owing to the high proportion of cloudiness and the lowered rate of evaporation during the winter, in addition to a more sparse vegetal cover, run-off can travel a considerable distance little diminished by absorption or evaporation.

Channel clearing and headward growth of gullies lead to integration of the discontinuous gullies formed by summer rains and convert small separate channels into parts of one great continuous drainage system. This development of long, continuous channels through which water is rapidly drained from the region is one of the most serious consequences of accelerated erosion in the Navajo country today.

INCIDENCE AND EFFECTS OF INTENSE PRECIPITATION

A plant cover sufficient to protect the ground from the average storm, or even from the 5-year or 10-year storm, may be quite inadequate to protect against the 50-, 500-, or 1,000-year storms. The timing of rains and the conditions immediately preceding intense rains also weight their effectiveness. Vegetation impoverished by a long period of drought (pp. 31–35) is much less able to withstand a heavy rain than is a plant cover brought to bountiful growth by a succession of well-spaced rains of low intensity.

The effects of heavy rains are amply shown in the gullies and gullied channels, so nearly universal in the Southwest today, and in the floods, wash-outs, and cave-ins that have caused destruction of life and valuable property. Heavy rains are not new to the Southwest. They are an essential part of the meteorological regimen that has characterized this region at least since the readjustments that followed the close of the Ice Age (*91*). Run-off from heavy rains here as well as in other parts of the country, however, is now more rapid than it was before white settlement (*103*). From the earliest records to the present there has been an ever-increasing cry that floods are getting higher upstream, channels are cutting more deeply, downstream reaches are aggrading, and the vegetal cover is not so good as it once was.

The occurrence of destructive rains in the latter half of the last century is amply shown by newspaper accounts, journal entries, and official correspondence. Representative storms and their effects are described below.

The Arizona Miner (*1*) for August 8, 1868, reported:

> About 9 o'clock Sunday morning last there occurred, in Yuma county, in this Territory, one of those dreadful catastrophies in Nature, known as a "water spout," which * * * is without a parallel in similar phenomena. Mr. James Grant, mail contractor on the La Paz and Prescott route * * * left La Paz Sunday morning, and proceeded about 14 miles when he beheld a tremendous black cloud to the eastward, moving toward him from the direction of Granite Wash. Nothing daunted, he kept on his journey until arriving at the big ravine, 14 miles this side of Tyson's Well, now Rovert's Station—where he found the freight trains of Miller Brothers and Campbell & Buffum, of Prescott, in a badly demoralized condition. While the wagons, or a part of them, were crossing the ravine or wash, a flood of water, which came very near destroying the whole train rushed upon them * * *.

On the 31st of August, 1872, the Arizona Miner (*98*) published a delayed letter from Camp McDowell, stating:

> On the 9th inst., we had the greatest flood in this section that has ever been witnessed here, 3 60–100 inches of water fell (by the hospital guage,) in less than two hours, and nearly 7 inches fell in less than 12 hours. The damage is immense. The Government ditch is nearly all washed away. We lost over $5,000 worth of hay.

A few years later, in 1880, the Indian Agent on the Navajo Reservation commented (*16, p. 132*).

> The effect of the heavy winds and rains has been to destroy in many localities the entire crops of wheat and corn. The rains were unusually severe this season, more so than for four or five years past. The dam at the agency, about completed, was carried away by one of those extraordinary floods in about half an hour's time, and rocks weighing tons carried a distance of several hundred yards.

Bourke, a keen observer of natural phenomena, described (*17, pp. 5–6*) many of the storms his party encountered in Arizona and New Mexico in the summer of 1881.

> Those who are not familiar with the fearful type of thunder-storms which arise in the Trans-Missouri region can form no conception of the havoc wrought by those which assailed the vicinity of Santa Fé in the first week of August 1881, and taxed to the utmost the engineering ability of the managers of the Topeka and Santa Fé Railroad to keep their trains running with anything like regularity. The worst storm of the series (that of the early morning of August 2), although spasmodic in its nature, was phenomenal in the amount of water falling during the time it lasted. * * *
>
> Consequently we were not astonished to learn, as we did at breakfast, that the railroad track had been washed away, and that there was no probability of trains running on schedule time for several days.

Constant storms forced Bourke and his party to remain at Keam's ranch in Keams Canyon from August 13–15, 1881. He says (*17, pp. 276–277, 280–281*):

> The first evening after our arrival, as the sun was setting, the mist thickened suddenly, and a fearful cloud-burst broke upon us; in less time than it takes to write these lines it had flooded the creek-bed, raised the water to a depth of three inches on the level ground around the house, carried away the dam, which was built of ponderous sandstone slabs two feet on a side, and then subsided as quickly as it had come.
>
> Inside of half an hour the whole tempest had come and gone. Eight to ten feet of water had swept like a solid wall down the narrow channel of the creek, and the stars were again shining!
>
> * * * * * * *
>
> No description could do justice to one of these Arizona cloud-bursts. Mr. Keam's house lies in a narrow gorge only 100 yards wide, and the receptacle of every drop of water falling within an area of ten miles square. It does

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not take much calculation to show the power of one of the storms prevailing here during the rainy season.

Following the trail southward through the Hopi Butte country to the Mormon settlement of Sunset, on the Little Colorado River, Bourke's party reached the Breaks of the Little Colorado in the afternoon of August 21, 1881 (*17, p. 347*).

Here could be made out the grade of what must at one time have been a very respectable piece of engineering, a road down into the valley below, or rather down to the lower bench.

* * * * * * *

Whoever had done the work had done it well, but fruitlessly. A fearful cloud-burst must have swept over this place lately, and with immense power had hurled great cubes of rock from their positions or gnawed out awful gaps 5 and 6 feet deep and 8 and 10 feet wide in the path we were to descend.

The destructive power of some of the storms of a single month in 1881 is well shown by Bourke's accounts. Then, as now, railroad tracks were washed out, substantial rock dams were carried away, and roads were made impassable by gullying. Other summer storms in northeastern Arizona led the Indian Agent (*80, p. 190*) to report, September 1, 1888:

Some of the dams constructed last year have washed out; in fact it would be difficult to make a dam in this country to withstand the terrible floods during the rainy season, without a great outlay of expense. For this reason the construction of dams, except for temporary uses, should be abandoned and the work directed to reservoirs, ditches, and the developing of springs.

The heavy rains of 1880–1890 are of particular interest because of the evidence that acceleration of erosion first became apparent in many of the valleys of the Southwest during that period (pp. 104). Among the excessive and destructive storms of the 1880's General Greely (*47, pp. 14, 17*) in a report on the climate of the arid regions of the Southwest listed for Arizona and New Mexico.[23]

September, 1880.—The rainfall of the 21st, measuring 2.80 inches, caused a flood at Silver City, [N. Mex.] which damaged buildings and drowned a boy.

August, 1881.—Three floods visited Silver City during the month, on the 7th, the 15th, and the 20th, of which the second did considerable damage.

August, 1881.—Near Wickenburgh, Ariz., a cloud burst, causing the Hassayampa River from being perfectly dry at sunset, August 6, 1881, to be a stream a mile wide at 11 p. m., and from 2 to 15 feet deep; in 13 hours the river was again dry. On the 17th a flood interrupted communication and did much damage in the Salt River Valley near Phoenix.

October, 1881.—Great damage was done to the Atchison, Topeka and Santa Fé Railway on the 6th, and all traffic was suspended south of Las Vegas. In the Rio Grande and Galisteo valleys there were numerous heavy washouts, and in many places the road bed was covered with great heaps of sand.

August, 1882.—Serious washouts occurred on the 24th between Casa Grande and Yuma.

March, 1884.—At Florence on the 7th a cloud-burst flooded the streets 4 feet deep. On the 10th several miles of track were washed away east of Yuma. On the 11th the Gila broke through its levees and flooded Yuma.

July, 1884.—The flooded Colorado washed away parts of the railway bridge at Yuma on the 1st and 3d.

April, 1886.—Heavy rain on the 19th and 20th caused Santa Fé Creek to assume the proportions of a river. Telegraph communication was interrupted, railroad bridges were washed away, and several miles of track destroyed.

June, 1886.—High water in the Rio Grande, in the Valverde, completely overflowed the towns of Chamberino, Launcen, and Nombre de Dios, this on the 2d and 3d of the month. Between the 7th and 10th the freshet having moved downstream washed away houses and railway tracks, destroyed bridges, and submerged three towns in the Mesilla Valley.

August, 1886.—This was a month of floods at Yuma. On the 1st, light rain fell during the greater part of the day. Seventy-five miles west of Yuma the rain was heavy, causing a washout on the railway and delaying trains. On the 15th there was a thunderstorm measuring 1.57 inches, of which 0.80 fell in 20 minutes; the railway was washed out both east and west of Yuma, causing a complete suspension of traffic for several days. On the 27th, heavy rain in the mountains washed out the track east of Yuma and delayed trains.

September, 1886.—Between the 11th and 13th, heavy rains fell between Socorro and Albuquerque, washing away several miles of track, a bridge over the Salida was rendered insecure, and several houses were destroyed in Socorro and San Marcial.

July, 1887.—On the 7th a remarkably heavy rain fell at Nogales, flooding streets, destroying bridges, and washing away railway tracks. During the prevalence of a thunderstorm on the afternoon of the 8th, a cloud-burst occurred on the east fork of the White River in the mountains east of Fort Apache. A volume of water 3 feet deep came down the cañon, which subsided in two hours. On the afternoon of the 13th another heavy rain occurred at Nogales in connection with which there was reported a cloud-burst in the mountains southeast of Sonora. Railway traffic was stopped for nearly a month.

September, 1887.—Heavy freshets came down the Santa Cruz and Rillito on the 9th, destroying several miles of track and some bridges near Pantano. On the 12th, 5 miles of track and three bridges were washed away on the Sonora railroad. Near Dragoon a railway embankment 50 feet high was washed out for a distance of 8 miles.

The nineties and the early years of the next decade were not without intense storms. 1905, however, stands out as a particularly wet year (pp. 18–21); in January, February, March, April, and November precipitation was far more than normal at many stations, but the summer months were drier than usual. Because the rains were mostly of the winter type, characterized by large total precipitation rather than high intensity, many widespread floods resulted. Records of a few of the rains of 1905 and their effects in damage to property and loss of life, as published by the Arizona Republican, of Phoenix, are listed below:

[January 11] From authentic sources it was learned that while [it was] the heaviest rain for seven years in Central Arizona, the losses to the railroads comprised nothing but minor washouts * * *. The situation was much better than would have been the case if the precipitation had been of the midsummer, torrential character. [See *2, p. 1*.]

[February 6] Mr. Green had 100 acres of barley and some alfalfa * * *. It was all rooted up but about ten acres, and that was badly damaged. There is no sign of the young alfalfa. If it had been older something might have been expected of it yet, but this crop was removed by the roots, the surface of the ground being sheared off or cut full of miniature arroyas. [See *3, p. 1*.]

[February 20] The worst that was feared has happened and for the third time this year the Gila bridge is wrecked. At least 400 feet of it was taken away by the flood waters Saturday night and Sunday and by this time the break may be still larger. [See *4, p. 5*.]

[March 15] A Mr. Brown * * * said that one farm under the Arlington canal had been taken bodily and another of 160 acres adjoining it was more than half gone, and a part of the property of the Arlington Land and Cattle company had been swallowed up by the river.

The river has at no time overflowed its banks in that immediate neighborhood but has risen almost to the top of the banks. The water runs with terrible swiftness and the banks melt away, whole acres at a time. The erosion is increased by heavy drift wood which the water hurls against the loose soil. [See *5, p. 6*.]

[March 17] Tempe and the surrounding country was visited by the worst rain and hail storm so far yet this season yesterday afternoon. * * * Mr. Sim-

[23] The data on Arizona and New Mexico quoted from Greely have been rearranged chronologically.

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mons * * * reported that in forty-five minutes the precipitation amounted to 1.42 inches and it seemed from that place to be raining as hard or harder on all sides.

* * * * * * *

About 500 feet of the M. & P. track went out * * *. [See *6, p. 7.*]

[April 16] J. T. Hord who has lived for some years on a farm near the river at the south end of the Novinger road [near Phoenix, Ariz.], has moved to town. * * * Of the sixty-five acres he had title to a week ago only twenty-five acres are left and with the forty acres that were swept away in the flood, went his honey extractor, the building it was in, various outbuildings, an outside cellar, nearly all the mesquite and shade trees on the farm and all of his back yard. The water had undermined his main house so bad it was no longer safe to stay in it and one-half of it is sticking out over the angry stream, or was yesterday. [See *7, p. 4.*]

[April 26] Gallup, N. M., April 25.—The flood situation on the Atchison, Topeka and Santa Fe railway was practically unchanged tonight and it is regarded as very doubtful if any trains can be moved before late tomorrow if then.

* * * * * * *

Bridge No. 90, over the Rio San Jose, just at the west switch at Horace, is in a very dangerous condition and may go out at any moment. The snow is very deep in the mountains and all the streams are running bank full in some places overflowing the lowlands. [See *8, p. 1.*]

[November 30] All other flood news now takes a back seat and the Maricopa & Phoenix railroad bridge over the Gila river again steps into the limelight. As was feared Tuesday night, disaster overtook it and yesterday morning it was learned that four hundred feet of the long structure had been swept away and fears are entertained that the breach will be further widened before this morning. The bridge is somewhere between 1500 and 2000 feet long * * *. [See *9, p. 3.*]

Heavy floods on the lower Colorado River in the spring of 1905 enlarged the intake to the irrigation canals of the Imperial Valley, and the river cut a new channel 75 miles across southern California to the Salton Sink. This basin had been dry when first explored by the Spanish in 1774 and remained dry almost continuously until the Salton Sea was formed in 1905.

Protracted winter, spring, and fall rains such as caused the extensive flooding in 1905 are very effective in clearing out and widening channels and in bringing about integration of gully systems. There is little information available on the effects of the 1905 rains on soil erosion. However, as the heavy winter and spring rains produced a good vegetal cover, it is to be expected that erosion would have been felt much more in enlargement of channels already started than in the cutting of new gullies down vegetated slopes.

The tropical storms that moved up the California coast in September 1939 (pp. 13–14) caused extensive damage in Arizona and in the southern part of California. The storm of September 4–7 brought the heaviest rain Phoenix, Ariz., had experienced in 28 years. Canal banks broke, traffic was interrupted, fields and homes were inundated, and gullies were carved on agricultural land. Traffic on the Atchison, Topeka & Santa Fe Railroad was interrupted for several days by wash-outs between Valentine, Ariz., and Goffs, Calif. Before the damage from the storm of September 4–7 could be fully repaired, rain from the second tropical cyclone reached the area. Many of the reconstructed sections of track were washed out again, and other sections untouched by the first storm were badly damaged. Bridges, culverts, bulkheads, and embankments were most seriously affected. Thousand-foot sections of track were undercut or removed in at least six locations. Several of the breaks were nearer 2,000 feet in length.

In a few areas additional damage was done by other storms coming still later in September.[24]

The Southern Pacific Co. had no more than average storm damage to the Arizona portion of its lines in September 1939. In southeastern California the storm apparently was heavier, and in the two States damage to the railroad right-of-way approximated $175,000.[25] The Arizona Highway Department reports that in its opinion this was the heaviest storm experienced in northwestern Arizona in the past 50 years. Traffic was delayed on U. S. Highway No. 66 between Kingman and Topock and on U. S. Highway No. 80 between Hassayampa and Yuma because of run-off in the dips. A stretch of about 10 miles of U. S. Highway No. 93 between Kingman and Boulder Dam was so badly damaged that it will have to be rebuilt. The cost is estimated at $150,000. A timber bridge some 300 feet long across Detrital Wash was carried away bodily and will have to be replaced.[26]

Destructive floods from the abnormal September rains swept down the lower Colorado River Valley in California and Arizona early in the month. Property along the river was damaged extensively and canals and lands of the Yuma irrigation project and the Imperial Irrigation District were affected by wash-outs, gullying, and silting (*46, p. 754*).

Imperial and Coachella valleys suffered the greatest damage. Nearly every wash and water course ran full and many (with the exception of Alamo and New rivers) exceeded their previous maximum records. In a number of instances the channels were insufficient to carry all the water, and the runoff flowed as a sheet over the adjoining land cutting numerous gulleys varying in depth from inches to several feet. * * *

Truck gardens in many places were covered with several inches of sand and silt, leaving the fields perfectly flat, but eroded by large gulleys.

The Imperial district's canal system suffered probably the worst damage since the disastrous floods of 1905–06–07. Many of the canals were obliterated, others became uncontrolled flood channels, and miles of laterals were so devastated that it will be necessary to reconstruct them.

Less precipitation fell in the Navajo Country in the northeastern part of the State, but even if storms had been as heavy there accounts of the damage would be few. Records of destructive rains in the Navajo country come largely from reports of Indian Agents, as storms seldom receive notice in the public press unless they happen to disrupt highway or rail travel or damage irrigation or water-supply works.

Many storms have contributed to the cutting of the present large gully in Keams Canyon, on the Polacca drainage. Bourke's description of the heavy rains he observed there in 1881 (p. 113) shows the power of flash run-off.

In 1911, the Annual Report of the Moqui Agency, Keams Canyon, Ariz., stated that buildings of both the agency and the school were being injured by the constant cracking of the walls. This was believed to be due to the gradual slipping of the soil toward a large arroyo in front of the grounds. The arroyo, it was noted, was con-

[24] Letter to C. W. Thornthwaite from M. C. Blanchard, chief engineer, Coast Lines, Atchison, Topeka and Santa Fe Railway Co., Los Angeles, Calif. March 15, 1940.

[25] Letter to C. W. Thornthwaite from W. H. Kirkbride, chief engineer, Southern Pacific Co., San Francisco, Calif. March 19, 1940.

[26] Letter to C. W. Thornthwaite from F. N. Grant, deputy State highway engineer, Arizona Highway Department, Phoenix, Ariz. April 6, 1940.

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stantly becoming larger by reason of the heavy rains in July and August of each year.[27] The report for the same agency in 1913 shows a picture of the arroyo in Keams Canyon "within one mile of its beginning, where the canyon is narrow. Depth approximately fifty feet." The caption notes further that 10 years before there had been no evidence of such an arroyo.[28]

The annual report[29] for the next year states that the first days of July were rainy and that on Sunday, July 5, 1914 0.7 inch of water fell in 15 minutes. Great damage resulted. Rains between August 26 and September 3, 1915, in the vicinity of Keams Canyon destroyed roads and rendered communication exceedingly difficult.

In 1919 the Superintendent[30] of the Moqui Agency reported: "On July 15th, 1919, in Keams Canyon, one inch of rain fell in thirty minutes. This was a flood that caused one to wish he had an Ark."

Only 2 years later, on August 4, a cloudburst washed out the retaining walls at the Keams Canyon agency and destroyed roads, crossings, and bridges, cutting off all communication with the schools.[31]

It is apparent from the foregoing descriptions and from that by Hoover (p. 106) that the major gullying in Keams Canyon probably started between 1903 and 1911 but that the gully did not approach its present size until about 1915 or 1920. The part played by the occasional intense rains in the cutting of this gullied channel is clearly indicated by the above accounts.

Intense rains have caused accelerated cutting and serious property damage in many other parts of the Navajo country. A cloudburst on the evening of July 24, 1921, near Fort Defiance Agency rushed down Bonito Creek 10 feet deep destroying protective works that had stood for 16 years. A road and 200 feet of pipe line were washed away, cutting off the water supply. Damage was estimated at $10,000 to $12,500.[32] [33]

Superintendent Kneale[34] of the San Juan Agency at Shiprock, N. Mex., reported on September 19, 1925:

> I have to report a cloud burst yesterday P.M., about 3:00, lasting practically one half hour. The water flowed over the highway near the athletic field to a depth of three feet; the ware house, jail, and all cottages were surrounded by water to a depth of one feet or more; water flowed down the highway leading toward Farmington to a depth of one foot. Some of our crops are buried under many inches of ooze and some are washed away; fences were destroyed; ditches filled and obliterated; bridges and roads washed out; the basement at the Mesa School was partially filled with mud and water. However there was no accident or loss of life.
>
> There have been numerous such storms, during the past six weeks, on all sides of us, keeping the arroyas full and the roads for the most part impassable, but this one hit Shiprock squarely.

[27] LAWSHE, A. L. ANNUAL REPORT FOR THE FISCAL YEAR, 1911, OF THE MOQUI INDIAN SCHOOL, ARIZONA. [Ms., Nat. Arch.]

[28] CRANE, LEO. ANNUAL REPORT OF THE SUPERINTENDENT, MOQUI INDIAN RESERVATION, ARIZONA [FOR 1913]. PICTORIAL SECTION. [Ms., Nat. Arch.]

[29] CRANE, LEO. ANNUAL REPORT OF THE SUPERINTENDENT, MOQUI INDIAN RESERVATION, ARIZONA [FOR 1914]. NARRATIVE SECTION. [Ms., Nat. Arch.]

[30] CRANE, LEO. EIGHTH ANNUAL REPORT [1919] OF THE SUPERINTENDENT FOR THE MOQUI INDIAN RESERVATION KEAMS CANYON, ARIZONA. NARRATIVE SECTION. [Ms., Nat. Arch.]

[31] DANIEL, [R. E.] Telegram to the Indian Office, Washington, D. C., from Moqui Agency, Keams Canyon, Aug. 4, 1921. [Ms., Nat. Arch.]

[32] PAQUETTE, [PETER]. Telegram to the Indian Office, Washington, D. C., from Fort Defiance, Ariz., July 25, 1921. [Ms., Nat. Arch.]

[33] ——— Letter to Commissioner of Indian Affairs, Washington, D. C., from Fort Defiance, Ariz., July 26, 1921. [Ms., Nat. Arch.]

[34] KNEALE, A. H. Letter to Commissioner of Indian Affairs, Washington, D. C., from the San Juan Agency, Shiprock, N. Mex., Sept. 19, 1925. [Ms.; Nat. Arch.]

If records of heavy rains and resulting erosion damage in the Navajo country were more complete, a much more detailed picture should be available of the close relation between storms and erosion suggested by these scattered accounts of the cutting of Keams Canyon Gully and the damaging erosion near Fort Defiance and at Shiprock Agency.

As there is no indication that there has been either an increase or a decrease in the average annual amounts of precipitation in the past 2,000 years or that heavy storms are now any more frequent or more severe than they have been in the past (pp. 43–46), the explanation of the increased erosion by run-off and the heightened floods must be sought outside of the field of meteorology.

GRAZING

Evaluation of the role of overgrazing in bringing about accelerated erosion in the Southwest can be based in part on correlation of the time of starting of heavy grazing and the date of gully cutting in various valleys. As the Southwest developed primarily as a cattle country, it is only natural that the introduction of large herds took place as early as or earlier than the establishment of permanent white settlements. Herds grew in size rapidly, and the grazing load increased until in many areas it soon exceeded the safe range capacity. In humid years when the vegetal cover was at its best the large load could be carried. With the coming of a dry year or a succession of dry years, however, the cover was far from sufficient for the livestock. It was inadequate also to protect the land from erosion.

The facts are clear that acceleration of erosion followed close on the heels of the introduction of heavy grazing. Considering the large number of valleys throughout the Southwest where this is found to be true, the relation can hardly be fortuitous.

Rillito Creek, near Tucson, began cutting after the opening of the Army post at Fort Lowell in 1872. According to Smith (*96, p. 98*) the valley was first settled in 1858, and at that time was an unbroken forest, principally of mesquite, with a good stand of grama grass and other grasses between the trees. When the Army post was opened hay was needed in large quantities. A few years of cutting hay killed much of the grass, and cattle introduced during the seventies further destroyed the forage and developed trails, which soon eroded to gullies.

According to a rancher (*53, p. 12*), the San Pedro Valley, Ariz., had a luxuriant growth of vegetation in 1870. He continues:

> There were fully 50,000 head of stock at the head of Sulphur Spring Valley and the valley of the Aravipa in 1890. In 1900 there were not more than one-half that number and they were doing poorly.

Another rancher (*53, pp. 13–14*) on the San Pedro said in 1900:

> Of the rich grama grasses that originally covered the country so little now remains that no account can be taken of them.
>
> * * * * * * *
>
> Twelve years ago 40,000 cattle grew fat along a certain portion of the San Pedro Valley where now 3,000 can not find sufficient forage for proper growth and development. If instead of 40,000 head 10,000 had been kept on this range, it would in all probability be furnishing good pasture for the same number to-day. Very few of these cattle were sold or removed from the

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range. They were simply left there until the pasture was destroyed and the stock then perished by starvation.

Hoover states (*61, p. 45*) that the changed behavior of the Gila River is generally attributed to overgrazing and the cutting of timber in the upper basin.

Before 1870 there were few cattle, but they increased rapidly after the settlement of the Apache Indian troubles that year. During the eighties there was a series of wet years with abundance of natural forage. The ranges built up rapidly, and overgrazing resulted. During the same period the mountains of the Upper Basin in southeastern Arizona were being rapidly stripped of their timber for use in the mines. The hills were barer than now, because with the advent of the railways better mine timber was brought in from the outside; but the cutting for fuel continued. At the end of this series of wet years came the disastrous flood of 1891. Before this, flood waters of the Gila merely spread out over the flats and irrigated them. Now with the banks of the river unprotected by brush and grass, the channel suddenly widened, and many good ranches along the river were cut out. Smaller branches of the river in the upper basin cut channels as much as twelve feet deep. On the desert deep channels appeared in what had been grassy swales.

Diversion of water by irrigation projects farther up the Gila Valley and consequent reduction of flow is also thought to have contributed to the changes in the regimen of the river (*61, p. 45*).

The balance of grazing, vegetal cover, and climate can readily be upset. In a series of years with normal or greater than normal precipitation the range may have carried the grazing load with little detrimental effect. With the coming of a drier than normal season, year, or series of years the depletion of vegetation may have been so great as to adjust the grazing load automatically by starvation. Calvin [35] in a study of the history of the Upper Gila Region says:

With an immense grass-covered range, then, in its virgin condition, and with the additional advantages of a mild climate, Arizona was obviously destined to develop almost overnight into an important stock-raising country.

* * * * * * *

When the two transcontinental railroads crossed Arizona about 1880, they gave still further impetus to the livestock industry along with others. A great part of the sudden influx of population took to ranching. * * * Many made fortunes at first, but competition naturally grew keener. By the middle eighties, every running stream and permanent spring had its settler. Ranch houses were built, and ranges stocked with cattle brought from every part of the west.

In the fall of 1883, the first carload of pedigreed Herefords were unloaded in Arizona. * * *

In the early eighties, there was a heavy demand for beef in the great mining camps of the Territory and another from the California markets. * * *

Then about 1885 occurred a drastic deflation in the mining industry. * * * As a result, ranchmen turned for the first time to eastern markets and when a shipment of five hundred head brought the owner a gratifying price, a new trend in ranching practice developed. It became the custom for several years to retain the she stock on the range, and to hold the steers until three years old and sell them as feeders to the corn-growing states or to California.

The retention of cattle on the range then began to assume great importance for the purposes of the present study. By 1891 it was conceded that the ranges were stocked, says Campbell, to the limit of their capacity. Then the drouth arrived. * * *

Little effort was made by owners to sell or ship their stock, as they waited for the grass of the coming season. But 1892 was worse than its predecessor. By May cattle were dying. June, always a dry month in the Southwest, further dissipated the moisture which remained. The July rains did not come. The August rains did not come. Cattle were perishing everywhere.

[35] CALVIN, ROSS. THE HISTORY OF THE UPPER GILA REGION IN ARIZONA AND NEW MEXICO. [Unpublished manuscript, September 1935.] Mr. Calvin was research assistant, Soil Conservation Service, Safford, Ariz.

* * * Another year dragged onwards, and then in May, June, and July of 1893 occurred the worst losses of all. "All ranchmen concede," says Governor McCord, looking backwards in his Report of 1897, "that it (the loss) was no less than fifty per cent, and some insist that seventy-five per cent is not too great an estimate."

* * * * * * *

The first tragic half-cycle was complete, for the country had passed in twenty years from its virgin, grass-covered state to a parched, close-picked condition in which the last palatable leaf had temporarily been destroyed by starving animals. * * *

Sufficient history has been cited to show extreme unwisdom in the practice of overstocking by the ranchmen. They estimated the carrying capacity of the range and stocked it, not according to its minimum but its average—which without a reserve of some kind has always proved fatal.

Other changes incident on settlement have been at least contributory causes for acceleration of erosion in some areas of the Southwest. When settlers cut a short drainage channel to confine flood waters of San Simon Creek near Solomonville in 1883 (*79, p. 79*), they started a gully that is now at least 60 miles long. The gully of the Rio de Flag, Ariz., was started partly by erosion along an old logging road used in 1886–87 (*20*). The San Vicente arroyo which formed down the main street of Silver City, N. Mex., has been mentioned on p. 103. Bare of vegetation but unpaved, the street lay in a natural drainageway. It began to erode, and the channel enlarged rapidly to its present depth of more than 50 feet. Lumbering, forest fires, and overgrazing, Calvin says, are the reasons for the increased rate of run-off from the watershed above Silver City (*31, p. 39*). Setting aside of the Gila Forest in 1908 gave nature a chance to revegetate the watershed, and Calvin reports that floods are now so much smaller and less frequent that there is a popular notion that the area no longer receives the big rains that formerly fell there, an impression not borne out by the records. Revetment work and gully-control dams installed by the United States Soil Conservation Service and the Civilian Conservation Corps have further protected the city from the possibility of recurrence of destructive floods (*32*).

In southern Colorado, according to Duce (*44*), ranchers are unanimous in stating that trenching of valleys has taken place within the 60 years preceding 1918. Development of the arroyos, he says, seems to have been contemporaneous with ranching. Duce notes that cattle often trail down the center of a canyon, and he believes that wearing of trails and destruction of vegetation by livestock were the causes of the accelerated erosion.

Additional evidence of the part played by heavy grazing was presented by Dodge in 1909 (*42*). He found in the Chinle Valley strong indication that the run-off from rains formerly flowed over gently sloping valley floors in sheets. The Navajos, he says, charge that sheep, first introduced to the area by the white man, have closely cropped the native grass. This and the traveling of sheep in droves, often in single file, have aided in loosening surface detritus and giving water opportunity to become concentrated in streams. Dodge notes (*42, p. 531*) that, at the time he wrote, the main Chinle Valley and its larger tributaries were barren and were cut by arroyos, but—

one branch is grass-covered and flat-floored and supports willow trees. Water flows in sheets over the surface and is not concentrated in streams. This valley has never been occupied as a grazing area for sheep by the Navajos because of a superstition that it contains certain plants that are injurious to sheep.

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The presence of dead willows in branches of the Chinle Valley that have been grazed and are now deeply dissected by arroyos suggests that moisture conditions and the valley floor were formerly like those of the one remaining branch that has escaped erosion.

In the Navajo country, grazing of domestic animals could not have been extensive before the founding of the reservation in 1868. By 1872 about 44,000 head of sheep and goats had been brought into the the reservation (*12, pp. 198–199*), and growth of the flocks had undoubtedly increased the number considerably. Compared with the number of sheep and goats on the reservation in recent years, this number is very small. It seems hardly likely, therefore, that the grazing load of the seventies would be heavy enough to introduce serious erosion. In the eighties or early nineties the critical grazing load may have been reached.

As the small vegetational surplus was consumed, overgrazing prepared the way for erosion. Where part of the vegetal cover had been removed, even light storms were able to produce erosion. Sheet wash and rilling came first, followed by the cutting of gullies, which enlarged in each succeeding period of run-off. Gullying of the main channels of the washes and integration into continuous gully systems followed. The headward growth of gullies and the starting of new ones have gone on year after year during the period in which the overgrazed condition of the ranges has become increasingly acute. Natural grasses have been displaced by less desirable vegetation, and locally vegetative depletion has gone so far that only scattered remnants of sod on bare rock surfaces give evidence of the former soil and grass cover.

Overgrazing has altered the plant association on the mesa areas of the Polacca Wash drainage and has so increased the run-off that all rains except those of very low intensity cause soil erosion. The run-off from the lighter storms is too slight to do much gully cutting near the divides and seldom becomes sufficiently concentrated through coalescing drainage to cause channeling on the mesa tops. Light rains, however, do soak the walls of preexisting gullies and induce caving.

In the pediment zone along the Polacca Wash the gentler slopes, and especially the back slopes of the asymmetric ridges formed by slumping (p. 79), were formerly well vegetated, and grasses as well as brush and trees were present in many parts of the area. Hogans were frequently built within or adjacent to this zone, and these gentle slopes were subjected to heavy grazing. Many of the slopes which formerly were soil covered are now bare, and gullies have been cut in the benches where alluvial material was once deposited. Most of the grass has been destroyed, and except for local abundance of piñon-juniper, brush and weeds now compose the sparse plant cover of this zone.

The vegetal cover of the alluvial fans and valley flats of the Polacca drainage has also been seriously depleted by heavy grazing. The extensive gullying of the fans and flats, though, is influenced not only by overgrazing within the canyons but by depletion of vegetative cover on the mesas, which causes accelerated washing over the cliffs and down into the canyons.

The situation on the Navajo lands is like that in parts of Africa having similar climate. It is said that the overgrazed native pastures are today the most seriously eroding areas within East Africa. Pastures near the water holes are so badly overgrazed and trampled that water can no longer penetrate into the soil. Cattle trails develop into gullies radiating from the water holes, and the overgrazing spreads outwards so far that cattle may have to travel 20 miles for water.[36] Where pasturage is too poor for cattle, sheep and goats are substituted. When goats have devoured the ground vegetation they browse the lower parts of trees and shrubs up to a height of 5 or 6 feet (*33, pp. 130–139*).

In the Union of South Africa it has long been the native custom to drive livestock daily to and from a kraal, or enclosure. This practice closely resembles that of the Navajos, who use a corral until the surrounding area is grazed out and then move on. The development of centers of serious overgrazing and trampling is common in both areas and has led the Drought Investigation Commission of South Africa to state that the abolition of kraaling is their most pressing and necessary change in farm methods (*99*).

It has been held for many years by Bryan and others that overgrazing is not the basic cause of the acceleration of erosion in the Southwest. Part of the reasoning behind this stand is that the buried channels and filled washes within the present main valleys give evidence of at least three alternations of cutting and filling. Bryan says (*28, p. 281*), speaking especially of the Rio Puerco in New Mexico:

> It appears inherently most probable that the cyclic changes have a common, and doubtless a climatic, cause. The introduction of livestock and the ensuing overgrazing should be regarded as a mere trigger pull which timed a change about to take place.

From Bryan's viewpoint it might logically be concluded that anything man can do to reduce grazing and other surface irritations will in all probability be inadequate to prevent the continuance of accelerated soil erosion in the Southwest. If this view is in error, and the erosion has been the direct result of man's use of the land, there is every reason to believe that by judicious reorganization and restriction of land use the damage can eventually be checked. Expressing Bryan's hypothesis in another way, change of climate might be regarded as the debilitating agency that had lowered the resistance of the land—overgrazing as the germ or infection that had touched off the epidemic of accelerated erosion. Even if the present severe destruction could be checked, the general run-down condition would continue and a full cure would hardly be possible.

The other view, that held by the authors of this bulletin and by many others interested in actively combatting the soil destruction in the Southwest, is that overgrazing by livestock introduced by the white man has reduced the resistance of the land to erosion and that intense storm precipitation has been the germ or infection that caused the outbreaks of accelerated erosion. In this view, lessening of the grazing load would so build up the vegetal cover and the resistance of

[36] MAHER, COLIN. SOME ASPECTS OF SOIL EROSION IN THE NATIVE RESERVES OF KENYA COLONY. [1938.] [Unpublished manuscript.]

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the soil to erosion that only storms of extreme intensities would be able to cause serious erosion. The latter view is the more attractive in that it offers hope of continued use of the lands through wise control. Fortunately the evidence points strongly to the validity of this interpretation.

As has been seen in the discussions of the climate of the Southwest and of the possibility of climatic change (p. 38–46), meteorologic and climatologic considerations show no trend toward a more arid climate in the Southwest in the past few thousands of years and no evidence of any present day trend either toward more arid or more humid climate.

The large storm of high intensity and heavy fall of precipitation rather than a general climatic trend explains the accelerated erosion of the arid and semiarid lands. Large storms have always occurred. Before overgrazing lowered the resistance of the surface only the greatest rains could carve arroyos and enlarge wash channels. The lands recovered rapidly, moreover, and discontinuous channels had little opportunity to join with others to form long continuous waterways. Perhaps only the 100-year rain cut new channels on the naturally vegetated surface, perhaps only the 500-year rain. Big storms have been and always will be unpredictable. None may occur for many years, or two or more may take place a few days apart. Big storms, especially if grouped and if coming at a dry season or after a long drought, have always been able to cut channels and start a subcycle of accelerated erosion. Many of the periods of channel cutting before the coming of the white man to the Southwest may have been brought on in that way. Arroyos observed by Dellenbaugh (*40*) in places where he says there were no cattle and never had been may also have been cut by occasional storms of extreme intensity. Buried channels found in the valley fills of the Southwest doubtless resulted from earlier 100-year or 500-year rains, possibly some following the "great drought" of the last quarter of the thirteenth century A. D.

Big storms will continue to visit the Southwest. The lands can never be protected against the greatest of these storms, but much can be done to avert damage from the average summer storm or even from the 1-year or the 5-year storm. In the present state of the lands all these storms cause damage.

Various means can be used. Control of grazing and lessening of the grazing load are paramount. The plant cover must be increased. Water conserving measures such as pasture furrows will aid. Dams and other gully-control structures and water spreading devices will offer protection against all but the greatest storms. Structures must be carefully designed and be well suited to the peculiar foundations provided for them by the valley fills. They should be built to withstand the 25-year or 50-year rain, with the knowledge that a rain of greater intensity may destroy them. As grazing practices are improved and vegetation spreads to take a firmer hold on the soil, reduction of run-off will lessen the load imposed on control structures.

Confirmation of the view that overgrazing rather than climatic change has brought on the accelerated erosion in the Southwest is found in the vegetation on protected plots. Cooperrider and Hendricks report that a conservatively grazed fenced area near Albuquerque has approximately twice as much cover as the surrounding

range and hence probably somewhat more than twice the protection against erosion. Another plot, an old cemetery 2 miles southwest of Albuquerque, has a far higher percentage of grass than the surrounding overgrazed land and a total density of vegetation more than three times that outside the fence (*36, pp. 22–23*). The same trend is being shown on newly fenced areas in the Navajo Country where grazing is controlled and the number of livestock is limited. Not only is the vegetation better, but in the first year of the test the sheep within the enclosure weighed almost one-third more and grew about one-third more wool than those outside. The lamb crop in the controlled area was half again as large as that on the range outside (*87, pp. 38–39*). The management that was best for the land and was best adapted to protect the soil against accelerated erosion also yielded the most profits.

SUMMARY AND CONCLUSIONS

Local information, physiographic evidence, and comparisons of old and new surveys indicate that in the Polacca Wash, as in most other valleys of the Southwest, acceleration of erosion first became active 50 to 60 years ago. This acceleration, which was made apparent by the trenching of wash floors, was accompanied by a depletion of vegetation. It has commonly been attributed to a progressive desiccation of climate, but this explanation is not substantiated by available evidence, and study of the climate of the Southwest suggests other possible reasons for the changes in erosion.

Because of a more critical balance of climate and vegetation, climatic variation produces far greater differences in plant growth and erosion in dry regions than in humid lands. Variations in precipitation and temperature from year to year may result in marked shifts in the climatic pattern. Areas normally semiarid may be arid one year and subhumid the next. Differences between the precipitation for corresponding months in different years is even more striking. One year a given month may receive more than the average rainfall for an entire year. The next year the same month may receive none.

The diurnal and annual marches of temperature and precipitation, caused by the relation of the earth to the sun, are complicated by the invasion and interaction of the various air masses that enter the Southwest. These masses are cool and moist, cool and dry, warm and moist, or warm and dry, depending on the source region from which they come and the route they follow. They cause the variations in temperature and precipitation in the Southwest. The sum of the variations produced by the interactions of the different types of air masses which enter the Southwest determines the yearly departure of the climate from the normal.

Examination of evidence in tree rings, lake levels, cutting and filling of valleys, and in the development of pueblo peoples fails to reveal proof of any climatic change in the Southwest in the last 2,000 years. Climatic fluctuations of the magnitude experienced today have occurred, and intense storms and groups of intense storms have had their effect on the landscape, but if there has been any progressive change toward either a more humid or a more arid climate that trend is so slight as to be completely overshadowed by the shorter period fluctuations.

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Under natural conditions, in the Polacca Wash drainage and through most of the Southwest, the plant cover protected the soil and retarded the flow of water off the lands. In the valleys, deposition exceeded removal. Discontinuous channels were developed locally as a result of heavy storms, but most of the channels or arroyos extended only short distances and ended down drainage in alluvial fans. There was no continuous deep channel running the full length of the Polacca Wash.

With acceleration of erosion, short discontinuous gullies became more numerous. As long as these were separate units, rain falling in one part of a drainage basin might be felt as run-off for a few miles or tens of miles down valley, but the flow seldom traveled much farther. All but the largest channels were ephemeral, shifting or disappearing after each rain.

As acceleration of erosion continued, more of the gullies lengthened until they joined other gullies farther along the wash. The water, confined within narrow channels, traveled longer distances, and gully cutting proceeded more rapidly. Integration of drainage by the joining of discontinuous gullies increased the rate of headward cutting and of downward scour. Gullying in the Polacca Wash is believed to have started with at least five large discontinuous gullies, which later joined to form a continuous gully channel reaching from the headwaters area to the Little Colorado River. Gullies in many of the tributary canyons form a part of this continuous system. Discontinuous gullies that do not reach the main axial channel but end in fans are abundant on the valley sides. More and more of these lateral slope gullies are now becoming continuous—permanent tributaries of the main channels.

Gully cutting is the most obvious and most destructive of the erosive processes at work in the Polacca drainage, but sheet erosion and wind erosion are also reducing the usefulness of the lands. Owing to sheet wash on the mesa surfaces bare rock now is exposed where once was grass-covered soil. On pediment slopes and alluvial fans, sheet wash is gradually removing the most valuable part of the soil cover. Wind erosion is destructive in certain parts of the area and has become of increasing severity within the memory of the native inhabitants. Shifting sands have forced the abandonment of fields and corrals and are now so widespread along the lower Polacca that they obscure the basic structure of pediment, fan, and valley fill. Wind erosion will become still more dominant in this part of the area unless vegetation is planted to anchor the shifting dunes. In the Painted Desert section of the Polacca Wash the shifting material includes not only sand but fine chocolate-colored silts from the flood plain of the Little Colorado River.

The work of the wind may be beneficial locally in helping to check erosion by running water. Blow sand, being porous, absorbs even fairly heavy rains. Where irregularly deposited it also tends to catch some of the precipitation in pockets and prevents its running off over the surface. Shifting sands, by filling or damming rills and larger channels, retard destructive run-off and protect both the immediate locality and the area downstream. Sandy lands are among the best areas in the Polacca drainage for raising crops or for growing a protective covering of vegetation.

There is no evidence of any appreciable uplift or tilting of the land or any change in base level that might explain the recent acceleration of erosion in the Southwest. The agricultural history of much of the area, particularly of the Navajo and Hopi Indian reservations, shows no extensive cultivation and no use of harmful practices that would cause the widespread accelerated erosion. No evidence has been found of any progressive climatic change that would explain the recent increase in the rate of erosion.

Owing to the delicate adjustment of vegetation to climate in the Southwest, a succession of even a few dry years may so impoverish the plant cover that rains of heavy, or even moderate, intensity can initiate a period of accelerated erosion. Climatic records and news reports show that from time to time parts of the region have been visited by storms of exceptional intensity (pp. 112–119). These are as characteristic of the Southwest as is its semiarid climate.

For all given climatic conditions there is a certain minimum plant cover needed to protect the land against destructive erosion. In arid lands with little or no vegetation and low precipitation there may never be sufficient vegetation to offer protection from the infrequent rains. The dryness of the ground and the lack of well-marked water channels may prevent rapid run-off, but a permanent inadequacy of cover is characteristic. In semiarid lands the plant cover may be barely adequate to resist the impact of the climatic elements. The margin of safety is slight, hence the amount of vegetation that can safely be grazed is small. In subhumid and humid lands, although storms are more frequent and more intense, the cover of vegetation is thicker and a larger amount can be grazed without causing soil wastage. The marked contrast of the humid and arid lands in adequacy of cover must be considered in evaluating the permissible grazing in any area. In the Polacca drainage and on range lands through most of the Southwest the permissible amount has long since been exceeded. Vegetation now is far from adequate to protect the surface against the erosive forces.

The Polacca drainage is now suffering the results of a grazing economy that was introduced to the Indians of the Southwest about 1540 and has been practiced with little change to the present time. The human and animal population was not heavily concentrated in this part of northeastern Arizona until after the Civil War. It appears to have taken 15 to 25 years for the increased grazing on this land to reduce the vegetal cover to such an extent that changes in erosion became recognizable to the human inhabitants. Serious gullying at most other localities in the Southwest correlates well with expansion of the cattle industry stimulated by the building of the railroads. Acceleration of erosion is reported to have begun in much of the region between 1880 and 1890, and in certain areas probably a decade or two earlier.

Although accelerated erosion has carved deep channels almost the entire length of many of the major washes in the Southwest and has carried away millions of tons of soil material, this does not necessarily mean that gullying need continue or that entire valley flats must be lost to productive use. If the removal of vegetation can be curbed and revegetation begun, it may be possible to check the accelerated cutting. If the vegetal cover can be improved until it

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