Sedimentation Rates in Small Reservoirs in the Little Colorado River Basin

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1110-D

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By C. F. HAINS, D. M. VAN SICKLE, *and* H. V. PETERSON

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Measurement of sedimentation in stock reservoirs as a possible means of determining origin and movement of sediment

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By C. F. Hains, D. M. Van Sickle, and H. V. Peterson

ABSTRACT

Measurement of the rate of sedimentation in a group of small reservoirs located in land-use District 18 of the Navajo Indian Reservation, Arizona-New Mexico, suggests a possible method for determining the origin of sediment and estimating the rate of sediment movement from headwater areas underlain by various geologic formations. Land-use District 18 lies within the Little Colorado River basin. The area is underlain by sedimentary rocks, which range in age from Permian to Late Cretaceous and in character from coarse, well-indurated sandstones and conglomerates to soft fine-textured sandstones of aeolian origin and soft friable shales.

Measurements of sediment trapped in 35 reservoirs distributed over areas underlain by these formations show a striking difference in rate of annual sediment movement. Groups of reservoirs located on shale and soft sandstone trapped on an average 2 to 8 times as much sediment per square mile of drainage area as other groups located on well-indurated sandstone and conglomerate. In individual reservoirs the contrast is even more striking, the movement ranging from less than 0.1 acre-ft annually per square mile of drainage area in reservoirs underlain by conglomerate to more than 2 acre-ft in reservoirs located on the Chinle shales. The differences appear to be due mainly to characteristics of the underlying rock, although it is recognized that other characteristics of the drainage basin, such as soil, slope, cover, and land use, also have an influence.

To the extent that distinct differences in erosibility of the land can be attributed to geology, investigations of this kind offer a method for obtaining a ready inventory of the source and rates of sedimentation in areas where geologic mapping has been completed. The results would delineate areas of greatest erosion potential and thereby would be useful in devising plans of treatment aimed at abating erosion.

INTRODUCTION

Studies on sedimentation in a number of small reservoirs located on the part of the Navajo Indian Reservation lying along each side of the northern boundary between Arizona and New Mexico (see pl. 7) have been undertaken as a means of determining the origin and movement of sediment in areas underlain by various types of sedimentary rocks. Most of the reservoirs were constructed for storing water for livestock use, but some were installed as part of a land-treatment program designed to reduce erosion and stimulate reestablishment of vegetation. In capacity they range from less than 1 acre-ft to a maximum of 65 acre-ft. The dams are all earth-fill with side spillways.

The formations on which the reservoirs are located have a wide distribution throughout the Colorado Plateau. Therefore, accumulation of sediment in the reservoirs surveyed makes it possible to estimate within fairly close limits sediment movement from other parts of the Plateau underlain by similar geologic formations. Additional information obtained gives some indication of the influence of soil types, vegetation, slope, land use, and other factors on the erosibility of a given area.

Surveys of reservoirs offer about the only feasible plan for obtaining information on sedimentation rates in arid country. Typical of such areas, the streams feeding the reservoirs are strictly ephemeral, with flow occurring at unpredictable periods. Direct sampling of the stream flow was therefore impractical because it was difficult to anticipate the time of flow and to assemble the equipment and personnel necessary to obtain the requisite number of representative samples.

Essentially the method used was to determine the amount of sediment trapped in the reservoirs and to prorate this amount over the life span of the reservoir. This gave an average yearly sediment-production rate for a drainage area of known size. This rate was further modified by comparing rainfall during the life of the reservoir with the long-term rainfall of the area, which gave a general average expectancy of sediment production from the basin. The method has the disadvantage, of course, that data on sediment movement during individual seasons or storms are unknown, and thus no relationship between runoff and sediment can be developed. It does, however, have the advantage that small drainage areas of distinctive physical characteristics can be studied.

The area in which the reservoirs are located, land-use unit, District 18, of the Navajo Indian Reservation in Arizona and New Mexico, covers about 1,500 sq mi. It is a part of the Little Colorado River basin and exhibits many of the characteristics typical of the basin. In selecting reservoirs for study, an effort was made to obtain a distribution that would reflect the differences in erosion in various types of localities. Because detailed information on soil was not available and as there is an obviously close relationship between soil and the rock from which it is derived, division on the basis of geologic formations was considered both practical and desirable. A generalized description has been included of the chief physiographic and geologic features of the area, with particular reference to those factors that appear to have some effect on erosion, runoff, and climate.

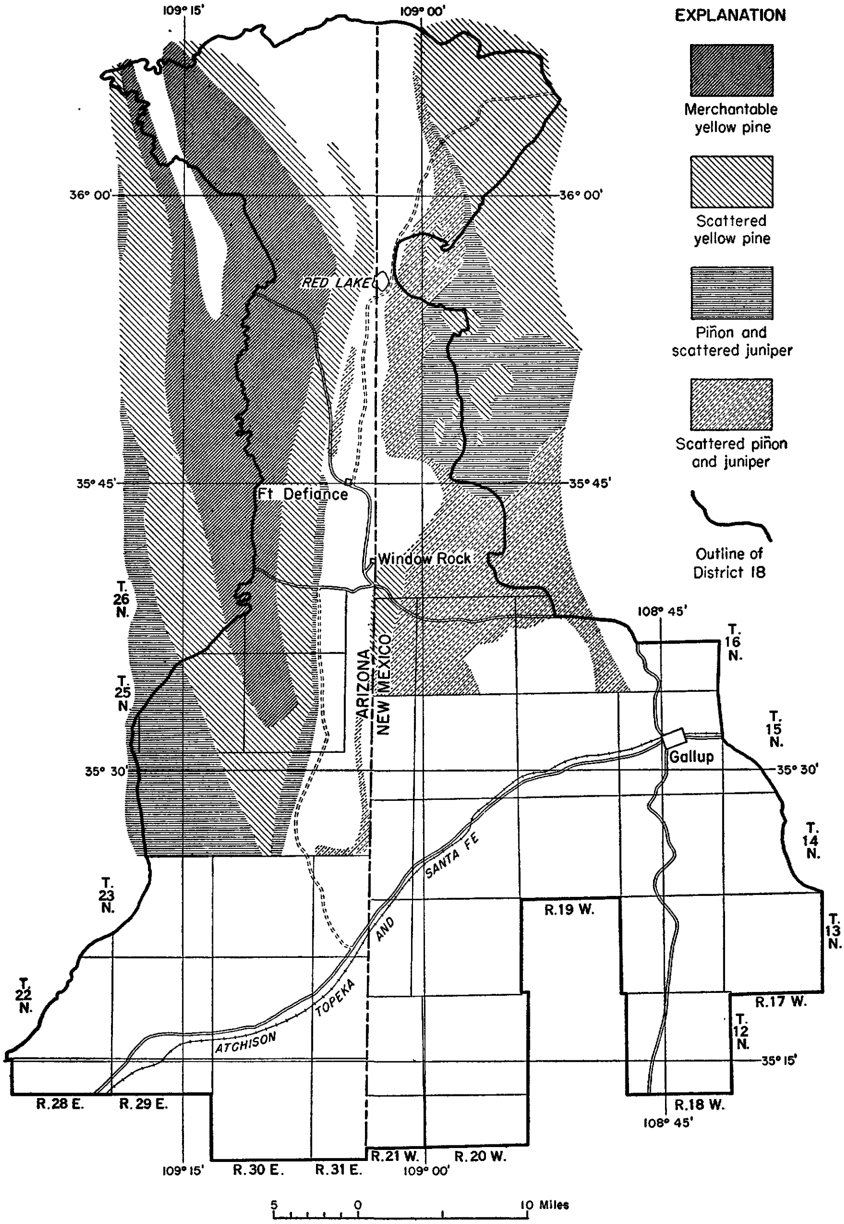

FIGURE 17.—Forest types of vegetation. From map by Gregory.

A part of the geologic map of the area by Gregory,[1] with some modification, is shown as plate 7. Figure 17 showing distribution of forest types of vegetation is also taken from Gregory's report.

[1] Gregory, H. E., 1916, The Navajo Country: U. S. Geol. Survey Water-Supply Paper 380.

Reservoirs containing water were surveyed by use of compass and pacing, dry reservoirs by plane table and stadia. Sediment deposits were probed, using ½-in. steel bars, to determine depth. In nearly all reservoirs three or more contours were surveyed to obtain the area-capacity curve. Bureau of Indian Affairs records were consulted for location, date of construction, and the general history of the reservoirs.

Data obtained from the study indicate significant differences in erosion characteristics of areas underlain by various geologic formations. It is believed that an expansion of the study to other parts of the Little Colorado River basin would furnish needed information on the general erosion potential of the area and would focus attention on particular tracts where the rate of erosion is critical.

Field surveys for the studies were made during the summers of 1946 and 1947 by C. F. Hains, hydraulic engineer, and D. M. Van Sickle, geologist, under the supervision of H. V. Peterson, staff geologist. The work was begun as a part of the general investigations of sedimentation being conducted by the Geological Survey under the Department of Interior's soil and moisture conservation program.

ACKNOWLEDGMENTS

Special acknowledgment is due members of the Navajo Indian Agency who made maps and records available and those who assisted in the field work. Especially helpful were R. E. Kilgore, conservationist, and John J. Schwartz, irrigation engineer, Window Rock, Ariz., and H. B. Coddington, conservationist, Mexican Springs, N. Mex.

PHYSIOGRAPHY

Erosion and movement of sediment within any given area, particularly in the semiarid West, are strongly influenced by such physiographic features as land forms; slope of the terrain; character of the drainage pattern, including both the main channels and the minor tributaries; type of cover, and possibly other less important features. Although no attempt was made in the studies to discriminate between individual features or to set up standards for determining their influence it nevertheless was obvious that erosion characteristics in certain parts of the area were attributable mainly to variations in physiography. Therefore, an effort has been made to describe the principal physiographic features of the area and to point out their relationship to the erosion problem.

The area studied lies in northwestern New Mexico and northeastern Arizona within the boundaries of the Colorado Plateau province. Flat-lying or slightly tilted strata, cut by deep canyons, with buttes and mesas rising abruptly from almost level, broad expanses, are the general features of the province. Gregory [2] in describing the Navajo country divided it into several geographic provinces. The area studied includes parts of three subprovinces—the Defiance Plateau, Black Creek valley, and the Manuelito Plateau.

DEFIANCE PLATEAU

The area studied lies along the eastern edge of the Defiance Plateau and extends eastward to the floor of Black Creek valley. A yellow-pine forest grows at the higher altitudes; Gregory [3] points out that this forest is somewhat unique in that the ground under the trees is almost devoid of the normal forest litter and young pines are few. In open parks there is only a sparse growth of grass and brush. At lower altitudes the forest is of the pinon-juniper type with a sparse cover of brush and grass occupying the spaces between the trees. Soils are generally thin and the valleys have no deep alluvial fills. The soils are predominantly sandy or gravelly, reflecting the characteristics of the parent rock.

BLACK CREEK VALLEY

Black Creek valley extends from just south of the Sonsela Buttes to Puerco River and occupies the middle part of District 18. The valley as described by Gregory [4] varies widely throughout its course.

> In the vicinity of Crystal its floor is flat and occupied by ephemeral lakes. Beginning at Hunters Point the valley narrows to one mile, then increases in width to Oak Spring, at which point it is replaced by a red-walled canyon, 600 feet deep and less than half a mile wide, cut through the Defiance monocline. Below the canyon the valley gradually increases in width until it joins the Puerco.

Extending along the eastern edge of the valley the colorful sandstone cliffs rise abruptly 100 to 200 ft above the valley floor. Just south of Red Lake and again near Fort Defiance, volcanic rocks jut 100 to 300 ft above the surrounding terrain.

Black Creek, the main stream in the valley, rises in the Chuska Mountains to the northeast. Its tributaries drain the eastern slope of the Defiance Plateau, the southwestern slopes of the Chuska Mountains, and the western slopes of the Manuelito Plateau. The channel has an average gradient of about 25 ft to the mile over its length of 60 miles from the Chuska Mountains to Puerco River. Generally the flow is ephemeral, but a reach of several miles in the headwaters maintains a permanent stream. All the tributary drainages are comparatively short. Only a few, which are spring fed, are perennial, and these for short distances only.

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[2] Gregory, H. E., op. cit., pp. 22–49.
[3] Gregory, H. E., op. cit., p. 35.
[4] Gregory, H. E., op. cit., p. 32.

The small drainage areas that are tributary to Black Creek, especially from the east, have the largest sediment movement in the district. Gully erosion is extensively developed along almost all the streams draining the eastern slopes of the valley. This erosion can be attributed to a number of factors, the chief one being that these basins contain a deep alluvial fill mainly of fine sand derived from the adjacent sandstone and shale formations. This material is soft and noncohesive and therefore particularly vulnerable to erosion once the protective cover is depleted or destroyed by heavy grazing or in other ways. Steep slopes aid in the development of gullies. Intensive efforts have been made to stop the erosion in certain localities. The use of dams and spreader dikes in one of the side tributaries (nos. 8 to 23 on pl. 7) is an example of such efforts.

Many of the dams were built as gully plugs intended only to reduce bank cutting and prevent further deepening of the channel; others were designed to divert water from the channel and spread it over adjacent areas, thus reducing crest flows and at the same time supplying water to range forage.

Channels of streams tributary to Black Creek on the west are generally carved in bedrock where they cross the Defiance monocline, so that the sediment load is small although the gradients are steep. On entering the main valley, however, the streams tend to gully, and the sediment load increases accordingly.

MANUELITO PLATEAU

The Manuelito Plateau occupies the area east of the Black Creek valley, south of latitude 35°45′. Of this geographic subprovince Gregory [5] says,

> In this area the high points are remnants of horizontal sandstone beds and are usually sharply defined by cliffs on all sides. The valleys are broad, open, flat-floored washes, in many places trenched by narrow arroyos cut in material which covers the rock floor. The valley slopes are gentle, and gullies rather than hills impede progress.

The area drains southward into Puerco River and thence into Little Colorado River. All the streams are ephemeral. Gullies are numerous, although the gradients of the streams incised in the valley floors are generally flatter than those on the Defiance Plateau and in Black Creek valley. The alluvial fill is fine-textured, a mixture of sand, silt, and clay derived from the underlying sandstone and shale formations of Cretaceous age. It is evident that the easily erosible material in this area exceeds that in the Black Creek tributaries, but the measurements show that erosion and movement of sediment are less. Reasons for this inconsistency are discussed later.

[5] Gregory, H. E., op. cit., p. 26.

Reservoirs 1 and 2 are outside the geographic subprovinces designated by Gregory, but as they occur on the same geologic formation as that underlying the Manuelito Plateau, they exhibit similar sediment-movement characteristics. The two reservoirs are several hundred feet higher than the plateau area, but otherwise their drainage basins are comparable to those found on the Manuelito Plateau.

GEOLOGY

Axiomatically erosion in any area is confined mainly to the soil mantle. As the type of soil is in turn dependent on the rock from which it originates, there is a close relationship between erosion and geology. Exceptions to this rule occur in the study area in places where some of the surface rocks are so poorly indurated that they weather rapidly and break down into particles small enough to be readily transported by wind and water. Soils do not accumulate on such formations, and the relationship between geology and erosion is a direct one. Also it should be noted that there is close similarity between the geology of the study area and that of the surrounding region. Formations like those described are widely distributed over much of northeastern Arizona and northwestern New Mexico. Thus, it is logical to assume that methods of measuring erosion and movement of sediment in the study area are in some degree applicable to the broad region in which the geology is similar.

Geologic information was obtained mainly from Gregory's descriptions and map of the area [6] and from field examinations of individual drainage basins. As previously noted, a reproduction of part of his map is included as plate 7 of this report. Modifications have been made by grouping a number of formations having similar characteristics under one heading. A short description of the formations in the area and the soil types that result from weathering of these rocks follows.

Essentially the area is underlain by three types of rocks: conglomerate, sandstone, and shale. As these rocks weather, the type of soil formed varies according to the parent rock. Conglomerates disintegrate into pebbles and minor amounts of sand and silt; sandstone into individual sand grains; and shales into clays and fine silts. Residual soils closely reflect this composition, but transported material may deviate considerably because the finer constituents are carried away in suspension. In general, transported soils are coarser than their residual counterpart.

The reservoirs are underlain in part by residual soil and in part by transported soil. As the reservoirs themselves are located on stream

[6] Gregory, H. E., The Navajo country: U. S. Geol. Survey Water-Supply Paper 380, 1916; Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, 1917.

channels, the immediate upstream area nearly always is underlain by an alluvial fill of varying thickness. In some places most of the sediment entering the reservoirs comes from the deposit of transported soils; in others there is evidence that residual soils are the greatest contributors. Specific data about the individual reservoirs and their relation to the geology and sedimentation rate are given in the latter part of the report.

The rocks underlying the area covered in this report are discussed in the following sections.

SEDIMENTARY ROCKS

The consolidated sedimentary rocks range in age from Permian to to Tertiary. Triassic, Jurassic, and Cretaceous rocks are more widely distributed in the eastern part of the area, whereas the older Permian strata are restricted to a narrow belt along its western edge.

PERMIAN ROCKS

The De Chelly sandstone member of the Cutler formation is the only formation of Permian age that crops out in this area. It is a light-red uniform-grained, relatively coarse textured cross-bedded well-indurated sandstone. The exposure forms a belt along the western edge of the Defiance monocline.

TRIASSIC ROCKS

The Moenkopi formation, which on the map is shown differentiated from the De Chelly sandstone member of the Cutler formation, is also exposed in restricted localities along the Defiance monocline. The formation consists of chocolate-red and banded arenaceous shales and thin sandstone beds. Because of their limited extent within the area of study, the beds have little, if any, influence on sediment production in the reservoirs examined.

The Shinarump conglomerate overlies the Moenkopi formation and consists of a relatively thin series of cross-bedded lenticular conglomerate and sandstone ranging in thickness from a trace to 100 ft. The pebbles are chiefly quartz, quartzite, and petrified wood. The Shinarump conglomerate forms a belt along the eastern edge of the Defiance Plateau.

The Chinle formation as used by Gregory in this area includes in its upper part a representative of the Glen Canyon group of Jurassic age. For the purposes of this report the authors have followed Gregory's usage. The formation underlies the floor of Black Creek and is exposed along the flanks of the valley at many localities. Only the shales and sandstone members of the formation were observed in this district, although the limestone conglomerate and the gypsiferous and calcareous members may also be present.

JURASSIC ROCKS

Jurassic rocks are undifferentiated in this report. They include highly colored sandstones that form the prominent escarpment along the eastern edge of Black Creek valley. In general, the sandstones represent wind deposits and are uniformly fine grained. In weathering, the rock breaks down into a fine-textured noncohesive highly erosible mantle. The unit that overlies the sandstone consists of alternating beds of sandstone and shale with occasional lenses of gypsum. Like the underlying sandstone it weathers into highly erosible sandy mantles.

CRETACEOUS ROCKS

The Cretaceous formations, as mapped, include the basal Dakota sandstone, the Mancos shale, and the Mesaverde formation with included later Cretaceous formations undifferentiated. None of the reservoirs studied are located in areas underlain by either the Dakota sandstone or the Mancos shale. Both these formations occur in a narrow, relatively steep belt along the western edge of the Manuelito Plateau. Areas underlain by the Mancos shale are probably among the highest silt producers in the district, and reservoirs rapidly fill with silt, which probably accounts for the general lack of reservoirs. The Dakota is a well-indurated, conglomeratic sandstone containing occasional beds of shale. Because of its resistance and limited areal distribution, it is not an important contributor of sediment.

The Mesaverde formation and later Cretaceous formations (undifferentiated) crop out over most of the Manuelito Plateau. Characterized by alternating beds of shale and massive sandstone, they weather into mesas with relatively steep slopes separated by gently sloping alluvial-filled valleys. The mesa tops contribute little sediment, but the slopes and valleys are vulnerable to erosion.

TERTIARY ROCKS

Only two small areas of the Chuska sandstone are present. Both are located near the Sonsela Buttes in the northern part of the area. Gray and white fine- to medium-grained sandstone, with lenses of conglomerate, are typical of this formation. No reservoirs are located near the outcrops.

IGNEOUS ROCKS

Tertiary volcanic rocks consisting of tuffs, ash, and lavas are scattered throughout the area. Also in the area are a few small volcanic necks and dikes. No reservoirs are located within the volcanic region.

STRUCTURE

Generally the structure of the area is relatively simple. The Defiance monocline extends northward along the western edge of the Defiance Plateau. Exposures of the Shinarump conglomerate and the undifferentiated Permian and Triassic sedimentary rocks form dip slopes along the monocline. The Black Creek valley has been carved in the soft Chinle formation at a lower altitude along the monocline. Eastward from the valley the dip flattens and the beds rise in steplike fashion to the Manuelito Plateau, which is capped by horizontal beds of the Mesaverde formation.

PRECIPITATION

According to available data the average precipitation of the area under study is about 12 in. annually. Mean annual precipitation at individual points probably ranges from 10 in. to 16 in. depending upon altitude, exposure, and other factors. Few records of precipitation within the area are available. Therefore, all estimates used in this study are based on the records obtained at the station near Fort Defiance as reported for Arizona by the U. S. Weather Bureau in Monthly Climatological Data. The mean annual precipitation at the Fort Defiance station for the period 1931–47 was 12.94 in.

Precipitation records for 37 additional years at stations in the vicinity of Fort Defiance were located after the above-mentioned computations were completed. The additional records were obtained at Fort Defiance prior to 1906 and at St. Michaels for the period 1906–24. As they indicate only slightly higher averages than those shown for the annual and for the summer precipitation at Fort Defiance during the period used, it was not necessary to revise the computations.

Approximately half the annual precipitation occurs as summer rain; part of the rest is snow. Usually the snow melt evaporates or sinks into the ground, but occasionally high temperatures, at times accompanied by rain, causes a small amount of winter runoff. Infrequently a convection-type storm occurring in early spring or late fall produces runoff, and on rare occasions heavy general winter rains are the cause of major floods of wide extent.

Convection-type storms produce most of the runoff in small basins. This runoff usually is only a small part of the precipitation, the larger part being absorbed by the soil, where it is utilized by plants or is lost by evaporation. The amount absorbed by the soil is governed by the infiltration rate, and only precipitation in excess of this rate produces runoff. Summer storms, although they may be of small magnitude, are generally of high intensity, and therefore many of them exceed the infiltration rates and produce runoff. However, there is still considerable doubt as to the minimum amount of even intense rain necessary to cause runoff. Comparison of precipitation and runoff at a number of locations in Arizona has shown that summer storms of less than 0.25 in. per day usually do not produce any flow.

When the factors influencing the infiltration rate in a given area are known, an estimate can be made of the amount of precipitation per day necessary to cause runoff, the runoff representing the excess of rainfall over infiltration. Figure 18 shows the total summer precipation at Fort Defiance compared with the proportion that falls at rates exceeding 0.50 in. per day. The assumption is made that in this case a 0.50 in. storm is necessary to produce runoff. It can be seen that under this assumption the greatest runoff would have occurred during 1945 and that no runoff would have occurred during 1935, 1942, and 1943.

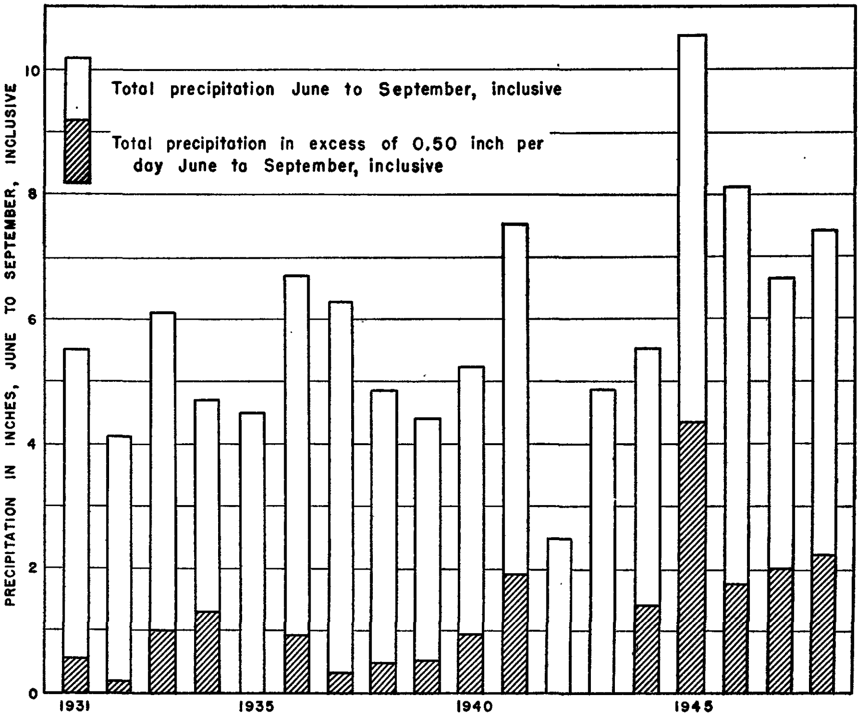

FIGURE 18.—Summer precipitation near Fort Defiance, Ariz.

In order to show the proportion of precipitation available for runoff, duration curves have been developed in figure 19 for the Fort Defiance station. These show the total summer precipitation in excess of various amounts per day. Daily precipitation was used, as this is the shortest interval record available. No effort was made to plot daily precipitation in excess of 1 in. because of the infrequent occurrence of storms of this magnitude, but a mental extrapolation of these curves will give some indication of the occurrence of the larger storms.

Only one storm producing more than 2 in. of rainfall per day was recorded during the 18 summers of record, but it will be noted from figure 19 that storms producing 1 in. or more of rainfall per day occurred during 50 percent of the summers, and storms producing 0.5 in. of rainfall per day occurred during 85 percent of the summers. Naturally, the runoff from storms of these magnitudes varies within wide limits, but the variation in sediment load doubtless is much

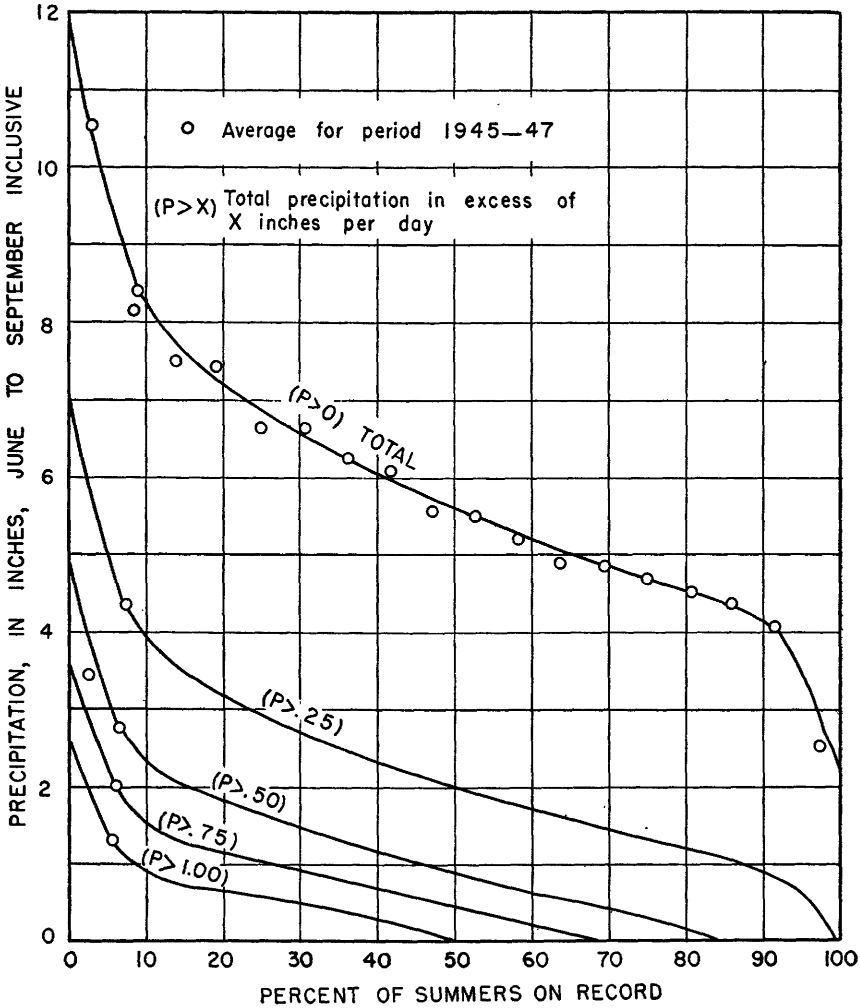

FIGURE 19.—Magnitude of summer storm precipitation, Fort Defiance, Ariz.

greater because the sediment-carrying capacity of any stream increases in greater degree than the magnitude of the storms and velocity of flow. Thus comparisons of rates of sedimentation at different reservoirs may not be entirely consistent, even where the measurements are obtained during synchronous periods, as relatively small local variations in the intensity and amount of precipitation in the area may be reflected by much greater variations in sediment movement. No pre-

Data from reservoirs impounded by dams, dikes, and spreaders in District 18, near Fort Defiance, Navajo Indian Reservation, Ariz. and N. Mex.

[Accuracy of records: G, good; F, fair; P, poor]

USGS reservoir no.	Indian Service reservoir no.	Location				Drainage basin					Reservoir										Accuracy of records	Sediment production [a] (acre-feet/square mile)	Annual sediment production for period [a] (acre-feet/square mile)	Estimated long-term annual sediment production [a] (acre-feet/square mile)
		Latitude	Longitude	South (miles)	West (miles)	Altitude (feet)	Area (square miles)	Length (miles)	Maximum relief (feet)	Geologic symbol	Area (acres)	Original depth (feet)	1948 depth (feet)	Capacity (acre-feet)	Sediment: Volume (acre-feet)	Sediment: Percent of original capacity	Water storage at survey: Depth (feet)	Water storage at survey: Volume (acre-feet)	Spilling	Age (years)				
(1)	(2)	(3)				(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
		° ′	° ′																					
1	18A-247	35 30	108 45	7.88	0.62	7,150	0.2	0.3	75	Kmv	2.5	8.0	3.9	4.88	1.9	28	0.5	0.12	Some	22	F	9.5	0.43	0.5
2	18A-285	35 30	108 30	10.50	9.75	7,325	1.8	3.8	700	Kmv	5.5	7.2	3.4	11.4	7.8	41	1.2	4.0	Large	[b] 12	F	4.3	.36	.5
3	18A-312	36 00	109 00	1.00	8.50	7,650	1.1	1.1	150	Trp	7.75	18±	17	48	5.5	10	11.5	17.0	Negligible	6	G	5.0	.9	.7
4	18A-41	36 15	109 00	15.00	9.50	7,525	.4	.8	100	Trs	4.58	10	9.5	17.7	.8	4.3	5.5	.9	Some most years	13	F	2.0	.15	.2
5	18A-42	36 15	109 00	13.00	10.50	7,550	1.1	2.4	150	Trs	2.5	14.5	10.5	13.3	3.2	19	6.5	4.6	Large most years	13	F	2.9	.22	.25
6	--	36 15	108 45	13.5?	9.7?	7,625	[c] 2.1	[c] 2.0	[c] 500	Ju	1.9	7.9	5.4	5.6	2.1	27	.3	.11	Large	5	P	1.0	.2	--
7	18A-313	36 15	109 00	12.75	4.2	7,425	.5	1.1	100	Trc	17.0	15	14.2	65	4.0	5.8	10.6	10.8	Some, once or more.	6	F	8.0	1.3	1.1
8	AAA-46-2	36 00	109 00	10.8	.1	7,150	9.3	6.2	1,400	Ju+Km	--	18	--	--	17.5	109	0	0	Large	2	F	1.9	--	--
9	AAA-46-3	36 00	109 00	10.8	.2	7,140	[d] 9.4	[d] 6.3	[d] 1,400	Ju+Km	--	19	--	--	19.2	107	0	0	Large	2	F	3.9	--	--
10	AAA-46-12	36 00	109 00	11.3	.5	7,150	1.2	1.7	1,000	Ju+Km	.44	7	--	--	.7	117	0	0	Large	2	P	.6	--	--
11	--	36 00	109 00	11.0	.6	7,150	.2	.8	900	Ju+Km	.82	7.1	3.8	1.4	.5	26	1	.02	None	2	G	2.6	1.3	1.1
12	--	36 00	109 00	11.0	.6	7,125	Dike	--	--	Ju+Km	--	--	--	--	.03	--	0	0	--	2	--			
13	AAA-43-14	36 00	109 00	11.2	1.5	7,000	[d] 12.4	[d] 7.6	[d] 1,500	Ju+Km	--	17	--	--	28.3	105	0	0	Large	5	F	5.3	1.1	1.1
14	--	36 00	109 00	10.3?	1.7?		Dike	--		Trc	--	3.5	1.7	.16	.02	11	0	0	--	2	--	2.4	1.2	1.0
15	AAA-46-4	36 00	109 00	10.4	1.85		.3	.4	50	Trc	.77	12	9	4.7	.7	13	1.0	.02	None	2	G			
16	--	36 00	109 00	10.5	1.75	7,100	Dike	--	--	Trc	--	4	3	.3	.05	14	0	0	Small	--	--	1.4	.7	--
17	--	36 00	109 00	10.7	1.8	to	[e] .07	[e] .7	[e] 100	Trc	.2	6	3.5	.7	.05	7	0	0	Some most years	[b] 2	P			
18	--	36 00	109 00	10.6	1.7	6,900	.7	1.4	1,000	Trc+Ju	.5	3.5	2.25	.5	.4	45	1	.1	Large	[b] 2	P	.6	.3	--
19	AAA-46-5	36 00	109 00	11.1	1.9		[d] 1.2	[d] 1.7	[d] 1,000	Trc+Ju	1.0	7	2	.5	1.3	72	0	0	Large	[b] 2	F	2.1	1.0	.9
20	AAA-46-1	36 00	109 00	11.2	2.0		[d] 14.5	[d] 8.1	[d] 1,600	Trc+Km	1.6	7	0	2.8	3.5	55	0	0	Large and diversions.	2	P	5.0	--	--
21	AAA-43-13	36 00	109 00	11.2	2.0	6,900	[f] .1	.5	100	Trc+Km	2.8	5	4	4.8	1.0	17	1.5	1.0	Small	5	--	--	--	--
22	--	36 00	109 00	11.2	2.0	6,900	Dike	--	--	Trc+Km	--	--	--	.6	.6	100	0	0	Large	--	--	--	--	--
23	AAA-43-15	36 00	109 00	11.9	2.5	6,800	[d] 15.1	[d] 9.0	1,700	Trc+Km	2.2	7.5	3.5	4.3	6.7	61	1.0	.4	Some	5	F	5.3	--	--
24	18-A-52	36 00	109 00	9.25	9.0	7,500	4.7	3.5	400	Trp	7.6	--	19±	64	.6	1	8	6.2	Some	12	F	.13	.01	.01
25	AAA-47	35 45	109 00	6.85	5.05	6,650	.6	1.3	150	Trc	2.2	11	9±	6.5	3	32	7.7	.9	Large	2	P	5.0	2.5	2.0
26	AAA-43-12	35 30	109 00	6.8	7.6	7,100	.1	.3	50	Trc?	.23	10.5	10.5	1.2	.02	1.6	1.0	.04	None	5	F	.2	.04	--
27	18-A-317	35 30	109 00	12.7	6.5	6,400	2.1	3.6	700	Trc?	5.1	19.5	17.5	35	1.8	5	5.5	5.0	Negligible	5	G	.9	.17	.15
28	AAA-43-5	35 30	109 00	14.9	13.9	5,950	[b] .1	.7	50	Trc+Trs	--	6+	2+	2	.5±	20±	--	--	Large	5	P	5	1.0	--
29	18A-146	35 45	109 00	11.6	10.1	7,650	.2	.8	50	Trp	2.3	7	6.8	6.8	.3	4.2	3.8	1.8	Large	[b] 12	F	1.5	.12	.1
30	18A-145	35 45	109 00	14.75	11.6	7,350	2.4	2.9	300	Trp	4.8	15	14	23.4	.6	2.5	10.5	11.2	Negligible	12	G	.25	.02	.02
31	AAA-43-8	35 45	109 00	.5	2.5	6,950	[e] .5	[e] 1.3	75	Trc+Ju	--	--	--	11±	.04	.3	0	0	None	5	G	.1	.2	--
32	--	35 45	109 00	.8	2.0	7,000	2.3	2.8	500	Ju	--	15	--	--	8.6	150	0	0	Large	5	G	3.7	.7	1
33	18A-194	35 45	108 45	10	4.9	7,425	2.3	2.0	150	Kmv	2.8	10.5	6.1	2.7	1.0	27	2.1	.27	Small	14	F	.4	.03	.03
34	18A-232	35 45	108 45	10.4	5.0	7,400	.15	.6	100	Kmv	--	8	5	1.0	.4	29	0	0	Large	[b] 10	P	2.7	.27	.3
35	1-42	35 45	109 00	1.6	2.1	7,000	18.2	7.0	900	Ju+Km	11.0	26	--	--	100±	110±	0	0	Large	5	G	5.5	1.1	1.2

[a] Sediment in upstream reservoirs included.
[b] Estimate based on information from local residents and relationship to other reservoirs.
[c] Includes adjacent drainage cut into reservoir.
[d] Entire drainage; not adjusted for upstream dikes and diversions.
[e] Contributing area only.
[f] Receives water from reservoir 20 through pipe and ditch.

EXPLANATION OF COLUMNS

1, 2. Self-explanatory.
3. Location obtained from files of Bureau of Indian Affairs. Locations are given in miles south and west from the stated point of latitude and longitude on 15-min quadrangles.
4. Altitude at reservoirs obtained by aneroid barometer.
5. Drainage areas planimetered from areal mosaics, scale, 1 in.=1 mile, except for reservoirs 1 and 2, which were determined in the field.
6. Lengths of basins from areal mosaics or drainage maps.
7. Maximum relief estimated in the field or taken from reconnaissance topographic maps having a contour interval of 200 ft.
8. Geology from field notes and Gregory's geologic map (pl. 7).
9. Reservoir areas at spillway level, planimetered or computed from field surveys.
10, 11. From data obtained in the field.
12. Capacity at spillway level in 1948 computed from area-depth relationship as measured in the field. In most cases three contours were surveyed.
13. Obtained by probing sediment deposits.
14. Percentages above 100 indicate that the reservoir is full and that deposition is now taking place above spillway level.
15. From data obtained in the field.
16. Computed from area-depth relationship as determined from field surveys. It is representative of conditions found at time of examination.
17. From data obtained in the field.
18. Age obtained from files of Bureau of Indian Affairs.
19. Appraisal of results at individual locations based on trap efficiency of reservoir, accuracy of sediment measurements, and length of records.
20. Sediment production per square mile (column 13 divided by column 5). Where upstream reservoirs have spilled, the computation includes all deposition in the upstream reservoirs.
21. Sediment production per square mile per year for the period of record (column 20 divided by column 18).
22. Estimate of long-term sedimentation based on data in column 20, length of record, and accuracy of records. Explanation of the adjustments used in compiling these figures is given in the description of the individual reservoirs, pp. 147–153.

cise data are available for measuring these local differences, and no effort has been made to compensate for them. However, where the life span of the reservoirs is not sychronous, general adjustments have been introduced in an effort to make the long-term estimates of sediment production more nearly comparable.

METHOD OF MEASURING SEDIMENTATION

As noted previously, sedimentation was measured by determining the quantity of sediment deposited in each reservoir. When the age of the individual reservoir is known, this measure can be converted into an average annual yield from a drainage basin of known size. If the annual rate is computed in this way, reservoirs of different life span would be expected to show considerable variation in the sediment caught because of differences in precipitation. Reference to figure 18 shows the great disparity, not only in the total quantity of summer rainfall, but in the recurrence. Thus in 1945, 42 percent of the summer rainfall occurred in daily storms producing more that 0.5 in., whereas 22, 30, and 30 percent respectively, occurred in the next 3 years.

Reservoirs constructed in the past 2 or 3 years, of which there are several, would not be expected to show as large sediment deposition as those in operation during 1945. An effort was made to adjust for this difference, but as sediment deposits laid down in individual seasons could not be identified, attempts at adjustment were found to be impractical, and in the final comparison reservoirs that have been in operation only 2 or 3 years have not been used except where they exhibit some well-defined sedimentation characteristic that is consistently a characteristic of the older reservoirs.

Another source of error in comparing sedimentation within the various reservoirs is the lack of data on the amount of spilling. As a large part of the sediment is carried in suspension by streams entering the reservoirs, a part of this load undoubtedly would not be trapped during any period of overflow, even though a reduction in velocity did occur in the reservoir reach. The efficiency with which a reservoir traps sediment diminishes progressively as the reservoir is filled. No record of the amount of spilling is available, but so far as possible, suitable adjustments have been made for this loss on the basis of information from local observers, remaining capacity of the reservoir, and evidence of small or excessive flow through the spillway. These points are covered in more detail in the description of individual reservoirs.

The accompanying table (facing page) contains information on the drainage-basin characteristics of the individual reservoir sites and measured and computed data obtained from the field examination. No particular system was used for numbering the reservoirs; they were simply numbered in the order in which they were surveyed.

RATES OF SEDIMENT PRODUCTION

In the following table the study reservoirs have been grouped on the basis of the geologic formation from which the soils of the drainage basins were derived, and the groups have been arranged in order of increased amount of sediment production. The difference between the amount of sediment derived annually from the first three groups and that derived from the last two is striking. Areas where the soil is derived from the Chinle formation and the Jurassic rocks produce about five times as much sediment as those underlain by the De Chelly sandstone member of the Cutler formation, the Shinarump conglomerate, and the shales and sandstones of the Mesaverde formation.

A part of the difference may be due to conditions within individual drainage basins, such as slope, type and density of vegetative cover, grazing use, variations in rainfall, and other features that admittedly have a direct influence on erosion. However, it is evident that these features are not solely responsible for the variations as, with one or two exceptions, there is rather close agreement in the rate of sedimentation at individual reservoirs within each group, and yet there is wide divergence among the groups. Thus, reservoir 3, which shows a sedimentation rate several times greater than the others in the area where the soil is derived from the undifferentiated Permian and Triassic rocks, still has a sedimentation rate well below that of reservoirs where the soil is derived from the Chinle formation and the Jurassic rocks. A similar variation in sedimentation rate is apparent in reservoirs located on soils derived from the Mesaverde and later Cretaceous formations, but even the highest production, recorded at reservoirs 1 and 2, is only about half that of the lowest producers in the Jurassic and Chinle groups.

Further investigation into reasons for the difference reveals that probably the controlling factor in the sedimentation rate at each of the reservoirs is the availability of erosible material in the drainage basin. There are three phases of the problem: the rate of weathering of the rock itself, the resistance to erosion inherent in the weathered material, and the amount of weathered material stored within the canyons and valleys during some previous period and now made available for removal because of some change in environment leading to greater and more rapid runoff.

It is obvious that hard, well-indurated rock weathers slowly under the conditions prevailing in the Navajo country. Removal of the weathered particles by water, and to some extent by wind, proceeds almost as rapidly as the rock weathers, and deep soil mantles are seldom, if ever, present. This is characteristic of a large part of the Defiance Plateau, which is underlain by the De Chelly sandstone member of the Cutler formation and the Shinarump conglomerate.

Comparative sediment production from various geologic formations

Geologic formation (with symbol) from which soils are derived (see pl. 7)	Reservoir no.	Area of drainage basin (square miles)	Length of record (years)	Estimated long-term annual sediment production (acre-ft per sq mile of drainage area)	Average annual sediment production for group (acre-ft per sq mile of drainage area)	General characteristics of drainage basins
Undifferentiated Triassic and Permian rocks, Trp.	3 24 29 30	1.1 4.7 .2 2.4	6 12 12 12	0.7 .01 .1 .02	0.2	Reservoirs all located on Defiance Plateau. Basin cover—forest interspersed with small open grassy flats. Slopes gentle. Soils thin and sandy, in places gravelly. No deep accumulations of fill. Erosion mainly from sheet wash; gullying neglible.
Shinarump conglomerate, Trs.	4 5 26 27	.4 1.1 .1 2.1	13 13 5 5	.20 .25 .40 .15	.25	Reservoirs 4 and 5 located on lower parts of Defiance Plateau. Basin cover—forest with open patches of sagebrush and grass. Slopes gentle. Soils sandy to gravelly. Erosion limited to sheet wash; no gullying. The drainage areas of reservoirs 26 and 27 are underlain by gravelly and sandy soils derived mainly from the Shinarump conglomerate.
Mesaverde formation and later formations, Kmv.	1 2 33 34	.2 1.8 2.3 .15	22 12 14 10	.5 .5 .03 .3	.3	Reservoirs located on plateaus characterized by isolated mesas and rolling shale hills, with relatively deep flood-plain deposits along major channels. Basin cover—scattered juniper interspersed with sage and sparse grass. Overgrazing is apparent in most localities. Gullying is main form of erosion with minor amounts of sheet wash.
Undifferentiated Jurassic rocks, Ju.	11 13 15 19 32 35	.2 12.4 .3 1.2 2.3 18.2	2 5 2 2 5 5	1.1 1.1 1.0 .9 1.0 1.2	1.1	Most reservoirs located in alluvial-filled narrow valleys. Soils are derived from weathering of sandstones and are characteristically noncohesive and highly erosible. Basin cover—sparse grass and shrubs. Extensive gully systems developed, but rapid sheet erosion on interfluviatile areas is also apparent.
Chinle formation, Trc.	7 25	.5 .6	6 2	1.1 2.0	1.6	Soils are fine-textured but noncohesive, and highly erosible. A large part of the sediment comes from sheet erosion, but where the protective cover is destroyed gullying is extensive, as at reservoir 25. Basin cover—generally sparse shrubs and grass. Deep fills occuring on the valley areas are particularly vulnerable to both sheet and gully erosion. The rock itself is also highly erosible.

Even the valleys are devoid of deep-fill deposits, and many of the stream channels are eroded to bedrock. In addition to its shallowness, the mantle is very pervious, and high-intensity storms are required to produce surface runoff. This aids in sustaining a moderately heavy vegetative cover, which in turn impedes erosion.

Possibly the rate of erosion on the Defiance Plateau approaches the normal as nearly as any observed in the study area. The weathering and the removal of the weathered rock appear to have been in balance for a long period. It is believed that grazing has not been sufficient to change materially the rate of erosion over the area as a whole, although there are some indications that deterioration of the cover owing to excessive grazing has had some effect in places.

In contrast with the De Chelly sandstone member of the Cutler formation and Shinarump conglomerate, the sandstones of the Jurassic and the shales of the Chinle formation weather rapidly to form naturally deep fine-textured mantles everywhere except on the steeper slopes. Removal of material from steeper slopes and subsequent deposition in areas of gentler slope have resulted in deep alluvial fills within the valleys and along the narrow canyon floors. So long as this fill was protected by an adequate vegetative cover there was little tendency to excessive erosion, but once the cover deteriorated or was destroyed, both sheet wash and gullying developed, contributing to the high rates of sedimentation indicated at reservoirs in areas where the sands were weathered from these rocks.

Contributing further to this high sedimentation rate is the lack of any inherent resistance to erosion by the alluvial fills. The sandstones of the Jurassic rocks break down into minute, rounded individual sand grains. Because of a deficiency of clay and silt, which ordinarily act as a cement, these deposits are particularly vulnerable to erosion, both from sheet wash on unprotected surfaces and from bank cutting in gullies. Some of the deepest gullies observed have developed in deposits of this origin.

Disintegrated material derived from the Chinle formation is, in general, fine-textured, consisting mainly of clay and silt mixed with minor amounts of sand. Possibly because of the relatively high content of both halite and gypsum in the deposits, the particles at the surface appear to be highly dispersed and thus are easily attacked by running water. Another factor that adds to the high rate of silt production from areas underlain by the Chinle formation is the low resistance of the rock itself to erosion. The shale facies of the formation are particularly soft and highly vulnerable to gullying and sheet erosion, and development of badland topography on the steeper slopes is characteristic, as exemplified by the spectacular badland erosion in the Painted Desert and along the rim of Paradise Valley. Thus, although the sandstone beds may be sufficiently indurated to resist rapid erosion, unprotected outcrops of the Chinle formation probably contribute at least as much sediment as does its residual soil mantle.

One of the surprising anomalies apparent within the groups is the comparatively low rate of sediment production from areas underlain by the Mesaverde formation and later Cretaceous formations. From general appearances it might be expected that these areas would have one of the highest rates, as there is usually an abundance of alluvial material available for transportation by water. The Mesaverde and later Cretaceous formations consist of alternating layers of shale and sandstone, which weather to a characteristic topography of low, rolling hills and sandstone-capped mesas, separated by shallow alluvial-filled valleys, many of which have been gullied almost their full length. The residual surface mantle is generally deep but compact; the mixture of clay and sand, derived respectively from the shale and sandstone members, forms a cohesive soil which appears to have an unusual resistance to sheet wash. The transported alluvium in the valleys shows a similar resistance.

Observation in areas underlain by the Mesaverde formation and later Cretaceous formations indicates that gully erosion is probably the largest source of sediment. The fact that gullying has not developed to any appreciable extent in the drainage basins of any of the four reservoirs considered in this group may account for the relatively low sediment production. Had the reservoirs been located in basins where gullying was extensive, it is likely that the results would have been entirely different.

In addition to developing the geologic relationships, comparisons were attempted based on such factors as size of drainage area, topography and slope, type of cover, and grazing use. However, insufficient data relating to these factors—particularly on slope and condition of the vegetative cover—prevented the establishment of dependable relationships, even though variations in these factors should have some influence on erosion.

On the basis of sediment produced from the areas underlain by various geologic formations, the total sediment production from District 18 has been estimated at 900 acre-ft annually. The areas underlain by the rock formations discussed herein constitute 91 percent of District 18. The sediment production from each is shown in the following table.

Estimated annual sediment production from District 18, Navajo Indian Reservation, New Mexico-Arizona

Geologic symbol (see pl. 7)	Percent of area	Total area (sq mi)	Sediment production (acre-ft per sq mi)	Total sediment production (acre-ft)
Trp	14	210	0.21	45
Trs	10	150	.25	35
Kmv	36	540	.3	160
Ju	9	130	1.1	140
Trc	22	330	1.56	530
Total	[1] 91	[1] 1,360		910

[1] Remainder of District 18 is underlain by rocks for which no information on sedimentation rates is available.

An annual rate of sediment production of this magnitude, from an area of the size and character studied, appears inordinately high. Applying this rate to 22,100 sq mi area of the Little Colorado River basin above the Grand Falls gaging station, the annual rate of sediment production would be about 13,000 acre-ft. The only actual measurements of suspended load [7] carried by the river were made at the Grand Falls station during the flood of July 6 to September 26, 1931. The records show that approximately 5,500 acre-ft of sediment passed the station during this period, obviously an extraordinarily large movement. The inconsistency between this figure and the above estimate is explained by the fact that total sediment movement within a given basin is not necessarily a measure of the total sediment carried out of the basin through main drainage channels. The reservoir accumulations represent movement from small segments of the basin located mainly in the steeper and more dissected headwater areas of the tributaries. Had the sediment not been trapped in the reservoir, at least some would have been deposited in flatter reaches of the downstream flood plain. Only the part of the sediment that actually reaches the main channel through the principal trunk gully systems or other well-defined water courses can be carried out of the basin during flood periods. Moreover, the lower parts of river basins contain areas of flat slopes that may have somewhat lower rates of sediment production than headwater areas that contain suitable sites for small reservoirs.

It should be noted also that the summer storms that cause sediment movement in small areas usually are local in extent and do not produce sufficient runoff to carry the sediment any great distance. There is nearly always a marked recession in the flood peaks as they move downstream, and part of the sediment load is dropped as a result. This, of course, is the chief process whereby the deep valley fills have been formed. It is believed that if, in such an area as the Little Col-

[7] Howard, C. S., 1947, Suspended sediment in the Colorado River, 1925–1941: U. S. Geol. Survey Water-Supply Paper 998, pp. 144–145.

orado River basin, a storm occurred that was large enough to cause flow without marked diminution through all the tributaries, the total sediment movement would more nearly approach that shown by the reservoir measurements. For smaller storms the measurements simply give an indication of the potential sediment production for various parts of the basin.

DESCRIPTION OF INDIVIDUAL RESERVOIRS

No. 1.—Reservoir 1 is known to have spilled, but probably not significantly, except during recent years when sediment has reduced storage capacity. Present source of sediment is largely from sheet erosion of residual soils, as the drainage area has not been gullied to any appreciable extent. The higher ridges have a piñon-juniper cover, but the lower slopes and valley floors are grass-covered. In some places there is evidence of overgrazing. When first constructed, the reservoir provided a nearly permanent supply of water, but since loss of capacity from sedimentation has occurred it goes dry for a part of each summer. The estimated long-term sediment production was raised slightly upward to compensate for losses over the spillway.

No. 2.—Large amounts of spilling, especially in recent years, probably account for the lower rate of sedimentation in reservoir 2 compared with reservoir 1. Cover and other physical conditions are similar except that part of the basin has been logged and a small part is cultivated. Sheet erosion is apparent, particularly in the logged-over area, and a discontinuous gully system has developed along parts of the main channel. The long-term sediment production has been estimated to be the same as at reservoir 1, chiefly because of known losses over the spillway. Probably current sedimentation is somewhat higher but improvement is expected as the cover increases on the logged-over area. The reservoir now has little value for stock watering because of its shallow depth.

No. 3.—Reservoir 3 is located on the Defiance Plateau. Heavy forests cover the ridges and slopes, and narrow grassy valleys border the stream channels. Type of cover indicates the highest precipitation in the area. The reservoir undoubtedly always contains water, derived principally from winter and early spring runoff. Most sediment obviously comes from sheet erosion, although some of the grassy areas contain a few shallow gullies. In general, the amount of sediment produced from the area seems large, considering the forested character of the drainage basin. Trap efficiency in the reservoir is high, as indicated by the large capacity per unit of drainage area, although some spilling has occurred. The long-term estimate of sedimentation has been reduced somewhat to compensate for the above-average precipitation during the life of the reservoir.

No. 4 and 5.—Reservoirs 4 and 5 are located on lower parts of the Defiance Plateau. The drainage slopes are gentle, and the sandy to gravelly soils are derived from the underlying Shinarump conglomerate. The cover is sage interspersed with grass and fringed with forest. Erosion is limited mainly to sheet wash, but there are a few shallow active gullies. Deposition has partly filled some of the existing gullies located as much as 1,000 ft upstream from the reservoirs—5 or 6 ft above spillway elevation. Some spilling has occurred at both reservoirs, and the long-term estimates of sediment production were raised slightly to compensate for this loss.

No. 6.—Reservoir 6 has been breached owing to overtopping of the dam, caused directly by inadequate spillway construction. As a result, the data have little significance because there is no means of estimating the loss of sediment carried by the stream or the amount removed from the reservoir as a result of the dam failure. Therefore, no estimate has been made of the long-term sediment production.

No. 7.—Reservoir 7 is one of the most useful examined during the study because it is of adequate size and well adapted to the drainage basin. It is used as a stock reservoir. Spilling has occurred at times, but it appears that generally most of the sediment has been trapped. Soils in the drainage basin are usually fine-textured, being derived mainly from the underlying shales of the Chinle formation. Sediment production is largely from sheet erosion, as gullying is not extensive. The estimated long-term sediment production was reduced somewhat below the measured rate to compensate for the greater-than-average precipitation during the 6-year life span of the reservoir.

Nos. 8–23.—Reservoirs 8 to 23 are considered together because of their location and the purpose for which they were constructed. Not all are reservoirs in the strict sense as some are dikes utilized to divert and spread water and they provide no storage. Their location in the drainage basin is shown by the inset on plate 7.

Ostensibily the construction in this area was aimed at arresting severe gully erosion. The dikes were constructed to divert water from shallower parts of the channel and spread it over adjacent flats; larger dams formed reservoirs on deeper reaches of the gully system thus providing considerable storage for water and sediment detention. Prior to being completely filled with sediment the larger reservoirs provided water for stock. Reservoirs 13, 21, and 23 have been in operation 5 years, the others only 2 years. According to local Indian residents, all the available storage filled with sediment within a short period after completion, but even so there has been little movement of sediment out of the area as it has been deposited either behind the dams or on the spreading areas.

Some of the worst erosion observed in the district occurs within the general area in which this group of reservoirs is located. A discontinuous gully, which started below reservoir 23, extends upstream for several miles. In the reach between reservoirs 21 and 8, unfilled parts of the gully range in width from 25 to 100 ft and in depth from 7 to 40 ft. The tributary gully on which reservoirs 14 to 19 are located is somewhat shallower; the average depth being about 7 ft. The gully on which reservoir 10 is located is 7 ft deep at the dam but deepens to 18 ft at its junction with the parent channel.

The erosion above reservoir 13 is taking place in a narrow canyon that cuts eastward through the high escarpment formed by the massive sandstones of the Jurassic rocks, which crop out along the east side of Black Creek valley. Prior to the recent cutting the canyon was filled to a depth of 10 to 40 ft with fine-textured sandy alluvium derived chiefly from the adjacent sandstone cliffs. This filling left a flat valley an eighth of a mile to half a mile wide between the sandstone outcrops. Because of its noncohesive character, the fill material is highly erosible. Vegetation is the only protection against erosion, and where gullies once start they tend to cut to bedrock on the steeper grades. Directly above reservoir 13 the gully depth is controlled by bedrock; below that point the grade lessens as Black Creek valley is approached, and the gully becomes shallower until it finally disappears below reservoir 23. Side gullies have developed in tributary valleys in the same manner, their depth in most localities being accordant with that of the parent streams.

Doubtless much of the sediment stored in the reservoirs and above the dikes comes from bank cutting and from the upstream advancement of headcuts in some of the tributary gullies. It is evident, however, that part of it is caused by sheet erosion on the valley floor, but probably an even larger amount is contributed by direct flow from the steep sidehill slopes. Vegetative cover on the slopes consists of a scattered growth of juniper and pinon trees and some shrubs interspersed with areas of bare rock. The valley floor has a sparse to moderate covering of grass and low shrubs, which generally is not dense enough to prevent sheet wash.

The drainage areas above reservoirs 11, 13, 15, and 19 are eroding in the manner described above. Reservoir 13 is the only one of the group located on the main gully and sediment movement from the drainage areas above this point is considered to include the total deposition at all localities on the main stream channel during the period of record. The drainage area above reservoir 11 is not gullied, and silt production from the basin may be considered as indicative of normal sheet wash from valley floor and relatively steep sidehill areas are small compared with that above reservoir 13. In other respects the drainage basins are similar.

A significant feature of the findings is the close agreement of the rates of sedimentation found at each measuring point. The rates at the four stations range from 1.0 to 1.3 acre-ft per square mile of drainage area per year. This variation is probably within the limits of error in measuring, so that the rate at each may be considered identical. As it might be expected that gullied areas would show greater movement of sediment than ungullied ones, the situation is somewhat anomalous and difficult to explain. The most logical explanation appears to be that, because of the highly erosible character of the sandy soil derived from weathering of the sandstones of Jurassic rocks, all flows that cross these soils, either on an unprotected surface or in gullied channels, carry practically a capacity load of sediment. On the assumption that runoff from equivalent areas is about the same, the indicated relation would hold. Observations in other localities having these same soil types show a similar high erosion rate, indicating that generally such soils can be classed as among the most erosible found in the whole area.

No. 24.—Some spilling has occurred at reservoir 24 through an outlet pipe, but it is believed that only a negligible amount of sediment has escaped. A permanent spring maintains a good vegetative growth in the main drainage channel leading to the reservoir, thus reducing bank cutting to a minimum. The drainage area in general has a fair grass cover, which prevents excessive sediment movement. Erosion from the north fork of the drainage basin has caused deposition of a small fan in the channel near the outer edge of the reservoir, but this material did not invade the deeper storage. The sediment deposit was difficult to measure, owing to the indistinct contact between the newly deposited sediment and the original floor of the reservoir. The record is not accorded much weight on this account.

No. 25.—Reservoir 25, located on the floor of Black Creek valley, has the highest rate of sediment production measured during the study. The drainage area reflects this condition; both sheet and gully erosion are developed to a greater degree than in the surrounding area. Part of this can be attributed to rather severe overgrazing, owing to the basin's central location near the Indian settlements. The reservoir is known to have spilled considerably, but there is evidence that most of the sediment load has been retained. The long-term estimate of sediment production from the area has been reduced somewhat from the measured amount to compensate for high precipitation during the period of record.

Nos. 26 and 27.—The drainage basins of reservoirs 26 and 27 are adjacent, and both are located in areas underlain by the sandstones and shales of the Chinle formation. The small drainage area of no. 26 is unusually flat. In addition, a coarser facies of the Chinle formation, which strongly resembles and may actually be a part of the Shinarump conglomerate, predominates throughout the basin.

Weathering produces a coarse, gravelly soil containing numerous pebbles and pieces of petrified wood, and therefore sedimentation from the basin is low. Reservoir 27 drains the top of a low mesa, which has a sparse cover of juniper and shrubs. The basin is underlain by coarse sandstone interspersed with conglomerate, and shallow gravelly and sandy soils are characteristic. No gullies have developed, but in places there are indications of sheet erosion. Along the channel floor there is considerable gravel, very little of which has been carried to the reservoir. The long-term estimate of sediment production in both reservoirs has been lowered somewhat to compensate for the above-normal precipitation prevailing during the past few years. Because of their basin characteristics both reservoirs have been grouped with other reservoirs located on areas underlain by the Shinarump conglomerate.

No. 28.—Reservoir 28 is on the main channel of the Puerco below its junction with Black Creek and has thus been subjected to heavy flood and sediment movement from both streams. As these streams drain areas containing more than one formation, the total sediment deposition is not considered truly representative of any locality having characteristics related to a particular geologic formation, and the record, therefore, has not been used in making estimates of long-term sediment production.

Nos. 29 and 30.—The adjacent basins draining to reservoirs 29 and 30 are similar to no. 3. Both are located on the Defiance Plateau, which has a forest cover of ponderosa pine on the ridges and grassy flats along the channel flood plains. No. 30 had one of the lowest measured sedimentation rates, the obvious reason being its location at the lower edge of a long, gently sloping grassy flat, which has trapped much of the sediment carried by the stream. Soils in both basins are thin and sandy, containing in many places well-rounded gravels that are residuals from underlying conglomerates. Deep accumulations of fill are absent, and as a consequence few gullies have developed. Some spilling has occurred at no. 29, but it is believed that little if any sediment was lost through this overflow and that the measured rate of sedimentation is about normal for the long-term expectancy for the type of terrain found in this drainage basin. Reservoir 30 is located below a seepage area, and the shallow, gullied inflowing channel is bordered by sedges and grass, which indicates that the flow is probably permanent.

No. 31.—Although the sedimentation in this reservoir was measured, it was afterward found that the greater part of the flow from the basin had been diverted into an adjacent area. Therefore, the apparent rates of sedimentation have no significance in making an estimate of long-term production.

No. 32.—The drainage area above reservoir 32 is underlain by sandy soils similar to those found in the vicinity of reservoirs 8 to 23. Indicated rates of sediment production are somewhat lower than at the latter location, but this can be attributed to excessive spilling caused by the reservoir being completely filled with sediment.

Nos. 33 and 34.—Reservoirs 33 and 34, located on the Manuelito Plateau, have drainage areas underlain by sandstones and shales of the Mesaverde formation and later Cretaceous formations. Both basins have a cover of scattered juniper interspersed with grassy areas. Overgrazing is apparent, and generally the small valleys are deeply gullied; yet silt contribution from the two basins is low. This low rate of sedimentation can, in part, be attributed to the gentle slopes of the drainage basins, but apparently the soil itself must have an inherent resistance to erosion. The mixture of clay and fine sand that results from the disintegration of the underlying sandstones and shales seemingly forms a compact mantle from which particles are not easily detached and removed by water. Reservoir 33 shows an exceptionally low sedimention rate, which apparently is attributable only to the inherent resistance of the soil to erosion, as the basin differs otherwise but little from adjacent areas.

No. 35.—Gage readings on water levels were begun at reservoir 35 in April 1945 and were continued until the summer of 1947, when sedimentation had completely filled all available storage. Originally the reservoir had a large storage capacity and it had been hoped that runoff data provided by the gage readings would be useful in supplementary hydrologic studies on stock reservoirs. However, sedimentation occurred at such a fast rate that the original capacity survey, made at the time that the gages were installed, was obsolete after the first storm. No resurvey of the capacity was attempted, as the gages silted over rapidly. By analyzing the readings of water levels and the notes supplied by the observer regarding the level of the sediment line, it has been possible to make an estimate of sedimentation rate.

Owing to the lack of an accurate capacity curve and because there was considerable ungaged spilling from the reservoir, it has been impossible to compute runoff from the drainage basin. There are indications, however, that 150 to 200 acre-ft of runoff occurred during the latter part of July and the first part of August 1945. This flow deposited about 50 acre-ft of sediment. Additional deposition occurred during 1946 and storms occurring in 1947 completed the filling of the reservoir, covered a part of the spillway and left some sediment in adjacent fields. All gages are buried at present, and the station is no longer operative. Approximately 100 acre-ft of sediment is stored behind the structure.

Examination of the drainage basin disclosed that the sediment was from several different sources. Much of the debris within the reservoir is coarse sand, which doubtless is the coarser part of the original soil remaining after the finer particles were carried off in suspension, the sorting having taken place both in the reservoir and in the channels leading to the reservoir. The drainage area contains numerous gullies and side rills, and caving of the gully banks obviously has provided a large part of the sediment. Sheet erosion is also visible. Headcutting of the main channels has now proceeded until it is approaching the drainage divide, so there is no longer any substantial contribution from this source. How much of this headcutting occurred during the period of record is unknown, as the position of the headcuts was not determined at the beginning of the studies.

Soils in the drainage area are derived mainly from weathering of the sandstone of the Jurassic rocks and have the same characteristic lack of cohesion and high erosibility as soils in the vicinity of reservoirs 8 to 23. Significantly the rate of sediment production is practically the same in both localities, thus strengthening the suggestion that such areas furnish a near-capacity load for any flow that crosses the soils, either on the surface or in channels.

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