CIRC. 256

GEOLOGICAL SURVEY CIRCULAR 256

SEDIMENTATION IN SMALL RESERVOIRS ON THE SAN RAFAEL SWELL, UTAH

UNITED STATES DEPARTMENT OF THE INTERIOR
Douglas McKay, Secretary

GEOLOGICAL SURVEY
W. E. Wrather, Director

GEOLOGICAL SURVEY CIRCULAR 256

SEDIMENTATION IN SMALL RESERVOIRS ON THE SAN RAFAEL SWELL, UTAH

By N. J. King and M. M. Mace

Washington, D. C., 1953

Free on application to the Geological Survey, Washington 25, D. C.

CONTENTS

ILLUSTRATIONS

TABLES

SEDIMENTATION IN SMALL RESERVOIRS ON THE SAN RAFAEL SWELL, UTAH

By N. J. King and M. M. Mace

INTRODUCTION

Movement of sediment from upland areas and eventually into main drainages and rivers is by no means through continuous transportation of material from the source to the delta. Instead it consists of a series of intermittent erosional and depositional phases that present a pulsating movement. Hence, sediment carried off upland areas may be deposited in lower reaches or along main drainages if an existing combination of factors tend to effect deposition. During this period actual sediment movement out of the basin may be relatively small. Following any change in existing conditions, however, these unconsolidated alluvial fills may be subjected to rapid removal; thus, for a limited time, abnormally high sediment production rates occur until the deposits are either removed or another cycle of deposition is started.

To the extent that movement of sediment into the rivers is followed by eventual deposition in downstream reservoirs, the logical way to arrest such accumulation of sediment is to effect deposition on upland areas. At present the only feasible method of reducing this sediment load is to delineate the areas of largest sediment contribution and to devise some treatment program aimed at reducing erosion in these areas.

A program of erosion control has been proposed for the San Rafael Swell, which forms a part of the upper Colorado River drainage in southeastern Utah, through construction of erosion-control structures. Studies on the rate of sedimentation in a number of small reservoirs have been undertaken as a means of determining the origin and movement of sediment in areas underlain by various types of sedimentary rocks. Studies of this nature have a distinct advantage in that the influence of precipitation, vegetation, soil types, slope, land use, and other less important factors are more easily related to erosion within a small area where individual features are not too complex.

Measurement of sedimentation rates in small reservoirs offers the only feasible source for data of this type. As streams tributary to the reservoirs are strictly ephemeral, flow occurs at unpredictable periods and only in direct response to precipitation. Direct sampling of streamflow is thus impractical because of the great expense involved.

Essentially, the method used in the study was to select a group of small reservoirs that were constructed by the Civilian Conservation Corps in the period 1936-42. Individual study units were chosen with particular attention given to the availability of original surveys and records, condition of dam and spillway, effectiveness as a sediment trap, physiography, and geology of drainage basin. Resurveys were made to determine the amount of sediment trapped in each reservoir and this amount prorated over the period required for deposition, in each case the life of the reservoir. Hence, the annual average sedimentation rate could be determined for a given set of conditions. Further analysis of these data permitted adjustment of the rates of reservoir sedimentation for the loss of sediment during reservoir spill, to obtain an estimate of the rate of sediment production from the drainage area. The primary objection to this method is that without records of water-level changes no relationship can be determined between runoff and sediment movement.

All reservoirs were surveyed by use of plane table and alidade, and as no permanent reference points had been established at the time of construction, elevations were adjusted to correspond as closely as possible to those used in the original surveys. Contours below spillway level were run at intervals of 2 feet or less on all reservoirs, not only to determine the present area-capacity relationship, but also to provide a check on the accuracy of original surveys. Reservoirs containing water too deep to wade were sounded from boats and spot elevations located on the plane table. Bureau of Land Management maps were used to determine the location, date of construction, and other pertinent data related to each reservoir. Monuments were left at each reservoir to facilitate resurvey.

Local detailed geologic studies on coal measures in Upper Cretaceous rocks have been made by several writers (Andrews and Hunt, 1948; Baker, 1946; and Gilluly, 1928). A few local soil classifications are available, but no soil map of the entire area has been made. Because detailed information on soil was not available and as a close relationship apparently exists between soil and the rock from which it was derived, study units have been classified on the basis of the underlying geologic formations.

Field Work

Field work on which this report is based was started June 19, 1950, by a party consisting of the senior author and M. D. Whittier, engineer aid, under the supervision of H. V. Peterson, staff geologist, Salt Lake City, Utah, and R. W. Davenport, chief of the Technical Coordination Branch, Water Resources Division, Washington, D. C. The junior author joined the party

July 5, 1950, and continued with the work until October 5, 1950, when the study was completed.

Acknowledgments

Special appreciation is acknowledged to the Bureau of Land Management for its loan of the original reservoir surveys. Especially helpful was Conway Parry, conservationist, Bureau of Land Management, who materially aided the writers in the selection and initial location of the reservoirs to be studied.

PHYSIOGRAPHY

Physiographic features within any given area constitute an integral part of the study of the process of erosion and movement of sediment and cannot, therefore, be adequately covered in a general description. Thus, individual features such as land forms, character of the drainage pattern, slope of the terrain, type of vegetative cover, and other less important factors may reflect separate or combined influence on runoff and transportation of sediment. Although no attempt was made to evaluate the influence of individual features, a discussion of the general features of the San Rafael Swell is necessary to show its relationship to the overall area with which this report is concerned.

The San Rafael Swell lies in southeastern Utah within the boundaries of the Colorado Plateaus province. As the name implies, the structure is a huge swell or dome whose greater axis trends northeast for almost 70 miles and whose minor axis is about 30 miles long. It is bordered on the east by the Green River Desert, on the south by the Henry Mountains and the Waterpocket Fold, on the west by the Wasatch Plateau, and on the north by the Book Cliffs. A generalized physiographic map of the area (fig. 1) has been reproduced from a physiographic map of Utah prepared by the Department of Geology of Brigham Young University, Provo, Utah.

Differential erosion of the sedimentary rocks has carved the surface of the San Rafael Swell into a topography that is both rugged and picturesque presenting such forms as steep-sided mesas and buttes, long sloping cuestas, and wide strike valleys that contrast with numerous narrow canyons as much as 1,800 feet deep. The total relief within the area considered is about 8,200 feet; the altitude ranges from about 12,300 on the mountains west of the area to 4,090 feet at Green River on the east margin.

The most prominent topographic feature of the San Rafael Swell is a series of odd-shaped sandstone forms called "the Reef", that encircles an area in the heart of the Swell about 40 miles long and 15 miles wide, locally known as "Sinbad." These fantastically eroded forms are the remnants of an outcrop of massive cross-bedded sandstone that is much more resistant to erosion than the underlying shales. Cuestas and hogbacks, formed by resistant beds in the strata overlying this sandstone, encircle this belt of rugged topography exposing progressively younger formations toward the margins of the Swell.

Intervening between the "Reef" and the Book Cliffs is the high conglomerate-capped face of Cedar Mountain, which has a relief of about 1,500 feet. Between this mountain and the high escarpment of the Book Cliffs to the north lies an elongate valley carved in shale that parallels the Book Cliffs for many miles and is known by many local names. In the area in which this report is chiefly concerned, however, it is known as Price River Valley and Clark Valley. A counterpart to this valley lies on the west side of the Swell in front of the eastward facing escarpment of the Wasatch Plateau and is called Castle Valley.

Price River Valley and Castle Valley were formerly mantled by a gravel "apron" that sloped gently away from the cliffs. The present remnants of this apron or pediment appear as gravel-capped benches whose smooth surfaces present a distinctive contrast with the rugged shale surface in the intervening areas.

According to Gilluly (1928) the runoff over the entire San Rafael Swell ultimately reaches one or another of four perennial rivers that either actually cross the Swell, as in the case of the San Rafael River and the Muddy River, or have tributaries that drain portions of it. The runoff from the east, south, and west portion of the Swell and from most of Sinbad eventually reaches either the San Rafael River or the Muddy River. These two rivers have, as tributaries, many smaller creeks and washes that afford only ephemeral flow, but form a network that drains the greater part of the Swell. The northern and northeastern parts are drained through Cottonwood Wash and Humbug and Summerville Draws to Price River, and through Saleratus Creek and Cottonwood Springs Wash to Green River.

The vegetation of the region is typical of that found on the Colorado Plateaus. The higher parts of the region support pinyon, yellow pine, and juniper, whereas only the latter is found at intermediate altitudes. Rabbitbrush, greasewood and sagebrush are common in the region, particularly on bottom lands. These lowlands, however, are devoid of trees except for groves of cottonwoods along streams, occasional cottonwoods at springs, and orchard and shade trees in the various towns. Prickly-pear cactus is found in scattered localities, and several varieties of grass are present although not in sufficiently large amounts to permit heavy and frequent pasturage. Residual soils are very thin or not present at all, and the only productive soil materials are found on alluvial fills in the valleys.

GEOLOGY

In any area topographic and surficial features such as slope of terrain, drainage pattern, alluvial fills, and soils are mainly determined by the balance between climate and the character of the underlying rock. Logically then, in one small locality over which the climate is essentially uniform, any difference in erosional features may be ascribed to original differences in geologic features. Hence, as soils and alluvial fills within any drainage basin are generally derived from rock formations that underlie that drainage basin, their characteristics are limited by the chemical and physical properties of the source materials. Residual soils and weathered outcrops bear an even closer relationship to the local geology than their transported counterpart, because fine particles have not been carried away in suspension during the stage of transportation. As no soil classification has been completed in this area,

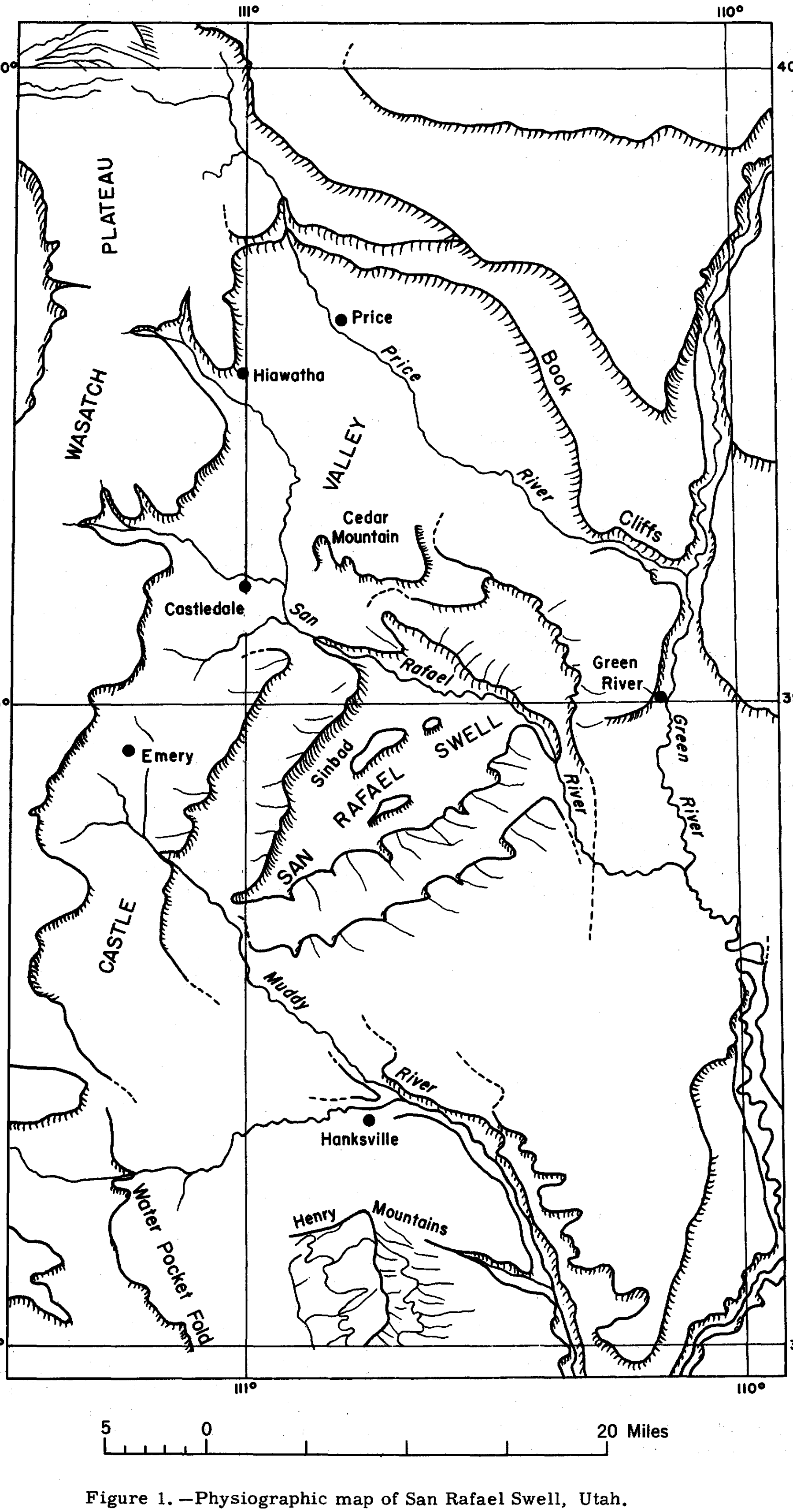


Figure 1. —Physiographic map of San Rafael Swell, Utah.

the writers believe that owing to this close relationship between surface materials and the underlying rocks, formations of different lithology will be covered by surface mantles that should exhibit different erosional characteristics. This method of classification may not be limited to the San Rafael Swell, but may be expanded to include the surrounding region, which is underlain by younger Tertiary formations that are not represented in the area studied. The following description of rocks that underlie the area emphasizes this difference in lithology as related to the respective surface mantles.

Geologic information was obtained from Gilluly's (1928) report on field examinations of individual drainage basins. Gilluly's geologic map covers the west and central part of the San Rafael Swell; the east and southeast parts are covered by Baker (1946) and Hunt and others (1952). A brief description of the rocks present in the area, together with the soil types that result from the weathering of these rocks, follows.

Essentially the area is underlain by four main types of rocks which, listed in order of decreasing areal extent, are shale, sandstone, limestone, and conglomerate. In the process of weathering, these rocks break down to form soils or surface mantles of varying characteristics depending on the parent rock. Shales disintegrate into clays and fine silts; sandstones, into individual sand grains; conglomerates, into pebbles with minor amounts of sand and silt; limestones, into limestone fragments and limy clays. The last two rock types are, however, of minor importance to this study because of their limited area of outcrop and relative resistance to erosion.

Although the distance and method of transportation of the constituent materials of soils generally alter their resemblance to the parent rock, erosion throughout the Swell has kept pace with or exceeded the rate of soil development such that existing thin soils or weathered mantles are very closely related to the parent rock. The exception exists in the alluvial fills along the stream channels that drain areas underlain by several formations of different lithology.

Rocks underlying the area are grouped for this report as follows:

Sedimentary Rocks

Sedimentary rocks in the San Rafael Swell range in age from Permian to Recent. Permian and Triassic rocks crop out within the Sinbad area. The Wingate and Navajo formations of Jurassic (?) age and the Todilto limestone member of the Kayenta formation of Jurassic (?) age form the reef that surrounds Sinbad. Because no reservoirs were constructed in drainage basins underlain by these formations, there are no erosion data available for this area.

Later Mesozoic strata comprise nearly all the remainder of the area, and extensive outcrops of Cretaceous shales and sandstones occur along the northern and western margins of the Swell. In Sinbad, the Shinarump conglomerate crops out in a narrow band that encircles the limestones and sandstones of the Moenkopi formation, Kaibab limestone, and Coconino sandstone, that together underlie most of the area. Outside the Sinbad area conglomerate beds several feet thick are found only in the Morrison formation, and limestone occurs as thin lenses in the Morrison formation and as one bed about 20 feet thick near the base of the Carmel formation.

A generalized description of the formations is given in the geologic column, and erosion characteristics peculiar to each formation will be discussed under "Rates of sediment production."

Alluvium

As erosion within any area is confined mainly to the surface mantle, the character and extent of all surface materials is of primary importance to any erosion study. The balance between surficial features and erosion, therefore, depends not only on the character but also on the amount of surface material that can be readily transported. These surface materials may be classified as residual, weathered in place; or transported, weathered elsewhere and carried to the present location.

Although residual soils or mantles make up the surface cover over a large part of the San Rafael Swell, erosion has removed most of the readily erosible material leaving only thin residual mantles or bare bedrock outcrops. Locally these soils may contribute large amounts of sediment to streams that drain the area, but in general the contribution from this source is not great.

Deposits of transported materials are the large contributors of sediment to the streams draining the area. They may be classified as colluvium or alluvium, dependent upon the method of transportation. Colluvium is sediment that has moved downslope by gravity and has been deposited near the toe of the slope. Alluvium is sediment that has been transported by streams. For the purpose of this study, however, no distinction will be made as most so-called colluvial slopes have been at least partially modified by the action of wind and water.

Although residual soils and colluvium provide a seemingly inexhaustible source of sediment, an even greater source exists in the form of alluvial fills along the innumerable tributaries and main drainage channels. The unconsolidated sediment in these fills has little inherent resistance to erosion, and any channel flow readily transports the maximum amount of sediment possible under the given hydraulic condition. This lack of cohesion, especially in fills derived from sandstones, may be attributed to the absence of suitable binding materials such as clays. Such reasoning, however, cannot be applied to fills derived from shales as these deposits consist primarily of particles in the clay and silt size. As may be expected, fills of this nature prove to be fairly resistant to erosion as long as they remain completely dry. Once the particles are wetted, however, they readily become dispersed and lose almost all inherent resistance to erosion. These deposits are most susceptible to erosion during periods of high precipitation and runoff when erosional forces are most active. For the present, however, greatest emphasis is placed on the fact that nearly all alluvial fills are easily eroded and thus may be subjected to rapid removal.

The actual extent of alluvial fills within the study areas could not be determined with any degree of accuracy as most areas are either not gullied or existing gullies have not been cut to bedrock. Generally, fills ranged from less than 1 foot in width and 1 foot in depth near the heads of small rills to a maximum width of several hundred feet and a maximum depth of 10 to 15 feet along the larger drainage channels. Owing to their erratic nature it is hardly possible to describe them in any general summary. Table 4 includes specific data relative to their character and extent within any study area as well as the amount of gullying.

Alluvial fills along the main drainage channels throughout the San Rafael Swell are often extensive, ranging from several hundred feet to more than a mile in width and averaging at least 200 feet in depth. Observations along Saleratus Wash revealed a central gullied channel at least 100 feet wide having vertical walls as much as 30 feet high, which are constantly being undercut as channel meandering diverts flow from one bank to the other. Smaller tributary channels, often as deep but not as wide as the main channel, have almost completely dissected extensive fills bordering the drainage for a distance of almost 20 miles upstream from Green River, Utah. This is but one example of main channel erosion; many other examples of similar gullying can be observed along Cottonwood Wash, and Humbug and Summerville Draws or along almost any of the larger tributaries of the San Rafael, Price, or Muddy Rivers. Hence, extensive alluvial fills not only border the main drainage channels but they are being currently removed through active channel erosion in the form of gullying.

Igneous Rocks

A number of sills and dikes occur in the southwestern part of the Swell but have no appreciable effect on the erosional features of the formations within the area. One reservoir (No. 1) located within this area of past igneous activity has a small outcrop of diabase within its drainage basin. The diabase sill in this drainage basin probably exerts little influence other than restricting the surface area of erodible materials.

Table 1. —Generalized section of rock formations in the San Rafael Swell[1]

System	Series	Group and formation	Character	Thickness (feet)
Quaternary		Alluvium and terrace gravel	Sandy clay, sand, and gravel in alluvial fans; terrace gravel on benches along streams.	
		—Unconformity—		
Cretaceous	Upper Cretaceous	Mancos shale	Gray marine shale; sandy beds in lower part, rather persistent sandstone members about 200 feet and 600 feet above the base.	4,000±
		Dakota (?) sandstone	Conglomerate; coarse and fine sandstone, in places quartzitic; gray and greenish clay.	0-55
		—Unconformity—		
Jurassic	Upper Jurassic	Morrison formation	Clay and shale, variegated, dominantly green-gray, maroon, and mauve; gray sandstone and conglomerate, very lenticular, massive and cross-bedded, especially abundant toward the base, where they form the Salt Wash sandstone member; subordinate thin lenticular limestones; gypsum locally at the base; in the northern part of the area a conglomerate 250 to 350 feet below the top.	415-847
		—Unconformity—		
	Upper and middle Jurassic	San Rafael group: Summerville formation	Thin-bedded, chocolate-colored sandstone, earthy red-brown sandstone and shale, some gypsum, and a little limestone in some sections.	125-331
		San Rafael group: Curtis formation	Greenish-gray conglomerate, shale, and gray thick-bedded sandstone.	76-252
		—Unconformity—		
		San Rafael group: Entrada sandstone	Thin-bedded red shale and sandstone at the base; thick, massive red-brown earthy sandstone above, poorly bedded, weathering in rounded forms.	265-844
		San Rafael group: Carmel formation	Dense limestone and buff and red sandstone at the base; dominantly red and green shale, thin sandstones, and thick beds of gypsum toward the top.	170-650
	—(?)—	—Unconformity (?)—		
Jurassic (?)	Lower Jurassic	Glen Canyon group: Navajo sandstone	Tan to light-gray massive cross-bedded limy sandstone, with a few thin limestone lenses.	440-540
		Glen Canyon group: Kayenta formation	Red-brown sandstone, green and red shales, shale conglomerate, irregularly interfingering and channeled.	44-240
		Glen Canyon group: Wingate sandstone	Buff to tan and dark-gray massive cross-bedded limy sandstone, with a few thin lenses of limestone. Usually stained red by wash.	360-400
		—Unconformity—		
Triassic	Upper Triassic	Chinle formation	Green and red micaceous sandstones and thin red-brown shale; limestone conglomerate variegated marl; all lenticular, channeled and interfingering	141-225
	Upper Triassic	Shinarump conglomerate	Cross-bedded lenticular conglomerate, sandstone, clay, and shale, interfingering. Much silicified wood. Quartz and chert pebbles in the conglomeratic portions	70-178
		—Unconformity—		
	Lower Triassic	Moenkopi formation	Green-gray pyritic shale; gypsiferous green and red shale; red micaceous ripple-marked sandstone; gray to buff sandstone; and red sandstone. Very limy throughout, with a thick, persistent gray marine limestone and sandstone member, the Sinbad limestone member 140 to 200 feet above the base.	735-850
	—Unconformity—			
Permian		Kaibab limestone	Light-gray to cream-colored cherty limestone; some oolite, somewhat sandy in places; equivalent to only uppermost part of typical Kaibab.	0-85
		Coconino sandstone	White to buff, sugary, friable to hard, massive cross-bedded quartz sandstone on uneven grain. Some grit toward the base; the lowest 40 feet largely limestone. Base not exposed. May include much more than typical Coconino sandstone.	715

[1] Gilluly, James, 1929, Geology and oil and gas prospects of part of the San Rafael Swell Utah, U. S. Geol. Survey Bull. 806-C.

Structure

The structure of the area is relatively simple. The Swell is an elongated, asymmetric domal fold whose axis trends north by east. The central Sinbad area is encircled by a high ridge or "hogback" of Jurassic sandstone. From this ridge outward to the Book Cliffs and Wasatch Plateau escarpments, the Swell has a steplike appearance. Clark and Castle Valleys are cut in monoclinal structures and parallel these escarpments. A number of small folds and faults are present in the area but have no relevance to this study.

PRECIPITATION

Thus far this discussion has been limited to erosion as indirectly influenced by the slope of terrain and lithology of formations that underlie the area. Active erosion is apparently set off by precipitation that is abnormal in relation to conditions existing in the area. Actually the ideal precipitation with respect to the erosion problem would be the maximum amount that could fall without exceeding the rate of infiltration. Precipitation exceeding this amount causes runoff and incites erosion, whereas precipitation less than this amount deprives the soil of sufficient moisture to support a protective vegetative cover. Hence, dry years tend to denude the soil mantle of its vegetative cover and thereby lower its resistance to erosion, whereas wet years with high-intensity storms actually cause runoff and associated erosion. Precipitation data for stations on the San Rafael Swell have been analyzed in an attempt to compare precipitation records during the life of the reservoirs with the long-term average for the area and then adjust known rates of sedimentation to long-term rates.

Although no precipitation data are available near the center of the Swell, excellent long-period records have been kept at six stations along the outer margin. These records, as reported by the U. S. Weather Bureau in the "Monthly Climatological Data" for Utah, cover an average period of 43 years and show the average annual precipitation range from a maximum of 12.91 inches at Hiawatha to a minimum of 5.23 inches at Hanksville. Available data would indicate that the average annual precipitation near the center of the area is about 6 to 7 inches. An index map showing the location of the stations is given as figure 2, and a summary of climatological data is given in table 2.

Analysis of temperature records available for the same stations shows that above-freezing temperatures may be expected from April to October inclusive. The year was divided into a 7-months summer season (April-October) and a 5-months winter season (November-March). Although occasional winter storms cause off-season runoff, because of the high altitude, the bulk of winter precipitation falls as snow. Winter runoff, therefore, is so infrequent that for the purpose of this report only summer precipitation will be considered. Runoff from snowmelt is recognized as a possible contributor especially to channel erosion, but unfortunately data are not available to determine its actual effect.

Although records covering 32 to 54 years are available for individual stations those records before 1930 are incomplete for several stations and do not supply the necessary data for detailed storm analysis. Nevertheless, the seasonal precipitation data were plotted for the entire record period (fig. 3) and the long-term seasonal averages compared to the averages for the period 1930-50 (see extreme right-hand bars on fig. 4). The close comparison between these averages for individual stations would indicate that the period 1930-50 may be considered representative of the long-term period. As the maximum age of the study reservoirs is 14 years, the period 1930-50 will determine the precipitation pattern not only over the life of the reservoirs, but also for the period immediately prior to their construction. Many methods may be used to assemble available precipitation data for the area, but for the purpose of this report, methods were limited to (1) a determination of average daily intensities; (2) total summer precipitation in excess of the estimated rate of daily infiltration; (3) frequency of occurrence of storms of a given magnitude.

Average storm intensity and seasonal distribution of precipitation over the San Rafael Swell are remarkably consistent. About two-thirds the annual precipitation occurs from April to October inclusive. Typical convection-type storms provide most of this, with daily totals ranging from a trace to a maximum of 2.16 inches. Averages of daily precipitation for the six stations show that 80 percent of the days with precipitation had amounts less than 0.25 inch, whereas 7 percent had over 0.50 inch per day and only 1 percent experienced over 1.00 inch per day. The number of days with precipitation greater than specified amounts is listed for individual stations in table 3.

Summer storms are generally of the convectional type; they cause precipitation of small magnitude but of sufficiently high intensity to exceed the amount readily absorbed by the soil. Runoff, therefore, is a function of a number of variables such as soil development, vegetative cover, and land slope and generally represents only a small part of the total precipitation. An evaluation of rainfall-runoff relationship from precipitation data is further complicated because amounts recorded as daily totals usually fall within a few hours. The question arises as to the minimum amount of daily rainfall that will produce some surface runoff. Comparisons between precipitation and runoff

Table 2.—Station index and summary data for U. S. Weather Bureau stations on San Rafael Swell, Utah

Station	County	Location		Elevation (feet)	Annual temperature				Annual precipitation				Summer precipitation Apr. 1-Oct. 31			Winter precipitation Nov. 1-Mar. 31		
		Latitude	Longitude		Yrs. Record	Max. (°F)	Min. (°F)	Average	Yrs. Record	Max. (inches)	Min. (inches)	Average	Max. (inches)	Min. (inches)	Average	Max. (inches)	Min. (inches)	Average
Emery	Emery	38°56	111°14	6,260	48	99	-20	45.8	49	16.84	0.54	7.55	13.42	0.45	5.12	8.59	Trace	2.36
Castle Dale	Emery	39°13	111°01	5,600	43	104	-35	45.6	46	17.05	3.29	8.69	12.46	1.42	5.50	7.67	0.72	3.03
Hiawatha	Carbon	39°29	111°01	7,230	28	95	-18	45.0	32	22.09	6.66	12.91	17.58	3.80	8.81	7.29	1.48	4.30
Price	Carbon	39°36	110°49	5,500	34	108	-31	48.6	38	19.55	4.47	10.24	15.33	1.75	6.36	5.98	1.74	3.48
Green River	Emery	39°00	110°09	4,087	48	112	-42	52.5	54	12.12	3.11	6.10	9.40	0.37	4.03	4.79	0.35	1.96
Hanksville	Wayne	38°25	110°41	4,456	36	112	-35	52.1	38	9.14	2.24	5.23	8.50	0.82	3.76	4.57	Trace	1.58

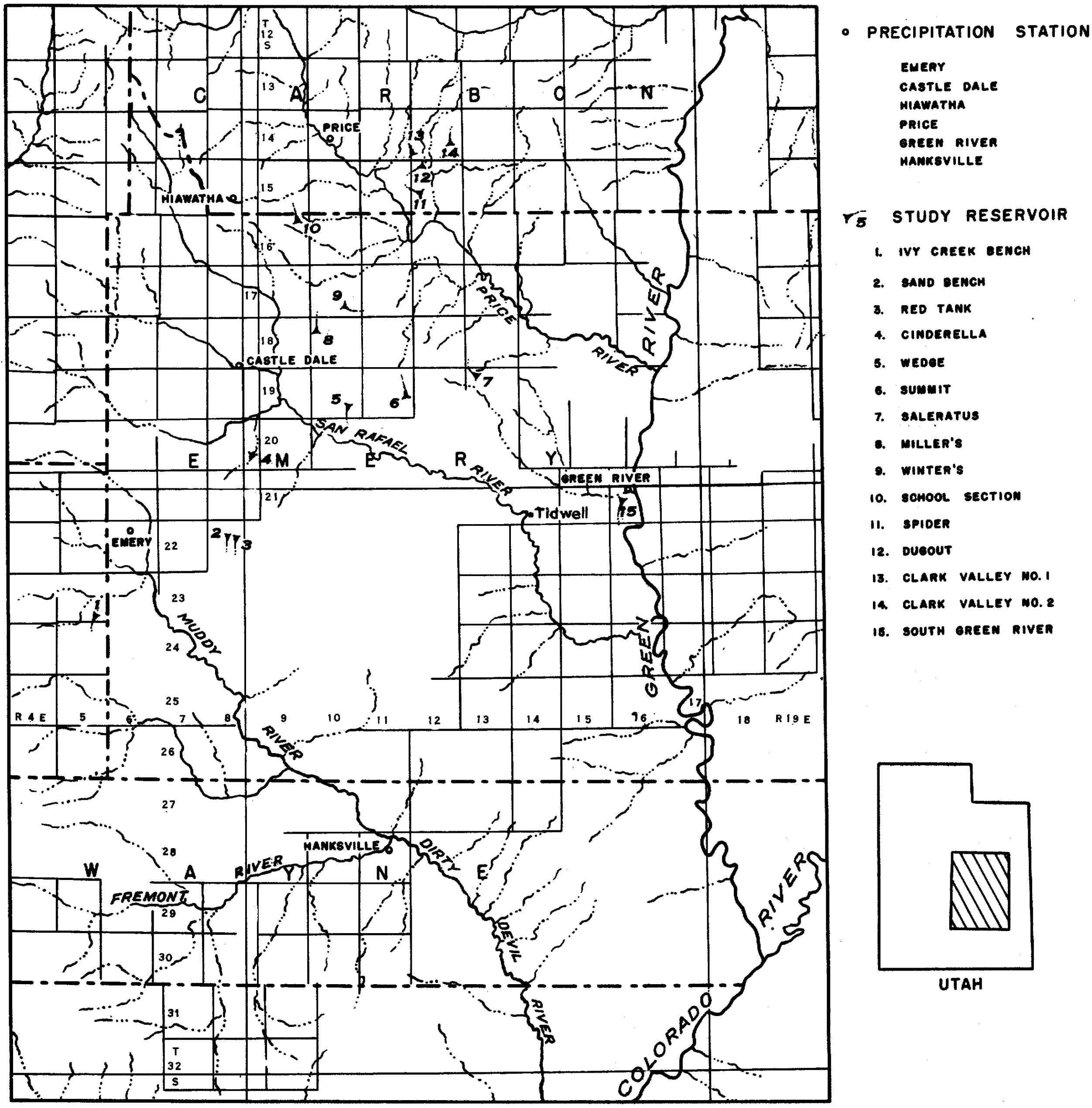


Figure 2. --Index map of Utah, showing San Rafael Swell and location of precipitation stations and study reservoirs.

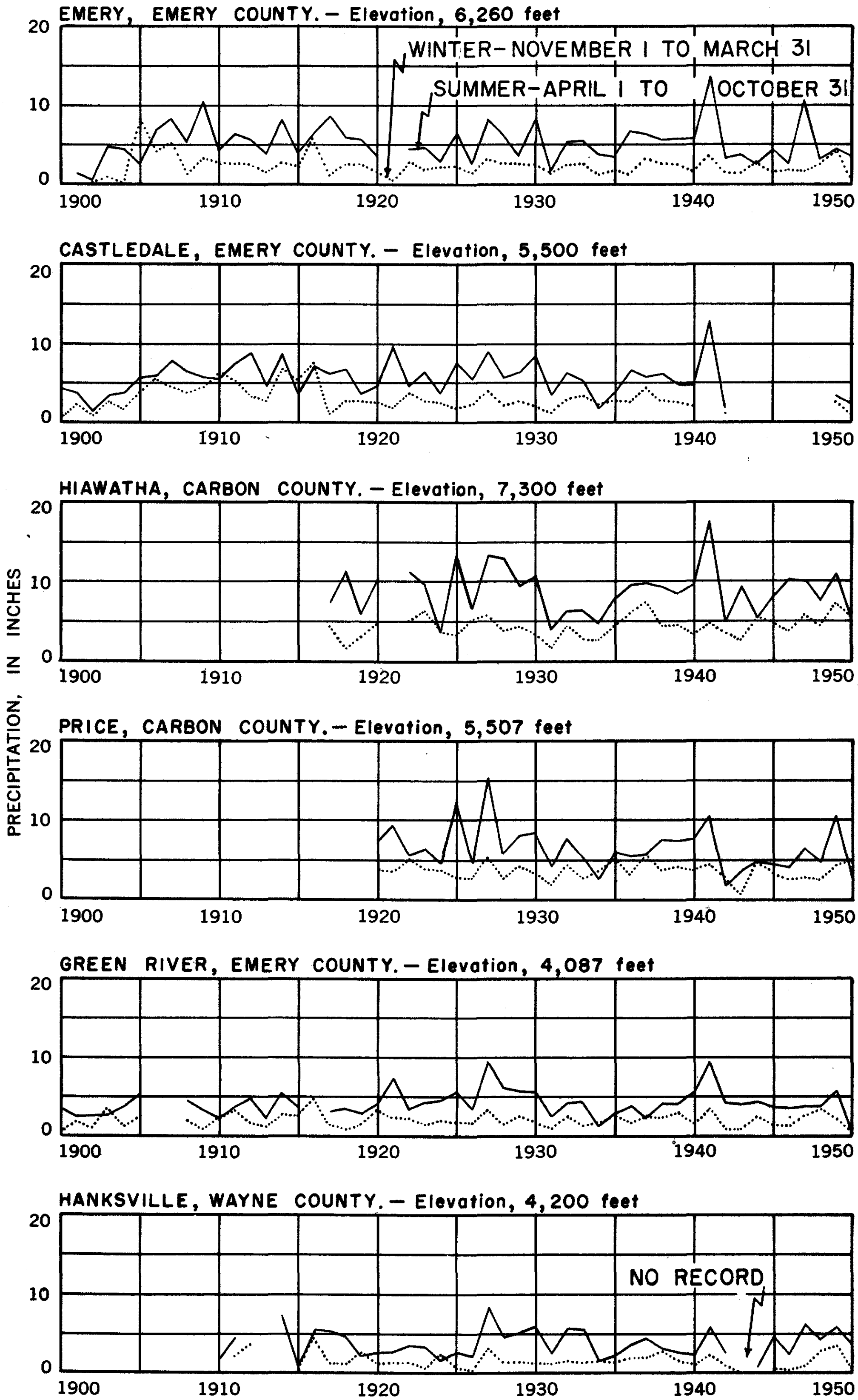


Figure 3.--Seasonal precipitation for stations on the San Rafael Swell.

Table 3.--Size-frequency data for daily rainfall stations on the San Rafael Swell, Utah[1]

Amount of precipitation (inches)	Number of days, period 1930-50, for indicated total days with precipitation																				
	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950
Emery (altitude, 6,260 feet), Emery County																					
	30	14	25	27	13	19	26	19	28	21	24	34	12	17	15	25	20	26	22	30	22
0.25	14	2	9	8	4	5	16	10	10	7	7	23	5	7	5	6	3	13	3	7	5
.50	5	-	4	2	1	-	3	4	2	3	4	12	2	2	1	2	2	6	1	1	1
.75	2	-	1	1	1	-	-	1	-	2	2	4	1	-	-	1	-	3	1	-	-
1.00	1	-	1	-	1	-	-	-	-	-	1	1	-	-	-	-	-	3	-	-	-
Castle Dale (altitude, 5,500), Emery County[2]																					
	43	27	31	29	21	32	34	35	44	44	66	57	14	-	-	-	-	-	-	13	11
0.25	11	4	8	6	2	4	12	7	7	8	8	19	1	-	-	-	-	-	-	5	4
.50	8	1	2	3	-	1	2	4	3	1	4	9	1	-	-	-	-	-	-	3	-
.75	3	-	-	2	-	1	-	2	-	-	-	3	1	-	-	-	-	-	-	1	-
1.00	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-
Hiawatha (altitude, 7,300 feet), Carbon County																					
	76	54	66	69	52	82	79	77	92	61	52	62	48	71	56	74	60	56	44	53	37
0.25	15	5	7	9	5	9	17	13	12	16	14	21	6	11	8	14	9	12	11	16	7
.50	5	-	2	3	2	3	6	5	5	4	5	11	2	8	3	2	4	4	3	8	3
.75	3	-	1	1	1	2	2	1	3	1	2	4	1	2	1	-	2	2	3	3	1
1.00	1	-	-	-	-	1	1	1	-	-	1	2	1	2	1	-	2	1	1	1	-
Price (altitude, 5,507 feet), Carbon County																					
	39	23	25	22	16	24	21	21	57	34	44	63	26	32	39	52	44	47	33	50	31
0.25	13	5	12	6	3	8	6	6	10	11	10	14	1	2	6	4	5	6	6	13	3
.50	3	1	5	3	-	3	3	2	4	6	2	5	-	1	2	2	-	3	2	6	-
.75	1	-	2	1	-	3	2	1	1	2	2	1	-	1	-	1	-	1	2	4	-
1.00	-	-	1	1	-	-	-	1	-	-	2	1	-	-	-	-	-	-	1	1	-
Green River (altitude, 4,087 feet), Emery County																					
	37	22	25	28	17	27	36	35	53	41	48	77	40	57	50	61	44	43	34	55	5
0.25	6	1	5	8	1	4	4	2	4	5	5	12	5	6	5	5	4	4	6	7	-
.50	4	-	2	-	-	1	1	-	1	1	-	5	2	1	2	1	-	2	1	-	-
.75	1	-	1	-	-	-	1	-	1	1	-	2	1	-	-	-	-	-	-	-	-
1.00	1	-	-	-	-	-	1	-	1	1	-	1	-	-	-	-	-	-	-	-	-
Hanksville (altitude, 4,200 feet), Wayne County																					
	41	28	27	14	9	12	18	14	18	20	38	42	18	*	18	26	46	55	45	62	35
0.25	7	3	6	9	2	5	6	6	5	4	4	8	5	-	-	7	4	7	6	8	2
.50	4	-	4	2	1	-	2	4	1	1	1	4	1	-	-	2	2	4	3	3	2
.75	-	-	3	1	-	-	1	2	-	-	-	2	1	-	-	-	1	2	2	-	1
1.00	-	-	2	-	-	-	1	1	--	-	-	-	-	-	-	-	-	1	-	-	1

* No record.
[1] For period April to October inclusive.
[2] No record, November 1942-October 1948.

at a number of locations in the southwest suggest that precipitation recorded as 0.25 inch or more per day will produce flow on soils derived from shales, whereas 0.50 inch per day or more may be required to produce appreciable flow on sandy soils.

Once the amount of precipitation per day necessary to cause runoff has been approximated for any area, it follows that a quantitative measurement of rainfall in excess of this amount should segregate years in which erosion has been most active. Figure 4 shows the total seasonal precipitation for each station compared with the proportion that falls at rates exceeding various amounts per day. Following this reasoning, the greatest average runoff would have occurred in 1941, whereas almost no runoff would have occurred during 1931 and 1934.

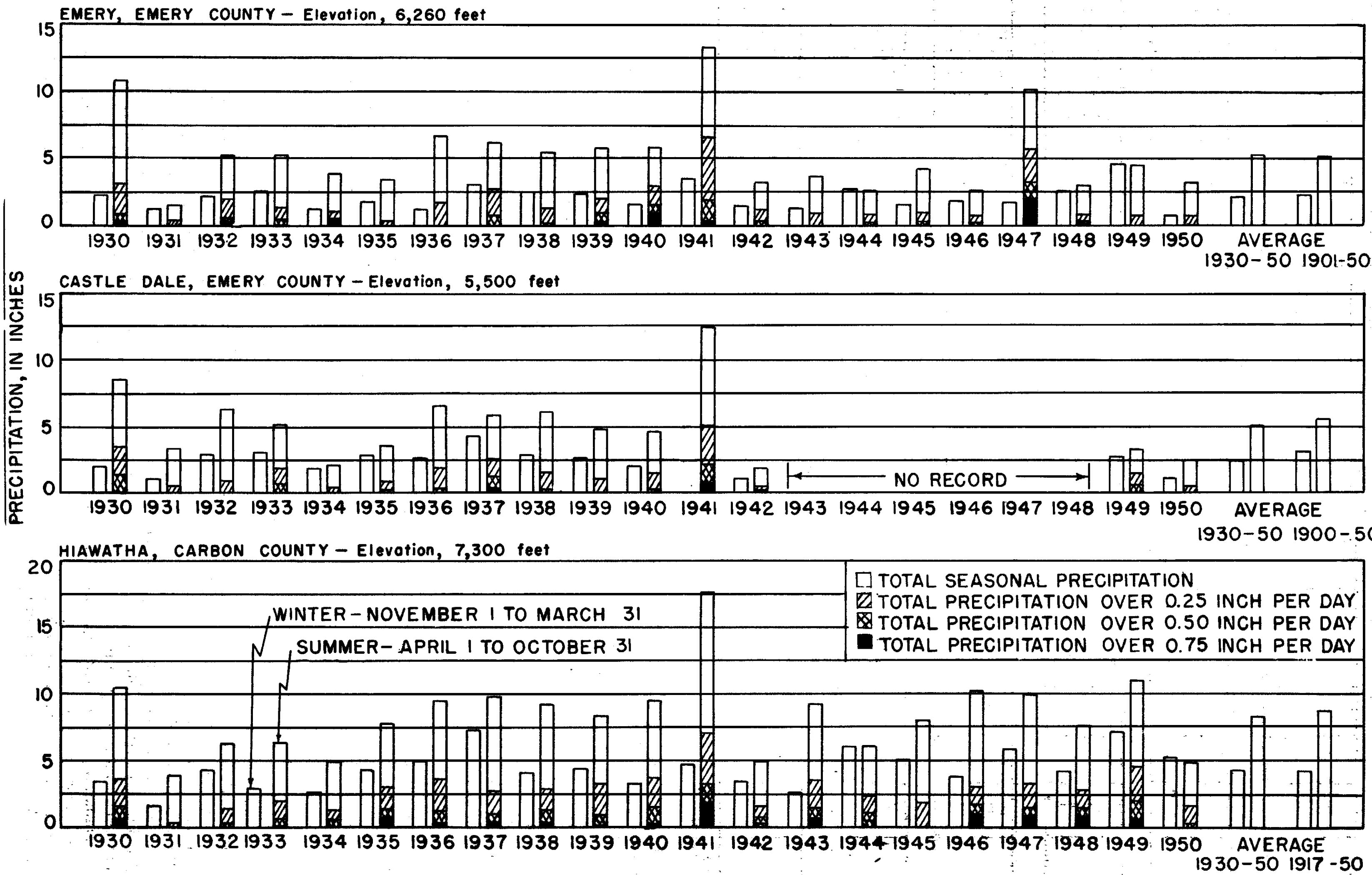
A determination of average storm intensity together with the amount of precipitation available for runoff may provide some relationship between the number of days with precipitation and the intensity of that precipitation, but it gives no indication of the seasonal recurrence of storms of a given magnitude. Hence, in order to show the proportion of precipitation available for runoff, occurrence-intensity curves have been developed for individual stations; these express the percentage of summers that have total precipitation in excess of various amounts per day (fig. 5). Interpolation from these curves permits rapid determination of the expected recurrence of runoff once the rate of infiltration is known for an area. For example:

For a drainage basin near Price where the rate of infiltration is about 0.25 inch per day, the (P-0.25 inch) curve taken from the Price station shows that about 100 percent of the summers will have runoff; 75 percent will have runoff in excess of 1.00 inch; 43 percent will have runoff in excess of 2.00 inches; and 7 percent of the summers will have runoff in excess of 4.00 inches.

Similar results may be obtained for any drainage unit once the average rate of infiltration is determined.

A general summary of the 6 stations shows that, although only two storms exceeding 2.00 inches per day occurred in the 21 years of record, storms of 0.25 inch per day or greater occurred during 100 percent of the summers, storms of 0.50 inch per day or greater occurred during 83 percent of the summers, and storms of 1.00 inch or greater occurred during 29 percent of the summers.

As may be expected, precipitation of the magnitude of 0.50 inch or more per day results from convection-type storms that vary greatly in intensity over short distances. This fact, coupled with the different infiltration rates for various types of surface mantles, accounts for the apparent difference in the amount of runoff between even small adjacent drainages. Minor differences in runoff may, however, be accompanied by a much greater variation in sediment load, because the carrying capacity of any stream increases exponentially with an increase in the volume and velocity of runoff.


EMERY, EMERY COUNTY — Elevation, 6,260 feet
CASTLE DALE, EMERY COUNTY — Elevation, 5,500 feet
HIAWATHA, CARBON COUNTY — Elevation, 7,300 feet
PRECIPITATION, IN INCHES
0
5
10
15
20
1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950
AVERAGE
1930-50 1901-50
1930-50 1900-50
1930-50 1917-50
NO RECORD
WINTER-NOVEMBER 1 TO MARCH 31
SUMMER-APRIL 1 TO OCTOBER 31
TOTAL SEASONAL PRECIPITATION
TOTAL PRECIPITATION OVER 0.25 INCH PER DAY
TOTAL PRECIPITATION OVER 0.50 INCH PER DAY
TOTAL PRECIPITATION OVER 0.75 INCH PER DAY

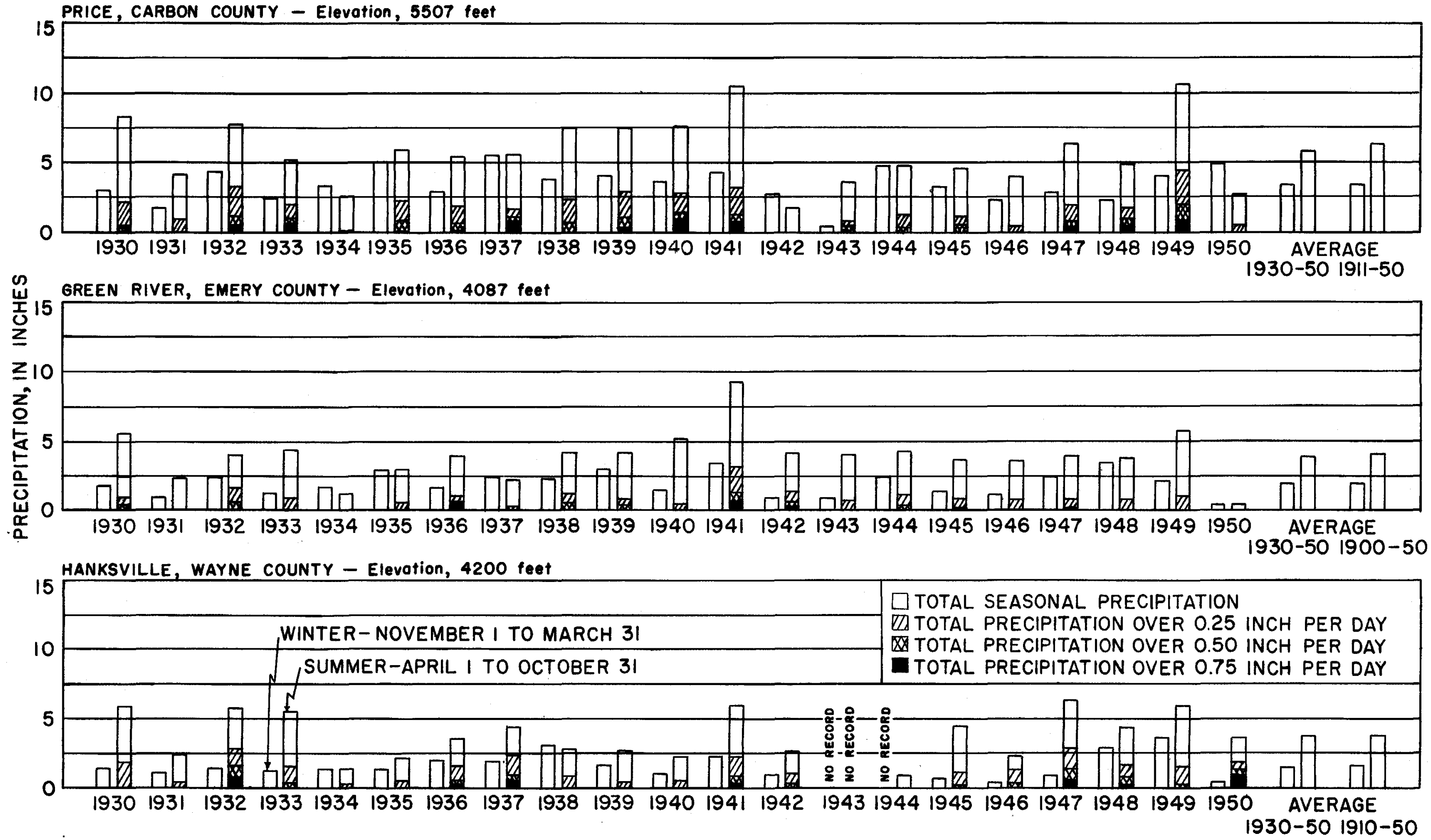
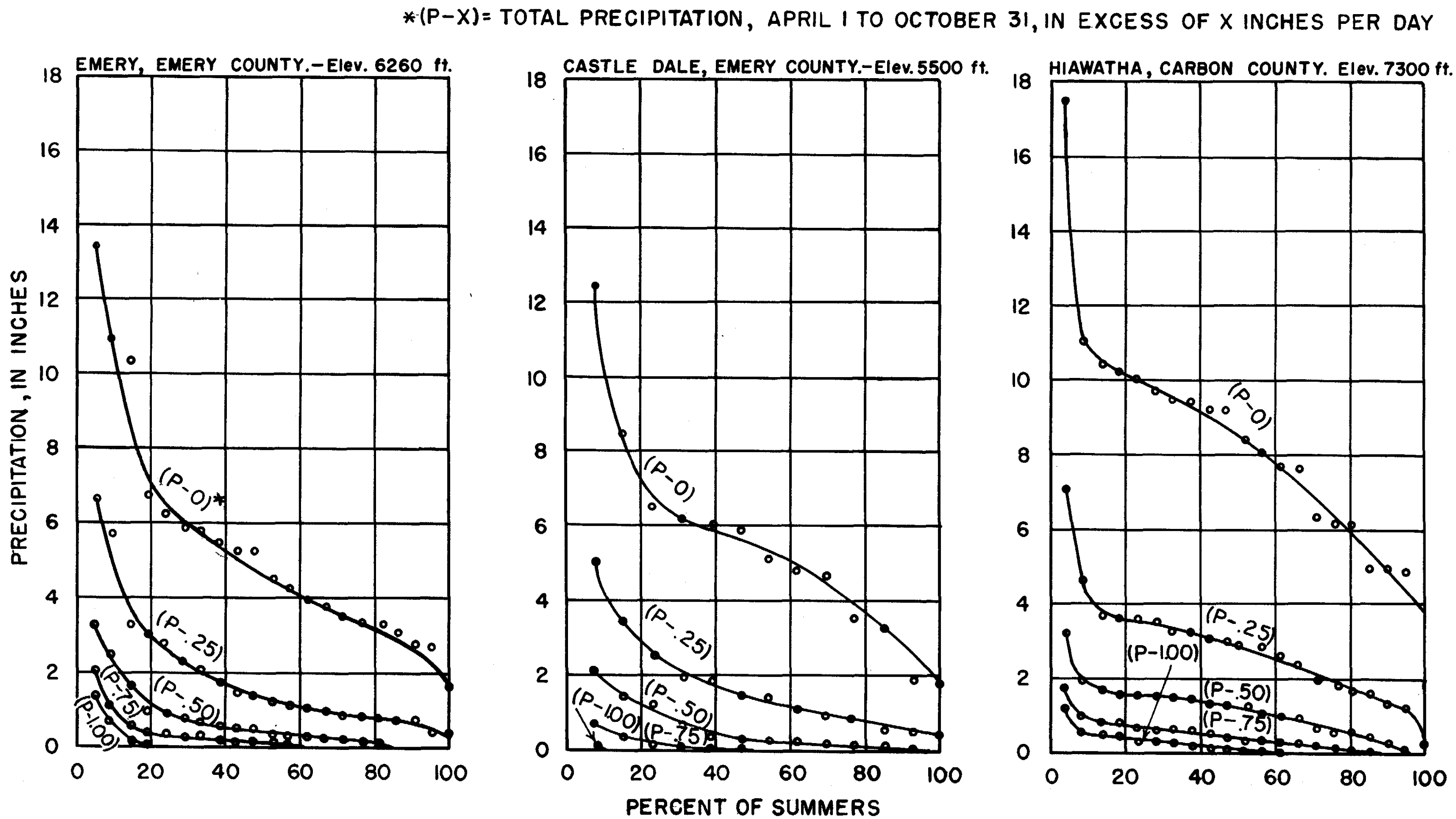


Figure 4.--Seasonal precipitation and intensity relationship.


*(P-X)= TOTAL PRECIPITATION, APRIL 1 TO OCTOBER 31, IN EXCESS OF X INCHES PER DAY
EMERY, EMERY COUNTY.-Elev. 6260 ft.
CASTLE DALE, EMERY COUNTY.-Elev. 5500 ft.
HIAWATHA, CARBON COUNTY. Elev. 7300 ft.
PRECIPITATION, IN INCHES
PERCENT OF SUMMERS
(P-0)*
(P-.25)
(P-.50)
(P-.75)
(P-1.00)
0
2
4
6
8
10
12
14
16
18
20
40
60
80
100

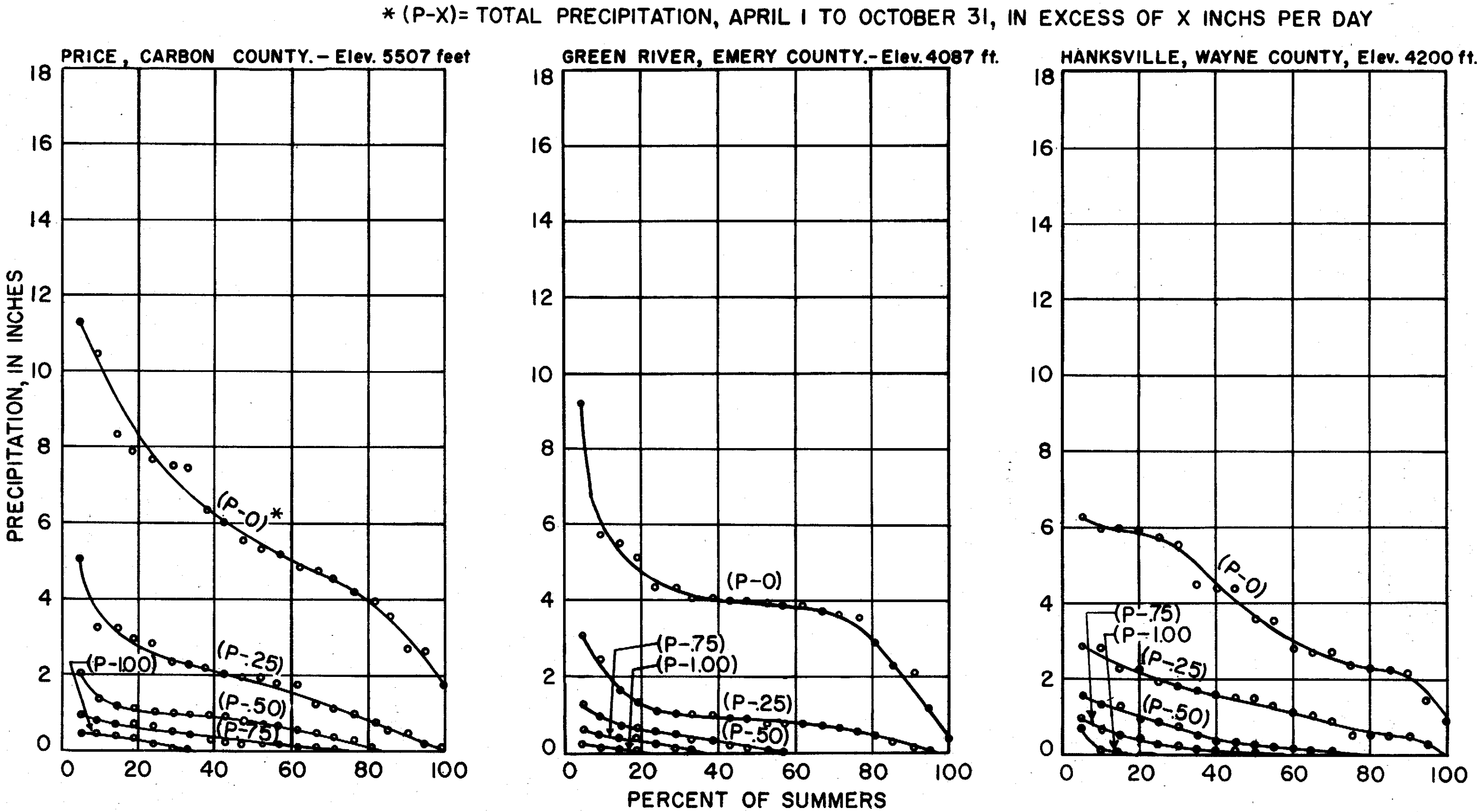


Figure 5. —Occurrence-intensity relationship of summer storm precipitation.

Hence, sediment-production rates at different reservoirs, although representative of the same period, may be entirely different. Because of the complete lack of precipitation data at the individual study areas, no effort has been made to compensate for this effect, but where the life span of reservoirs has not been synchronous, some may include wet or dry years that others do not, an effort has been made to adjust known sediment rates to a long-term estimate of sediment production.

SEDIMENTATION

Although the ideal objective of any erosion study would be to evaluate the effect of individual factors contributing to the movement of sediment, such a program is far too complex even in small drainage basins. Their combined effects, however, can be readily determined by measuring the actual movement of sediment out of any basin. By comparing sedimentation rates over the same period in different reservoirs, marked anomalies may be correlated with differences in certain erosional features. Hence, an indirect method may be used in the attempt to evaluate the relative importance of individual features so that necessary adjustments can be made when determining the long-term rates of sedimentation for different areas.

A group of representative reservoirs was surveyed with the assumption that they trapped a high percentage of sediment transported during periods of runoff. A quantitative measurement of sediment in each reservoir was then prorated over the life of the reservoir to yield the average annual sediment production for a drainage basin of known size. Theoretically such a method of determination should provide accurate results, but actually three important factors must first be taken into consideration, (1) inaccuracies in original surveys, (2) loss of sediment during reservoir spill, (3) effect of abnormal seasonal precipitation when reservoirs are not synchronuous in age.

Most original reservoir surveys were made before construction as part of an over-all range-development program. Hence, the original calculated capacity at spillway level includes the added volume provided by excavation of fill for the dam. During construction, however, the calculated capacity may have been altered somewhat by supplying some of the fill from above spillway level or by not establishing the spillway control at the exact predetermined elevation. Nevertheless, such inaccuracies are perhaps the least important sources of error as adjustments can generally be made following a second detailed survey of the reservoir, dam, and spillway.

Of far greater consequence are errors resulting from loss of sediment during reservoir spill. Coarse particles carried into a reservoir rapidly settle to the bottom following a reduction in stream velocity. Clay or silt particles, however, have such a low settling velocity that they remain in suspension long enough to be carried out of the reservoir during periods of spill. Owing to increased spilling as the reservoir is filled with sediment, the relative amount of sediment lost during spill increases progressively. The trap efficiency or percentage of sediment caught in a reservoir must be expressed as a function of the average particle size carried into the reservoir, the reduction of velocity between the inflow channel and the spillway, the depth or distance particles must settle, and the amount of spill. The general effect of the first three factors could be determined in the field, but no record of the amount of spill is available, except as the relative amount could be judged from the appearance of the spillway. Adjustments for this loss, therefore, have been made by estimating the trap efficiency of individual reservoirs from measured field data and applying this correction to measured sediment-production rates.

Trap Efficiency

Examination of the rates of sedimentation shows an obvious and appreciable variation with geologic type. In order to eliminate this effect in a study of the trap efficiency, the several rates of sedimentation were expressed in ratio to the average for their respective geologic or lithologic groups. These were further classified as to their relative amounts of spill according to the information given in column 16 of table 4. Although trap efficiency is dependent on both the character of the sediment and on reservoir size and design, the amount lost will be in proportion to the total amount of spill. Because the amount of spill depends largely on the capacity of the reservoir in relation to the size of the drainage area, data on their capacity per square mile of drainage area or C/A ratio are included.

Reservoir no.	Ratio of rate of sediment production to group average	Acre-feet per square mile
	Nebligible or no spill	
9	0.37	55.6
11	3.5	126
12	.4	38.8
Average	-	73.5
	Little spill	
2	0.76	32.2
15	.90	30.2
Average	.83	31
	Some spill	
1	0.42	15.8
5	.56	10.5
6	.63	25.5
7	.80	18.3
8	.24	23.8
14	.67	9.7
Average	.55	17.3
	Large spill	
3	0.11	19.8
4	.55	13.9
10	.24	7.6
13	.12	3.8
Average	.25	11.3

The above table shows a very significant decrease in rate of reservoir sedimentation and the value of C/A with amount of spill. This would indicate that about 75 percent of the sediment passes over the spillway and only 25 percent is retained in those reservoirs noted as having "large spill." Therefore, the following adjustment for trap efficiency to the observed data seemed necessary.

Negligible or no spill	1.00
Little spill	.80
Some spill	.50
Large spill	.25

The relationship of these factors to the value of C/A is shown on figure 6.

A minor decrease in relative rate of sedimentation with increase in drainage area may also be noted. This apparent effect may reflect a general tendency to the inclusion of flatter valley and plains areas with increase in drainage area. It may also indicate a temporary aggradation or accumulation of sediment in the channels below the steeper headwater areas. In an infinitely small basin practically all sediment movement is out of the basin, whereas in a very large basin considerable sediment movement may take place within the basin, but the amount depends on the extent to which channel and flood plain deposition or degradation, sedimentation or erosion is taking place during a particular period of observation. Although sediment-production rates from small areas tend to be higher than those from larger areas, no adjustments have been made because their significance in this study is small and probably transitory.

A third variable and perhaps the most difficult to evaluate is the effect of abnormal seasonal precipitation when the age of reservoirs is not synchronous. As noted previously the rate of sediment production is dependent on the occurrence and amount of runoff. Hence, reservoirs may be expected to show considerable variation in the amount of sediment caught annually because of the marked differences in seasonal precipitation. Figures 4 and 5 show the great disparity not only in the total seasonal rainfall, but in the manner of occurrence. Simultaneous records for the different stations show that local variations during the same summer are often larger than season to season variations at any one station. Few generalizations, therefore, can be made for the entire area. Nevertheless, the summer of 1941 was so abnormally high in both total seasonal precipitation and runoff that reservoirs constructed before 1941 should show somewhat higher sediment production rates than reservoirs constructed after 1941. Sediment-production rates at the two reservoirs constructed since 1941 were adjusted in accordance with records at the nearest precipitation station.

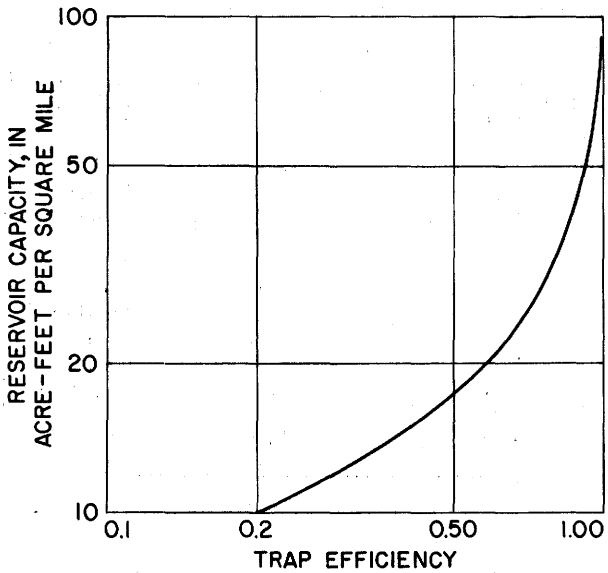


Figure 6.—Relation of trap efficiency to capacity-area ratio.

All available information from previous surveys and publications, together with measured and computed data obtained from field examinations, are summarized in table 4. Accompanying explanatory notes show the source of information and methods of computation for individual columns. The final results of the study are shown in columns 21 and 22, which express the adjusted annual sediment production in acre-feet per square mile of drainage basin for the life of the reservoir and for the long-term period respectively.

Compilations

Source of information and methods of computation used in setting up table 4:

Columns 1 and 2. Self explanatory.

Columns 3, 11, and 17. Location, original capacity, and age of structures from Bureau of Land Management files. Locations are described by quarter sections.

Column 4. Reservoir altitudes determined by aneroid barometer.

Column 5. Drainage areas including reservoir area planimetered from areal photos, scale 1 inch=1 mile, except for reservoirs 1, 5, 6, 10, 11, 13, and 14, which were determined in the field.

Column 6. Lengths of drainage basins determined either from areal photos or by field measurements.

Column 7. Maximum relief as determined by aneroid barometer.

Column 8. Geology from field notes.

Column 9. From field observations.

Column 10. Reservoir areas at spillway level as determined by planimetering plane table maps.

Column 12. Present capacity of reservoir at spillway level as computed from the area-depth relationship measured in the field. Contour intervals of 2 feet or less were obtained for each reservoir below spillway level.

Column 13. Average life capacity of reservoir with respect to drainage area. Average of columns 11 and 12 divided by column 5.

Column 14. Obtained by subtracting column 12 from column 11. Minor adjustments have been made to allow for obvious inaccuracies in original surveys.

Column 15. Percentage of original storage now occupied by sediment.

Column 16. Reservoir spill as indicated by the nature and amount of spillway erosion since construction.

Column 17. Life of reservoir.

Column 18. Appraisal of records based on trap efficiency of reservoir, accuracy of original survey, and length of record.

Column 19. Sediment production per square mile. Column 14 divided by column 5.

Column 20. Annual sediment production rate per square mile. Column 19 divided by column 17.

Column 21. Annual sediment-production rate adjusted for drainage area effect and trap-efficiency effect according to the method given on pages 14-18.

Table 4.—Data from reservoir and drainage

[In column 18 symbol g = good,

USGS no.	B.L.M. Project no.	Location	Drainage basin: Altitude (feet) [a]	Drainage basin: Area (sq miles)	Drainage basin: Length (miles)
(1)	(2)	(3)	(4)	(5)	(6)
1	110	SW¼, sec. 35, T. 23 S., R. 5 E.	6,580	0.24	0.76
2	176	NE¼, sec. 17, T. 22 S., R. 8 E.	4,900	.25	.75
3	177	NE¼, sec. 16, T. 22 S., R. 8 E.	5,000	.10	.65
4	25	SE¼, sec. 26, T. 20 S., R. 8 E.	5,890	.92	1.25
5	9	NW¼, sec. 35, T. 19 S., R. 10 E.	6,000	.80	1.60
6	63	SE¼, sec. 24, T. 19 S., R. 11 E.	6,375	.75	1.45
7	93	SW¼, sec. 8, T. 19 S., R. 13 E.	5,280	.54	1.30
8	76	SE¼, sec. 7, T. 18 S., R. 10 E.	5,820	.14	.64
9	67	SW¼, sec. 27, T. 17 S., R. 10 E.	5,720	.11	.62
10	215	SW¼, sec. 2, T. 16 S., R. 9 E.	5,870	3.45	3.40
11	74	SE¼, sec. 19, T. 15 S., R. 12 E.	5,590	.12	.79
12	128	SE¼, sec. 5, T. 15 S., R. 12 E.	5,670	[b].13	.60
13	154	NE¼, sec. 30, T. 14 S., R. 12 E.	5,705	.99	1.85
14	160	SE¼, sec. 23, T. 14 S., R. 12 E.	5,900	.46	1.53
15	3	SE¼, sec. 20, T. 21 S., R. 16 E.	4,250	.34	.74

USGS no.	Reservoir—Continued: Present capacity (acre-ft)	C/A Acre-ft (sq miles)	Sediment: Acre-ft	Sediment: Percent of original capacity	Spilling
(1)	(12)	(13)	(14)	(15)	(16)
1	2.40	15.8	2.80	53.8	Some
2	6.81	32.2	2.50	26.9	Little
3	1.934	19.8	[c].094	4.6	Large
4	4.55	13.9	16.4	78.3	Large
5	7.47	10.5	1.8	19.4	Some
6	12.06	25.5	14.10	53.9	Some
7	6.80	18.3	6.2	47.7	Some
8	2.85	23.8	.95	25.0	Some
9	6.02	55.6	.16	2.6	Negligible
10	16.49	7.6	19.1	53.7	Large
11	11.29	126.0	7.71	40.6	None
12	4.95	38.8	.18	3.5	Negligible
13	2.31	3.8	2.9	55.6	Large
14	3.96	9.7	1.02	20.5	Some
15	6.03	30.2	8.5	58.5	Little

a Altitudes determined by aneroid barometer.
b Including adjacent drainage cut into reservoir.
c Sediment in upstream structures included.
d Bulk of sediment deposited on flat before reaching reservoir.

basin studies on San Rafael Swell, Utah

f = fair, and p = poor]

Drainage basin—Continued			Reservoir	
Maximum relief (feet)[a]	Geologic symbol	Erosional characteristics	Surface area (acres)	Original capacity (acre-ft)
(7)	(8)	(9)	(10)	(11)
175	Kmn	Major gullying, minor sheet erosion.	1.49	5.20
325	Jcus	Sheet erosion.	3.35	9.31
150	Jecu	Sheet erosion.	.66	2.02
525	Kmn	Major gullying sheet erosion.	1.92	20.95
260	Jca	Minor gullying sheet erosion.	1.82	9.27
1,500	Jmscueca	Major gullying sheet erosion.	4.97	26.16
50	Je	Minor gullying sheet erosion.	3.06	13.00
75	Jm	Sheet erosion.	2.34	3.80
120	Jm	Sheet erosion.	2.06	6.18
500+	Kmn	Major gullying.	8.62	35.59
125	Kmn	Major gullying.	2.64	19.00
65	Kmn	Sheet erosion.	1.79	5.13
215	Kmn	Major gullying.	2.29	4.21
250	Kmn	Minor gullying sheet erosion.	.99	4.98
190	Jm Kmn	Major gullying minor sheet erosion.	2.51	14.53

Length of record (years)	Accuracy of records	Total sediment production (acre-ft/sq mile)	Ann. sediment production for period (acre-ft/sq mile)	Ann. sed. prod. adjusted for trap efficiency (acre-ft/sq mile)	Estimated long-term annual sediment production (acre-ft/sq mile)
(17)	(18)	(19)	(20)	(21)	(22)
12	g	11.66	0.97	1.9	1.9
11	g	10.00	.91	1.1	1.2
7	f	.94	.13	.5	.5
14	p	17.82	1.27	5.1	5.0
13	g	2.25	.17	.4	.4
13	f	18.80	1.45	2.9	2.9
12	g	11.48	.96	1.9	2.0
12	g	6.78	.56	1.1	1.0
13	g	1.45	.11	.11	.1
10	p	5.53	.55	2.2	2.2+
8	g	64.25	8.03	8.0	4.0+
12	g	1.38	.12	.12	.2
11	p	2.93	.27[d]	1.1	1.5+
11	g	2.22	.20	.4	.4
12	g	25.00	2.08	2.6	2.6

Table 5. --Comparison of sediment production from various rock types

Group classification (by lithology)	Reservoir no.	Geologic formation from which soils are derived. Symbol	Area of drainage basin (square miles)	Length of record (years)	Estimated long-term annual sediment production drainage area (ac-ft / sq mi)	Average annual sediment production for group drainage area (ac-ft / sq mi)	Remarks
Limestone, conglomerates, resistant sandstones	9	Conglomerates and siliceous shales of Morrison formation Jm	0.11	13	0.1	0.3	All structures except no. 12 are located in areas underlain by resistant bedrock with little or no soil mantle. Sediment contribution mainly from sheet erosion, gullying negligible. No deep accumulations of fill. Reservoir no. 12 located on Ferron sandstone with good soil cover. Sediment contribution from sheet wash which is minimized by sagebrush and grass covers.
	12	Ferron sandstone member of Mancos shale. Kmn	.13	12	.2		
	5	Limestone of lower Carmel formation. Jca	.80	13	.4		
	14	Gravel-capped pediment on Mancos shale. Kmn	.46	11	.4		
Friable sandstones	3	Sandstones of Entrada and Curtis formations Jecu	.10	7	.5	1.2	Reservoirs located in strike valleys cut in Curtis and Entrada sandstones. Soils are thin or absent with little vegetation. Many outcrops of bare sandstone form a large part of the drainage basins. Residual mantles of fine sand range in depth from a trace to 6 feet. Erosion mainly from sheet wash; gullying negligible.
	2	Sandstones and shales Curtis and Summerville formations. Jcus	.25	11	1.2		
	7	Entrada sandstone. Je	.54	12	2.0		
Shales and soft gypsum beds	8	Shales of upper Morrison formation. Jm	.14	12	1.0	2.6	Reservoirs located in wide shale valleys characterized by deep alluvial fills that are extensively gullied. Thin residual soils support limited vegetative cover of salt sage, grass and cedar trees. Shales weather so rapidly that rock itself is susceptible to sheet erosion. Interbedded shale and gypsum beds that underlie the drainage basin of no. 6 weather similar to shale with about the same rate of sediment production.
	13	Pediment and Mancos shale. Kmn	.99	11	1.5+		
	1	Lower Mancos shale. Kmn	.24	12	1.9		
	6	Morrison, Summerville, and Curtis formations. Entrada sandstone, shales and gypsum beds of upper Carmel formation. Jmscueca	.75	13	2.9		
	10	Mancos shale. Kmn	3.45	10	2.2+		
	4	Mancos shale. Kmn	.92	14	5.0		
	15	Mancos shale. Kmn Shales of Morrison formation. Jm	.34	12	2.6		
	11	Mancos shale. Kmn	.12	8	4.0+		

Column 22. Estimate of long-term sediment-production rate based on data on column 21, length of records, and accuracy of records.

RATES OF SEDIMENT PRODUCTION

As noted previously, erosion within any drainage basin is confined mainly to the surface mantle, the character of which is determined by the lithology of the rocks that underlie the area. Hence, drainage basins underlain by different types of rocks should exhibit marked differences in rates of sediment production. Table 4, column 22, shows that such a disparity does exist after corrections have been applied for differences in precipitation and for errors in quantitative measurements. The disparity, therefore, is largely attributed to differences in topographic relief or in geology as reflected by the character of the surface materials. Referring again to table 4, column 7, topographic relief has seemingly little direct effect on the rate of erosion as the two basins that have the highest and lowest rate of sediment production have the same maximum relief.

To examine the effect of geologic forces, the study reservoirs have been grouped in table 5 according to the lithology of the formations that underlie the drainage basins with each group arranged in increasing order of sediment-production rates. Such a classification shows a striking difference in the amount of sediment derived annually from each of the three groups. The third group, which consists mainly of shales, contributed almost twice the amount derived from friable sandstones and almost eight times the amount derived from conglomerates, limestones, and resistant sandstones. This classification has, however, the disadvantage that rates of sediment production cannot be assigned to formations that consist of several types of rock unless the area of outcrop can be determined for each rock type. It does have the advantage that a study of this nature can be expanded and possibly compared with similar studies in other areas. One such study in New Mexico and Arizona (Hains, Van Sickle, and Peterson, 1952) shows a remarkably close comparison of sediment-production rates from similar rock types in similar climatic environments. The comparisons are shown in table 6.

Table 6.—Comparison of sediment-production rates between New Mexico-Arizona and San Rafael Swell, Utah, for different rock types

Location	Conglomerates, limestones and resistant sandstones	Friable sandstones	Shales
New Mexico-Arizona	0.2-0.3	1.1	1.6
San Rafael Swell, Utah	.30	1.2	2.6

The lower sediment-production rate from shales in New Mexico and Arizona can be attributed to insufficient adjustment for sediment loss during reservoir spill. Actually trap efficiencies were not computed so that adjustments could only be approximated from field observations. To the extent that a much higher percentage of the clay particles derived from shales would be lost during spill than the coarser particles in groups 1 and 2, a closer agreement would be expected in the first two groups than in the third.

Unfortunately these studies have been limited to a few widely scattered basins in the intermountain region and little data on sediment-production rates are available for distinct lithologic groups. The comparisons shown in table 6, however, encourage further expansion of studies of this kind.

Although rates of sediment production have been shown to fall into three large groups, depending on the lithology of the rocks underlying the drainage basin, considerable variations exist within each group. Undoubtedly these smaller variations may be attributed to local conditions relative to slope, type of vegetative cover, grazing use, variations in rainfall, and other minor features. In the main, however, the ultimate controlling factor seems to be the amount and availability of erodible sediment within a drainage basin. As the amount varies greatly in areas underlain by different kinds of rock, these phases of the problem must be considered for each rock type, (1) the rate of weathering of the rock itself, (2) the character of the weathered material as reflected by inherent resistance to erosion or suitability as a medium for plant growth, (3) the amount of weathered material existing as residual soils or as alluvial fills that were deposited in old stream channels during some previous period and are now available for removal because of some change in environment that has lead to erosion rather than deposition.

Weathering of the hard, well-indurated conglomerates, limestones, and resistant sandstones of the first group is so slow under climatic conditions existing on the San Rafael Swell that individual particles can be removed by wind or water almost as rapidly as the rock weathers. In localities where thin soils have developed, however, a grass cover now retards sheet erosion to the extent that further soil development is taking place. Another factor that reduces sheet erosion on this rock type is the high infiltration rate afforded by the large average openings between the coarse particles in the weathered mantle or soils. Limited sheet erosion combined with an almost complete lack of gullying due to the absence of alluvial fills in the stream channels apparently accounts for the low rate of sediment production from this rock group.

Unfortunately, the actual area underlain by rocks of this group could not be determined, but a rough approximation would set the relative amount at 15 percent of the total area. Conglomerates of the Shinarump formation underlie a portion of the Sinbad area, but otherwise conglomerates are limited to the Salt Wash sandstone member of the Morrison formation and to the well-cemented gravel cappings on the pediment remnants extending from the Wasatch Plateau escarpment and Book Cliffs. Resistant sandstone members of the Moenkopi formation underlie a large part of the Sinbad and some resistant sandstones are found in the Mancos shale and as thin lenses in the Morrison formation. Limestones of the Moenkopi formation underlie the remainder of Sinbad, but otherwise limestones occur only as thin lenses in the Morrison formation and as one bed about 20 feet thick near the base of the Carmel formation.

In contrast to the resistant rocks of group 1, the friable sandstones of group 2 weather rapidly to produce surface mantles consisting primarily of rounded, individual sand grains with only minor amounts of silt and clay. Locally, sandy soils derived from this group are protected by an adequate vegetative cover, and sheet erosion is negligible, but once this cover becomes deteriorated, particles are easily moved downslope. Many bare sandstone outcrops together with local evidence such as hummocks and plant pedestals attest to the relative importance of sheet erosion on rocks of this type.

Rapid movement of surface materials into the stream channels with subsequent deposition of at least a portion of this sediment has resulted in relatively deep alluvial fills. Similar to their residual counterpart, alluvial fills derived from sandstones have very little resistance to erosion unless protected by an adequate vegetative cover. Once this cover is destroyed and gullying starts, fills of this nature are rapidly excavated producing abnormally high sediment rates until the fills are either removed or another cycle of deposition is effected. Unfortunately, no reservoirs were located in areas characterized by gullying in alluvial fills derived from sandstones of group 2, and no data are available for sediment-production rates from these areas. Nevertheless, it is the writers' contention that, if reservoirs had been located in these areas rather than in areas characterized by sheet erosion, much higher rates would have been obtained for group 2.

Although actual measurement of sediment-production rates from sandstones of group 2 was limited to basins underlain by the Entrada and Curtis formations, it is believed that these rates should be generally applicable to areas underlain by the Wingate and Navajo sandstones. Under this assumption nearly 35 percent of the surface area of the San Rafael Swell would be classified in this group.

Although about one-half the surface area of the San Rafael Swell is underlain by rocks of groups 1 and 2 this study would indicate that together they supply only about one-fourth of the total sediment contribution from the basin as a whole. The remainder of the sediment must, therefore, be derived from rocks of group 3. Field examinations in areas underlain by shales tend to confirm such a deduction, as rocks of this type are characterized by active sheet erosion that has locally dissected the surface into a miniature badland topography drained by well-developed gullies. The absence on these areas of a well-developed soil together with many plant pedestals and hummocks suggests that the removal of surface material by sheet erosion is as rapid today as it has been in the past. Nevertheless, shale outcrops with a slope of 30° or greater have a thin veneer of a few inches of weathered shale at the surface, and the more gentle slopes of 10° or less are often weathered to a depth of 1 to 2 feet. This would indicate that, although removal of the surface materials has almost kept pace with weathering, erosion has not been sufficiently active to remove all of the loose particles, and a seemingly unlimited amount of sediment could still be supplied by sheet erosion on rocks of group 3.

A more ready source of sediment exists, however, in the form of alluvial fills along the many channels that drain the extensive shale outcrops. Sheet erosion during the past has moved sediment into the channels and deposited it there as unconsolidated fills that were stable only so long as the upper surface was protected so that gullying could not start. At present most of these fills are in the stage of being removed, which may explain the abnormally high sediment production rates from these areas.

Rocks of group 3 consist primarily of shales of the Mancos and Morrison formations, which underlie most of the surface area on the west, north, and northeast portions of the Swell. Shales and gypsum beds of the Summerville, Carmel, and Chinle formations, although characterized by abnormally high sediment production rates, are only of minor importance because of their limited area of outcrop. Characteristics of the different formations are listed in further detail in table 1.

Thus far the study has been limited to a discussion of the rates of sediment movement from small drainage basins at the heads of tributary channels on the San Rafael Swell. Although detailed data on sediment movement from the entire area are not available, some general comparisons can be made between the relative sediment movement from the small study areas and from the San Rafael Swell as a whole.

Measurements of the sediment load transported by the San Rafael River were made in the 1947-48 and 1948-49 water years at Tidwell Ranch, near Green River, Utah, and give some indication as to the actual amount of sediment moved off the central, middle, and western portions of the Swell. These records are not representative of the long-term period, as precipitation during both years is below average for stations within this drainage. Nevertheless, they bring out a favorable comparison between the sediment movement into small upland reservoirs and the actual sediment movement out of the entire basin. The measured annual sediment-production rates from an area of 1 square mile varies from 0.30 acre-foot for group 1 to 2.6 acre-feet for group 3. On this basis the total annual sediment movement from the 1,690 square miles of drainage area above Tidwell near Green River would be expected to range from a minimum of 500 acre-feet to a maximum of 4,400 acre-feet. Actual measurements show 360 acre-feet and 1,140 acre-feet respectively for the water years of 1947-48 and 1948-49. The lower than expected actual sediment production for the 2 years of record may be attributed to below average precipitation during both of those years, but based on only 2 years record, it seems hardly possible to formulate any definite conclusions.

Further analysis of the 2 years of record shows that about half this total sediment movement occurred during the period of normal spring runoff from March to June. As the major part of this runoff is supplied by snowmelt on the Wasatch Plateau and only a minor amount comes from snowmelt on the Swell, the bulk of this sediment must be derived from the Wasatch slopes or from the main channel of the river where it crosses the Swell. Field observations on tributary channels as they cross Utah State Highway 10 near the foot of the Wasatch escarpment showed clear streams with low-sediment concentrations. Therefore, the major source of sediment at least during spring runoff probably is from deposits in and bordering the main channel of the San Rafael River. Following this conclusion, future studies on the San Rafael Swell should be made with particular emphasis on (1) the amount of erodible sediment in and bordering the main channels, (2) the manner of occurrence and character of the materials, and (3) the amount of sediment stored in the main channels following periods of runoff in response to local summer storms that are of sufficient magnitude to cause movement of sediment into the main channels, but not out of the basin.

SUMMARY AND CONCLUSIONS

Measurement of rates of sedimentation in a group of small reservoirs on the San Rafael Swell, Utah, offers a possible method for evaluating the relative production of sediment from areas having distinct, but different, erosional characteristics. Once the relative importance of erosional features such as slope, vegetation, land use, geology, and precipitation can be determined, areas of greatest potential sediment production can be delineated. This is a requisite for any future program of land treatment in the Colorado River basin designed for sediment abatement.

After adjustment for sediment loss during reservoir spill and for drainage area effect, measured rates of sedimentation in selected small reservoirs were converted into long-term estimates of sediment production. Suitable adjustments were made for differences in precipitation, condition of the drainage area, and other factors influencing sedimentation during the life span of the reservoir as compared with conditions that might be considered normal.

Reservoirs were divided into three groups based on the lithology of rocks underlying their respective drainage basins. Listed in order of increasing sediment production, they are (1) conglomerates, limestones, and resistant sandstones, (2) friable sandstones, and (3) shales and gypsum beds. The difference in the amount of sediment produced from the various groups is striking, being two to eight times as much from the shales and friable sandstones as from the resistant rocks of group 1. Variations within groups were comparatively small, undoubtedly reflecting the effects of slope, vegetative cover, and land use, but no definite relationship could be determined from the available data between sediment production and the latter named factors.

On the basis of group averages, the annual sediment production from the San Rafael Swell would range between 0.3 acre-foot per square mile for areas underlain by the rocks of group 1 to 2.6 acre-feet per square mile for areas underlain by the rocks of group 3. Hence, the average annual sediment production from the San Rafael River drainage basin above Tidwell, Utah, an area of about 1,690 square miles, would be expected to range from a calculated minimum of 500 acre-feet to a maximum of 4,400 acre-feet. Sediment records for the 1947-48, 1948-49 water years, show 360 acre-feet and 1,200 acre-feet respectively based on a conversion factor of 1,500 tons per acre-foot. Further analysis of these records shows that about one-half of this amount occurred during May and June as a result of normal spring runoff. But as nearly all spring runoff is supplied by snowmelt in the mountains, the bulk of this sediment must be obtained from the main channel rather than from tributary channels. These figures show what differences can be expected between upland rates of sediment removal at a particular period and the concurrent rate of transportation of sediment at downstream points of major streams.

These reservoirs have been monumented for repeat surveys, and it is recommended that further studies include the main channels on the San Rafael Swell with particular emphasis given to (1) amount of sediment in the form of old alluvial fills that are now available to erosion, (2) manner of occurrence, and (3) amount of sediment stored in main channels following runoff in response to high-intensity summer storms.

LITERATURE CITED

Andrews, D. A., and Hunt, C. B., 1948, Geologic map of eastern and southern Utah: U. S. Geol. Survey Oil and Gas Investigations, Preliminary Map no. 70.

Baker, A. A., 1946, Geology of the Green River Desert-Cataract Canyon region, Emery, Wayne, and Farfield Counties, Utah: U. S. Geol. Survey Bull. 951.

Gilluly, James, 1928, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806-C, p. 69-130.

Hains, C. F., Van Sickle, D. M., Peterson, H. V., 1952, Sedimentation rates in small reservoirs in the Little Colorado River basin: U. S. Geol. Survey Water-Supply Paper 1110-D, p. 129-155.

Hunt, C. B., and others, 1952, Geologic map of the Henry Mountains region, Utah: U. S. Geol. Survey Oil and Gas Investigations, OM 131.

INT.-DUP. SEC., WASH., D.C. 44849