Factors Contributing to Unusually Low Runoff During the Period 1962-68 in the Concho River Basin, Texas

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1999-L

Prepared in cooperation with the Texas Water Development Board

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By STANLEY P. SAUER

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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FACTORS CONTRIBUTING TO UNUSUALLY LOW RUNOFF DURING THE PERIOD 1962-68 IN THE CONCHO RIVER BASIN, TEXAS

By STANLEY P. SAUER

ABSTRACT

To determine the reasons for the unusually low runoff in the Concho River basin during the period 1962–68, the physical developments and climatic changes in the basin were identified and related to changes in the regimen of streamflow.

Land use, brush infestation, and land-treatment practices have not caused significant changes in the rainfall-runoff relationship.

The use of surface water for irrigation has increased very little during the past 70 years, and although the use of ground water for irrigation has greatly increased in the past 25 years, springflow has not been significantly diminished. The base flow of the streams is materially reduced by surface-water irrigation diversions. Diversions for municipal and industrial use have increased rapidly, but these diversions affect only the streamflow downstream from San Angelo.

Statistical analyses showed the annual rainfall to be highly variable, with little serial correlation. Records of rainfall during the period 1943-68 are significantly different in character from previous long-term records. The frequency of monthly rainfall equal to or greater than 2.0 inches during the period 1943–68, and especially during the period 1962–68, was significantly less than the long-term averages.

Analyses of annual runoff data, adjusted for depletions, show large variations in annual runoff. Coefficients of variation ranged from 0.8 to 1.4, and first-order serial correlations ranged from 0.01 to 0.28. The estimated recurrence interval of the 1962–68 drought is about 200 years.

The analyses of rainfall-intensity and runoff data indicate that the basic cause for the relatively low runoff during the period 1962–68 was the lack of high-intensity, long-duration storms rather than any physical changes or agricultural practices in the watershed.

INTRODUCTION

ACKNOWLEDGMENTS

The author is indebted to many private citizens and public officials and to various county, State, and Federal agencies for providing information used in this report. The information furnished by Mr.

Bryant Williams and Mr. Fred Ball of San Angelo and Mr. Elton Mims of Water Valley was especially helpful. Special acknowledgment is due to the Soil Conservation Service personnel in the San Angelo Area office and in the Work Units at San Angelo, Sterling City, Big Lake, and Eldorado. The Texas Water Development Board, the Texas Water Rights Commission, and the county agents of Tom Green, Irion, and Sterling Counties furnished valuable information.

PURPOSE AND SCOPE OF THE STUDY

Surface-water runoff in the Concho River basin was below average in each of the 7 years of the period 1962–68. During this period, runoff averaged only 6 to 40 percent of the long-term mean at streamflow stations in the basin.

Two large multipurpose reservoirs in the basin have not yielded a water supply of the magnitude to be expected from designs based on long-term Geological Survey streamflow records dating back to 1916. Twin Buttes Reservoir, completed in 1963, had not impounded any appreciable amount of water by the end of 1968, and the water in San Angelo Reservoir, completed in 1952, was much below the conservation outlet.

The purpose of this study was to determine the cause of the below-average runoff by analyzing all available records on streamflow, precipitation, evaporation, and land and water use.

Data on land and water use were collected from many sources. Methodology was developed to adjust historical streamflow records for the effects of man's activities, and statistical analyses of rainfall and runoff data were used to determine the recurrence probability of the drought.

DESCRIPTION OF THE BASIN

This report is concerned with the part of the Concho River basin that is upstream from the stream-gaging station Concho River near San Angelo (fig. 1), in Upton, Glasscock, Reagan, Sterling, Irion, Crockett, Coke, Tom Green, and Schleicher Counties, Texas.

This part of the basin has maximum dimensions of about 80×100 miles and an area of approximately 5,380 square miles, of which 1,280 square miles is probably noncontributing to surface runoff. The locations of hydrologic instruments are shown in figure 1.

The lowermost part of the basin (approximately 10 percent) is in the Rolling Plains land-resources area (fig. 1), which is characterized by deep soils and fairly level topography (U.S. Soil Conservation Service, 1959). Most of the basin (approximately 90 percent) is in the Edwards Plateau area (fig. 1), which is characterized by rolling to rough topography. Soils are a foot or more thick in the gently rolling areas, but they are almost nonexistent on the

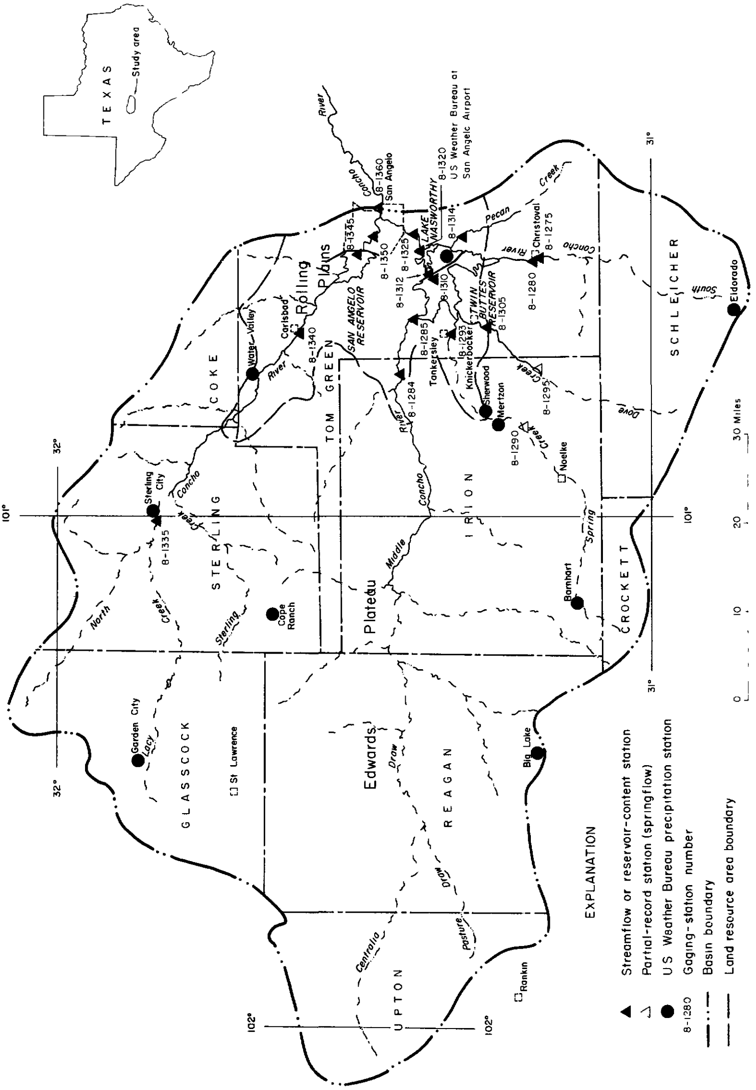


FIGURE 1.—Location of hydrologic instruments in the Concho River basin upstream from San Angelo. Base from U.S. Geological Survey State map. 1 : 500,000.

steep slopes. The rocks underlying the soil in many places are highly fractured limestones. Because of the topography, soils, and underlying rocks, low-intensity precipitation is generally absorbed without surface runoff.

The climate is subhumid to semiarid. Average annual precipitation ranges from about 20 inches at the eastern edge of the basin to about 15 inches at the western edge, with a fairly uniform decrease from east to west (Carr, 1967). Year to year variation in precipitation is large; annual totals have generally ranged from 5 to 40 inches. Average annual temperature is about 67°F. Average-annual net lake evaporation (gross evaporation less precipitation) is about 66 inches per year (Kane, 1967). According to Griffiths and Orton (1968), the probability of receiving 35 inches or more of precipitation in a year in this basin is about 3 percent, while the probability of receiving more than 40 inches of precipitation is less than 1 percent.

FACTORS CAUSING DEPLETION OF RUNOFF

LAND USE

Very few of man's efforts to develop a watershed tend to increase runoff. Increased cultivation, with associated land-treatment measures, tend to reduce runoff. It is, therefore, appropriate to review the land use in the basin to determine whether or not there have been developments that could significantly change the relationship between rainfall and runoff.

In determining land use in the basin, many publications (see "References Cited") and unpublished reports were reviewed. In addition, data were obtained from many local citizens and public officials and from the files of the Texas Water Development Board, the Texas Water Rights Commission, the Soil Conservation Service, and the Agricultural Stabilization and Conservation Service.

Aerial and on-the-ground inspections of the basin were made during the week of September 30–October 3, 1968, and again during the week of May 12–16, 1969. The aerial survey during May covered the entire basin.

Most of the land in the Concho River basin is used for ranching, and much of the area is in ranches exceeding 10,000 acres. The only metropolitan area of consequence is the city of San Angelo, which had an estimated 1965 population of 69,500. Excluding the city of San Angelo, population density in the basin is about two persons per square mile.

Early accounts of the condition of the range indicate a lush stand of grass prior to the time of settlement, which began after the Civil

War with the establishment of Fort Concho in 1867, at the site of the present city of San Angelo. The area was open range until about 1900, after which homesteading began. Overstocking and drought seriously depleted the range, especially in the 1930's. While early accounts speak of lush grass and perennial streams, they also speak of disastrous drought, which is a common occurrence in this climatic region.

Grazing practices are now much better than they have been in the past. The efforts of conservationists have been effective in pointing out the long-range dangers of overgrazing, and as a result, the range is in better condition than it was from 10 to 30 years ago. Although ground cover is fairly good, thereby tending to retard runoff, this condition alone cannot be responsible for the very low runoff observed in recent years.

Information compiled from the U.S. Census of Agriculture and the U.S. Census of Irrigation indicate no drastic changes in land use. Total irrigated land comprises less than 1 percent of the study area. Cropland irrigated by surface water totals 0.13 percent of the watershed. The acreage under cultivation has declined since 1950, and total cropland in the study area is estimated at not more than 3 percent of the total land area. Therefore, it may be assumed that developments in cultivated land use have not significantly affected the total runoff into downstream reservoirs.

BRUSH INFESTATION

About 33 percent of the total area of Glasscock, Irion, Reagan, Schleicher, Sterling, Tom Green, and Upton Counties is covered with a heavy growth of brush, principally cedar and mesquite. The cedar infestation is primarily in the shallow soils on the hillsides and ridges of the Edwards Plateau. Mesquite is predominant in the deep soils of the Rolling Plains but has gradually encroached upon much of the rest of the basin.

Brush infestation has been a problem since early settlement. For example, the North Concho River Soil and Water Conservation District 208 (1967) work plan quotes excerpts from a letter by Mr. David Williams, who settled on the North Concho River about 4 miles above Water Valley in 1879 and described range conditions at that time as having considerable brush cover in the deep soils of the river valleys.

Aerial photographs of the watershed were inspected and compared to identify changes in brush cover. The latest aerial photographs, dating from 1964 to 1968, were compared with photographs dating back to 1938. From these comparisons, it is obvious that brush infestation is not a new problem. Although there has been some increase in the density of brush cover in recent years, particularly in the deeper soils, no significant changes were noted. Efforts to control and reduce brush infestation through the programs of the Agricultural Stabilization and Conservation Service and Great Plains Conservation Program have met with varied success. As of July 1968, according to information in the files of the U.S. Soil Conservation Service, San Angelo Area Office, brush control measures had been applied to approximately 15 percent of the watershed. However, a considerable part of this area has been reinfested.

Many people engaged in agriculture feel very strongly that low-runoff conditions are caused to a large degree by brush infestation. They feel that if the brush were cleared off and replaced with grasses, more water would be available for infiltration to the ground-water reservoir and that streams would become perennial, yielding large quantities of clear, sediment-free water. However, because potential evapotranspiration is large compared to the average annual precipitation, it is unlikely that brush eradication would significantly increase total runoff. The small increase in brush infestation in recent years is not considered a major factor in causing low runoff during the period 1962–68.

LAND-TREATMENT PRACTICES

Land treatment refers to any practices for the conservation of land and water on farms and ranches, including deferred grazing, contour farming, terracing, and the construction of diversion ditches and stock ponds. Although the long-term effects are not known, there is ample evidence to conclude that most conservation practices tend to reduce surface runoff.

Terracing cultivated land and constructing diversion dikes is a conservation practice recommended by the Soil Conservation Service. It is estimated on the basis of aerial surveys and personal interviews that no more than 6 percent of the contributing area of the basin is drained through terraces or diversion dikes.

The construction of farm ponds for sediment control and livestock water supply is a recommended practice. However, the number of farm ponds in the basin is quite small because reservoirs in much of the Edwards Plateau area do not hold water. Runoff is so meager and erratic that farm ponds do not provide a dependable water supply. On the basis of information by U.S. Bureau of Reclamation (1960) and on the basis of aerial photographs, aerial reconnaissance, and personal interviews, it is estimated that drainage from not more than 8 percent of the area in the basin is intercepted by ponds and minor reservoirs, most of which were constructed during the period 1936–45.

Numerous channel dams have been constructed for diversion works and recreation facilities in the Concho River basin. According to information in the files of the Texas Water Rights Commission, permits have been issued for 41 channel dams, with a total conservation storage capacity of 6,240 acre-feet, in the basin above the gaging station Concho River near San Angelo. Recent aerial photographs verify this number of channel dams in the basin. Many of the irrigation canals and channel dams on Dove Creek, Spring Creek, and the South Concho River inspected in May 1969 were apparently quite old, indicating very little if any recent construction.

From information given in this section, it may be concluded that although land-treatment practices may have reduced surface runoff, they cannot be considered as a major cause of the unusually low runoff during the period 1962–68. Quantitative estimates of runoff depletion attributable to land-treatment measures are given in a later section of this report. (See table 6.)

GROUND-WATER USE

The use of ground water for irrigation in the Concho River basin has increased substantially in the last 25 years, with most of the developments being in the level upland areas of Glasscock, Reagan, and Upton Counties. The number of ground-water wells in relation to the amount of land irrigated during the period 1909–64 is shown in figure 2. Land irrigated with ground water increased from 22,000 acres in 1958 to 47,900 acres in 1964 according to Gillett and Janca (1965). The land area irrigated from ground water in the shallow alluvium along the streams is estimated to not exceed 2,500 acres.

Much of the Concho River basin is underlain by the Edwards and associated limestones. The basal sands in this group of rocks form the regional aquifer, known as the Edwards-Trinity (Plateau) aquifer. Ground water is naturally discharged through numerous springs along the dissected border areas of the plateau, where stream valleys have been cut down to the aquifer, or where they are connected to the aquifer through fractures in the limestone (Blank and others, 1966).

Springflow data were compiled for two stations in the Concho River basin (South Concho River at Christoval and Dove Creek Springs near Knickerbocker) and for four other stations, outside the Concho River basin, that receive substantial springflow from the Edwards and associated limestones (8–1445, San Saba River at Menard; 8–1485, North Llano River near Junction; 8–1500, Llano River near Junction; and 8–4490, Devils River near Juno). The four stations outside the basin are in an area extending from about

50 miles southeast to 85 miles south of San Angelo.

Information was compiled only for the months of December, January, and February of each year because during these months,

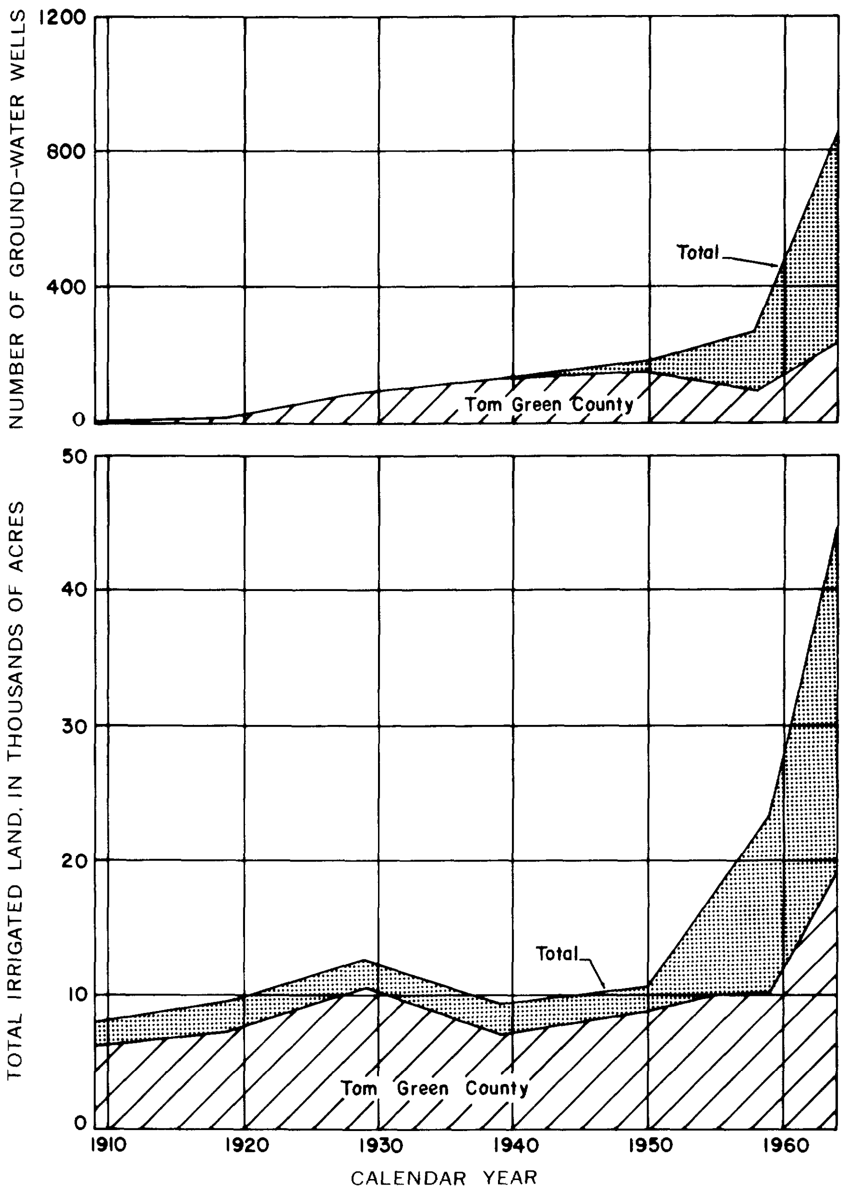


FIGURE 2.—Ground-water wells and total irrigated land, 1909–64. Note: Totals are for Glasscock, Irion, Reagan, Schleicher, Tom Green, and Upton Counties. Sources of data: U.S. Census of Agriculture, U.S. Census of Irrigation, and Gillett and Janca (1965).

measured flow is least affected by diversions for irrigation and evapotranspiration losses are at a minimum. Storm runoff was eliminated at each site. The value of average daily discharge for these 3 months of each year is a measure of the maximum amount of springflow.

The results of the springflow study are given in figure 3, which shows that springflow varied directly with annual rainfall and that base flow in the Concho River basin was not significantly different from base flow in the streams used for comparison. Springflows were generally higher during the period 1962–68 than during the severe drought period 1950–56.

Ground-water observation wells in Sterling County have not shown any large declines in water levels; therefore, ground-water withdrawals should not have affected springflow in the North Concho River to any great extent.

Municipal and industrial use of ground water in the basin is minor. According to reports submitted to the Texas Water Development Board, total municipal and industrial use of ground water in seven counties in the basin averaged about 3,000 acre-feet per year from 1955 through 1967.

It is concluded that the increase in the use of ground water for irrigation and for municipal and industrial supply has not materially reduced springflow in the Concho River basin and is therefore not a contributing factor to the unusually low runoff during the period 1962–68.

SURFACE-WATER USE

Surface water is used in the Concho River basin for irrigation and municipal supply. As of 1969, the only municipal use was by the city of San Angelo, and although diversions by the city have greatly increased (fig. 4), only the streamflow downstream from San Angelo is affected.

Surface-water irrigation has been practiced in the Concho River basin since before 1900. Settlement along the spring-fed streams began about 1870 and irrigation along Spring Creek, Dove Creek, and the South Concho River was developed to near full potential by 1900. The earliest authentic account of irrigation in the basin was by Taylor (1902), which included a detailed description of the irrigation ditches and diversion works. Most of the facilities described by Taylor are still in use today.

The latest detailed survey of irrigation (1958 and 1964) are reported by Gillett and Janca (1965). A comparison of irrigated acreage in 1900, 1958, and 1964 is given in table 1, which shows that the total acreage irrigated by surface water in 1964 was almost the same

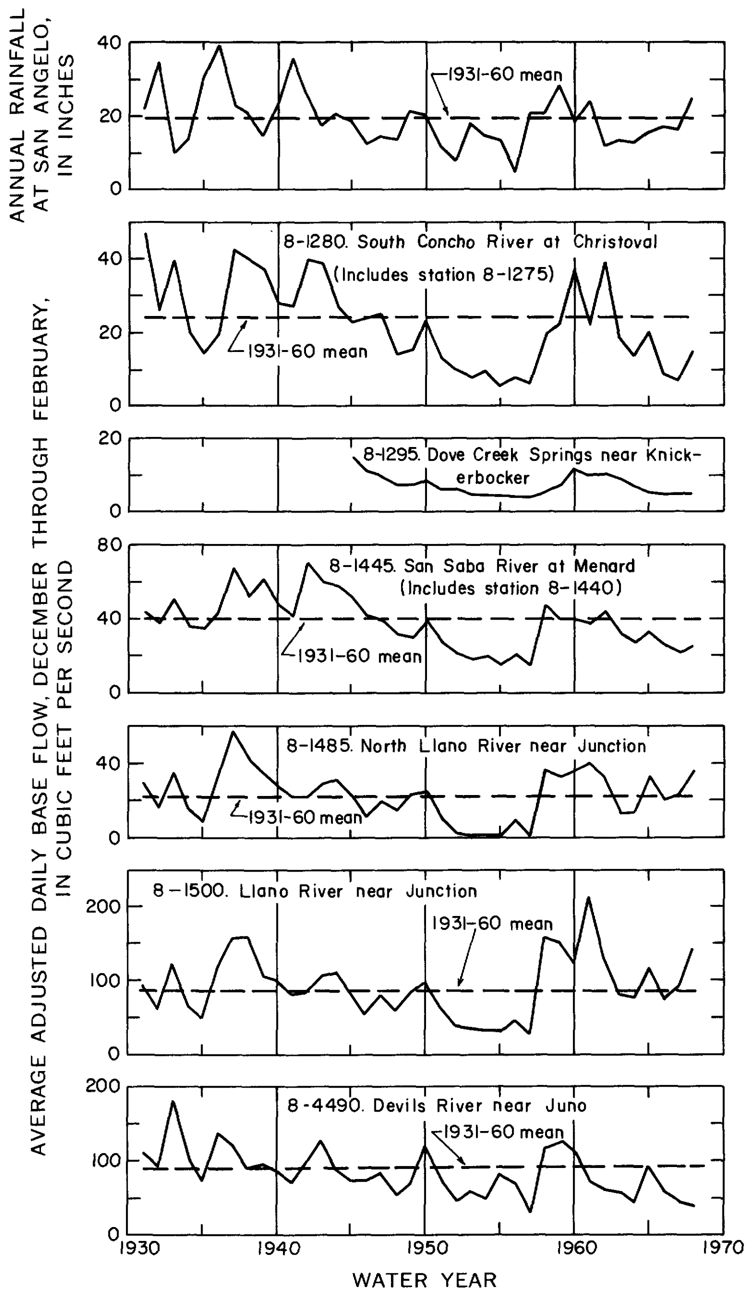


FIGURE 3.—Springflow from the Edwards and associated limestones at selected stream-gaging stations in west-central Texas and annual rainfall at San Angelo, 1931–68.

as in 1900. Almost all surface-water irrigation in the basin is in Tom Green and Irion Counties.

Because the use of surface water for irrigation has increased very little in the last 70 years, these diversions cannot be considered as a major cause of low runoff during the period 1962–68.

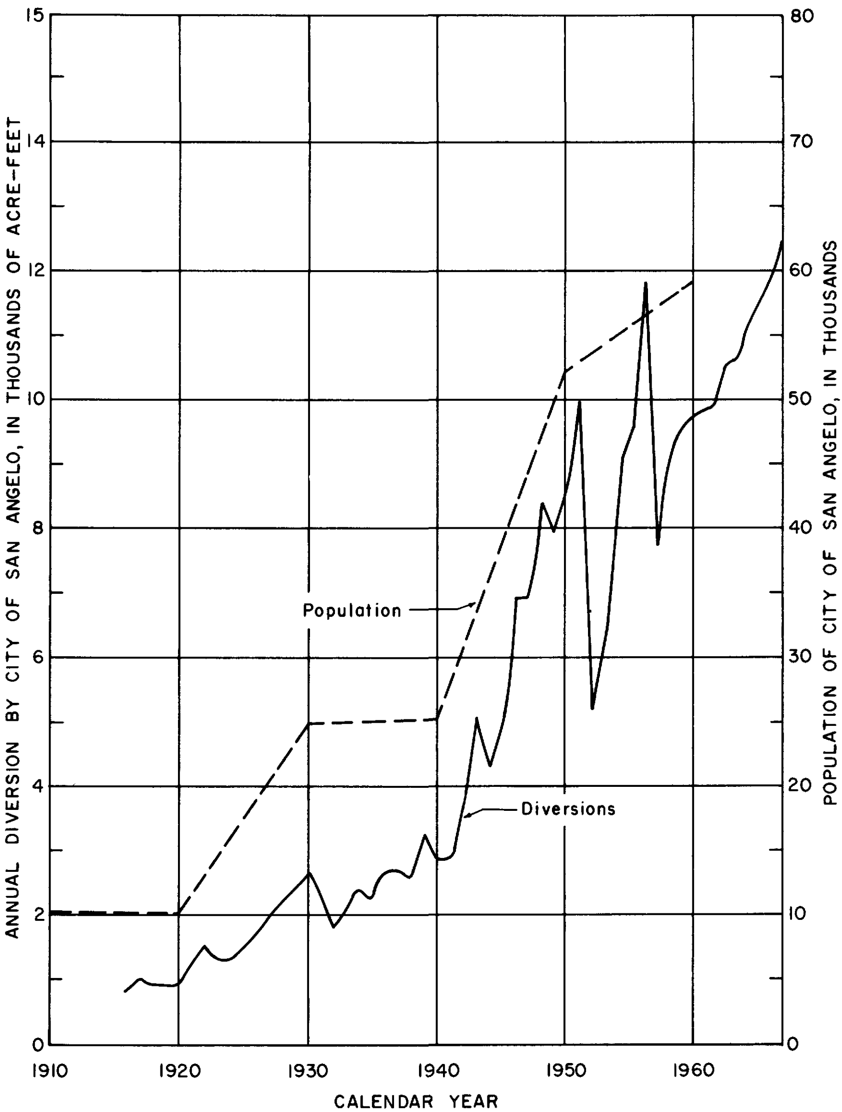


FIGURE 4.—Changes in population and surface-water use in the city of San Angelo. Sources of data: City of San Angelo and U.S. Census of Population.

TABLE 1.—*Comparison of acreage irrigated by surface water in the Concho River basin in 1900, 1958, and 1964*

[Compiled from Taylor (1902), Gillett and Janca (1965), and from information in the files of the Texas Water Development Board]

Station		Acres irrigated by surface water above indicated station		
		1900	1958	1964
8-1280.	South Concho River at Christoval	[1]50	50	50
1285.	Middle Concho River near Tankersley	0	200	0
1310.	Spring Creek near Tankersley	2,495	3,040	3,139
1312.	Twin Buttes Reservoir near San Angelo	3,905	4,085	3,876
1340.	North Concho River near Carlsbad	345	149	51
1360.	Concho River near San Angelo	4,340	4,904	4,362

[1] Acreage is estimated. Taylor (1902) notes an irrigation ditch but does not report the acreage.

ANALYSES OF RAINFALL DATA

AVAILABLE DATA

The earliest reliable rainfall records in the area date back to 1868 with records collected by the U.S. Army at Fort Concho. The location of stations and descriptions of long-term rainfall records used in this report are given in table 2. Rain-gage density is sparse, but the network established in 1940 increased the coverage significantly. Although records have been collected at other sites in the basin, only the records that were reasonably complete were used. At several locations, records from two or more stations were combined to develop a continuous record.

TABLE 2.—*Location of stations and description of long-term rainfall records*

Location	Period	Remarks
Barnhardt–Big Lake	1940–68	Barnhardt and Big Lake stations combined.
Cope Ranch	1940–68	
Eldorado	1940–68	Combination of records for three stations in the vicinity of Eldorado.
Garden City	1913–68	
San Angelo	1868–1968	Early records are for Fort Concho. Records for 1889–1903 estimated on basis of records for Fort McKavett; other short periods based on nearby stations.
Sherwood–Mertzon	1940–68	Sherwood and Mertzon stations combined.
Sterling City	1926–68	
Water Valley	1940–68	

STATISTICAL CHARACTERISTICS OF ANNUAL DATA

Rainfall is a random variable, subject to fluctuations in atmospheric circulation, that cannot be predicted far in advance except in terms of probability. Much time and effort has been spent in hydrology in searching unsuccessfully for deterministic cycles in weather. In a detailed statistical analysis of annual rainfall records in southwestern Texas, Friedman (1957) found no regularly occurring wet and dry cycles. He found no statistically significant trends and found serial correlation between successive values of annual rainfall to be negligible. Serial correlation, or dependence, described numerically by the serial correlation coefficient, is a measure of the degree of association between events 1 or more years apart. Correlation between events 1 and 5 years apart are described by the first- through fifth-order serial correlation coefficients, respectively.

SAN ANGELO RAINFALL DATA

As a first step in the analysis of rainfall data, records for San Angelo were checked to determine whether or not rainfall during the period 1962–68 differed significantly from the long-term mean. Sufficient data were obtained to establish a reasonably accurate record of rainfall for 100 years (table 2). In all cases, missing records were estimated on the basis of the closest available data.

Annual rainfall data, with 3, 7, and 11-year moving averages, are shown in figure 5. Accumulated departure from the record mean is shown in figure 6. The frequency distribution of annual rainfall for this yeriod is shown in figure 7. The statistical parameters of the 100 years of record are as follows:

1. Mean $(\bar{x}) = 20.62$ inches.
2. Standard deviation $(s_x) = 7.94$ inches.
3. Coefficient of variation $(C_v) = 0.38$.
4. Coefficient of skew $(C_s) = 0.68$.
5. First- through fifth-order serial correlation coefficients (r_1 through r_5) $= 0.18, -0.03, -0.05, 0.08$, and 0.13, respectively.

The first five serial correlation coefficients are within the 95 percent confidence limits for a random sample.

On the basis of the statistics and data shown in figures 5–7, the following conclusions may be reached in regard to the 100-year sample of rainfall at San Angelo:

1. Annual rainfall is highly variable, with serial dependence no greater than would be expected from a random sample. No cycles are evident.
2. The rainfall record since 1943 differs markedly from the record prior to 1943. Since 1943, annual rainfall was greater than the recorded mean of 20.62 inches only in 1949, 1957, 1959, 1961, and 1968. Since 1943, annual rainfall was greater than the 1869–1942 mean of 22.06 inches only 1949, 1959, 1961 and

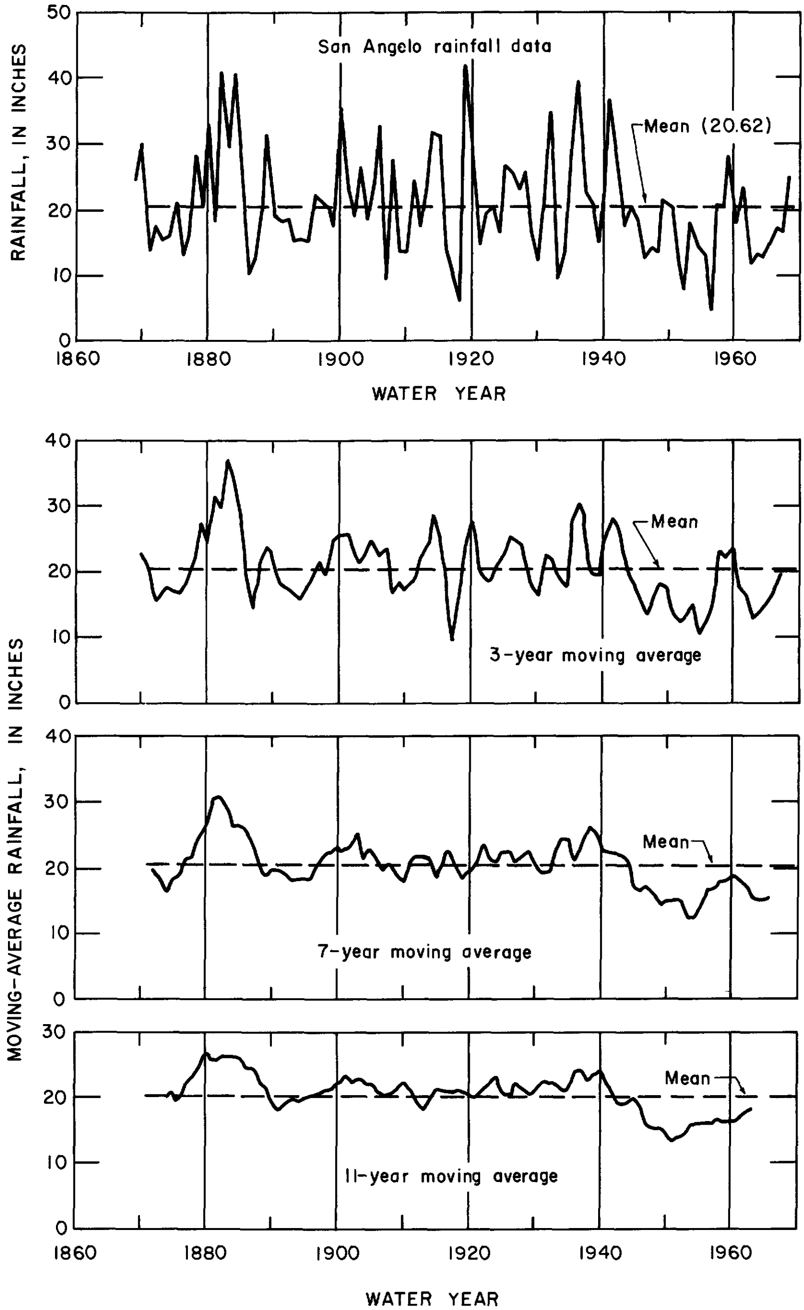


FIGURE 5.—San Angelo rainfall data, annual and 3, 7, and 11-year moving averages, water years 1869–1968.

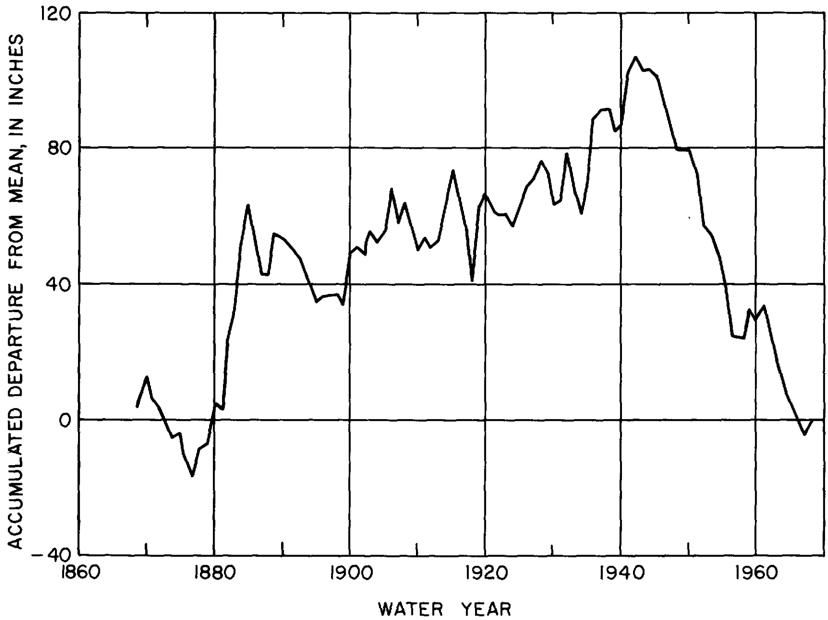


FIGURE 6.—Accumulated departure from mean-annual rainfall at San Angelo, water years 1869–1968.

1968. Maximum annual rainfall since 1943 was 28.17 inches in 1959. Annual rainfall in the basin during the period 1943–68 averaged approximately 75 percent of the long-term annual rainfall prior to 1943. A 25-percent decrease in average annual rainfall results in tremendous changes in the hydrologic regimen of a watershed, particularly in a semiarid zone.

3. The great Southwest drought of 1942–56, which Thomas (1962, 1963) describes at length, apparently has not ended in the vicinity of San Angelo.
4. If the data for period 1943–68 is representative of future conditions, then rainfall during the last 7 years was not particularly unusual.
5. The period 1931–42 was a comparatively wet period. (See comparison of various periods in table 3.)

OTHER RAINFALL DATA

Rainfall records dating back to 1915 were studied for three additional long-term stations, Ballinger, Fort Stockton, and Garden City, in west-central Texas. Garden City is shown in figure 1. Ballinger is located 35 miles northeast and Fort Stockton is located 150 miles west-southwest of San Angelo.

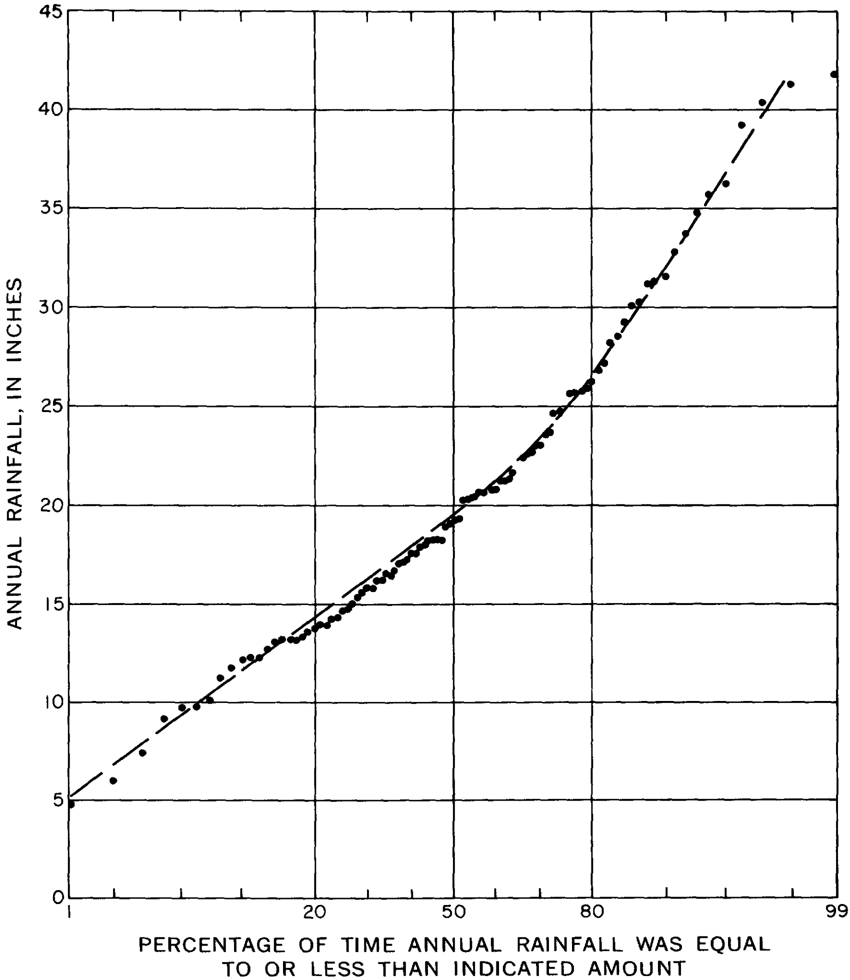


FIGURE 7.—Cumulative frequency distribution of annual rainfall for San Angelo, water years 1869–1968.

TABLE 3.—*Comparison of average annual rainfall for various periods*

Period (water yr)	Number of years	Average annual rainfall (in.)
1869–1968	100	20.62
1869–1942	74	22.06
1916–68	53	19.22
1931–68	38	18.95
1931–60	30	19.49
1931–42	12	24.23
1943–68	26	16.51
1962–67	6	14.42
1962–68	7	15.94

A comparison of average annual (calendar year) rainfall for various time intervals at the four locations is tabulated below:

Location	Average annual rainfall (in.) 1915–42	1943–67	1963–67
Ballinger	23.9	19.6	20.6
Fort Stockton	14.9	11.5	11.0
Garden City	18.5	14.6	14.2
San Angelo	22.1	16.1	15.6

This data indicates the character of rainfall at other long-term stations in the region was similar to that at San Angelo.

WEIGHTED-MEAN RAINFALL

Weighted-mean rainfall was computed for the entire basin and for each major subwatershed. The periods used in the computations for each area coincide with the periods of available streamflow records. Computations of mean rainfall were based on the standard Thiessen polygon weighting procedure, utilizing rainfall records for stations listed in table 2. The weight factor for each station was based on contributing parts of the watershed only, although it is recognized that rainfall on the noncontributing areas is important for ground-water recharge.

As would be expected, the weighted-mean rainfall exhibits statistical characteristics very similar to those at San Angelo. The statistical characteristics of the annual weighted-mean and station rainfall are shown in table 4. Three-year moving averages of weighted-mean rainfall for various locations for 1931–68 are shown in figure 8. The mean for 1931–60 is shown for comparison in each case. The 30-year period (1931–60) is currently used as the "normal" period by the U.S. Weather Bureau, although the increment of time is a calendar year.

Accumulated departures from the 1931–60 mean for the period 1931–68 are shown in figure 9. These illustrations (figs. 8 and 9) show a pattern similar to that shown in figure 6 for San Angelo. Departures from the mean are much more pronounced during the 1950–56 period than during any other period. This drought is generally believed to be the worst in at least 100 years (Lowry, 1959). These illustrations also show generally below average rainfall for the period 1962–68.

Storm rainfall characteristics dominate the rainfall-runoff process in most rural areas; therefore, annual rainfall totals are not necessarily the best indicators of potential storm runoff. However, it is axiomatic that above average runoff will not usually occur during an extended period of years of below average rainfall. Storm runoff is exponentially related to rainfall; therefore, in general, above average rainfall is required to produce average runoff.

TABLE 4.—*Statistical characteristics of annual weighted-mean rainfall and individual station rainfall*

Station	Period (water yr)	Mean (inches) ($\bar{x}$)	Coefficient of variation C_v	Coefficient of skew C_s	First-order serial correlation coefficient r_1
U.S. Weather Bureau individual station:					
Barnhardt–Big Lake	1941–68	16.55	0.35	0.60	0.28
Cope Ranch	1941–68	15.81	.36	.81	.26
Eldorado	1941–68	18.63	.34	.36	.17
Garden City	1916–68	16.65	.37	.56	.18
San Angelo	1916–68	19.22	.41	.81	.21
Sherwood–Mertzon	1941–68	17.91	.39	.70	.39
Sterling City	1927–68	19.81	.36	1.14	.10
Water Valley	1941–68	17.72	.35	.22	.23
U.S. Geological Survey gaging station (weighted-mean rainfall):					
8–1280. South Concho River at Christoval	1931–68	19.56	.38	.68	.23
1285. Middle Concho River near Tankersley.	1931–68	17.60	.36	1.12	.23
1310. Spring Creek near Tankersley	1931–68	19.03	.39	.73	.29
1312. Twin Buttes Reservoir near San Angelo.	1931–68	18.26	.37	.85	.24
1340. North Concho River near Carlsbad.	1925–68	18.45	.35	.90	.17
1360. Concho River near San Angelo	1916–68	18.40	.35	.69	.20

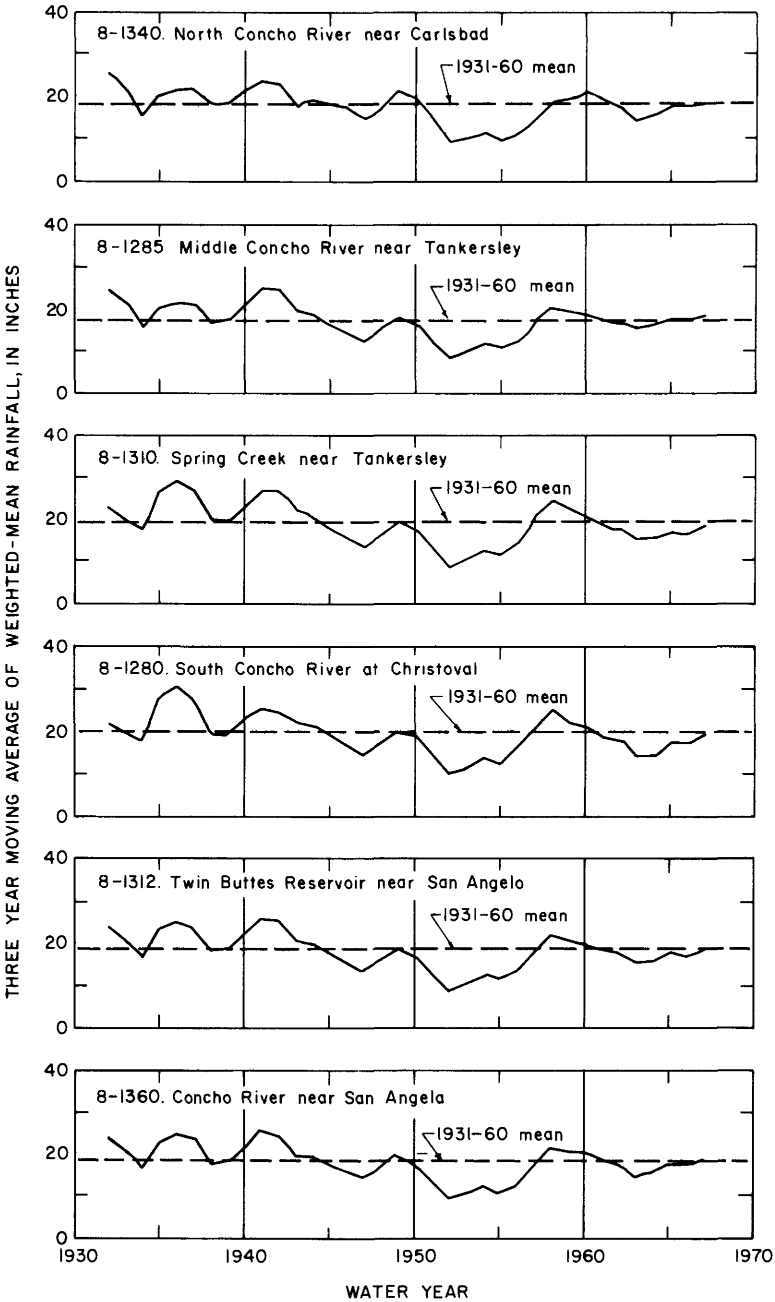
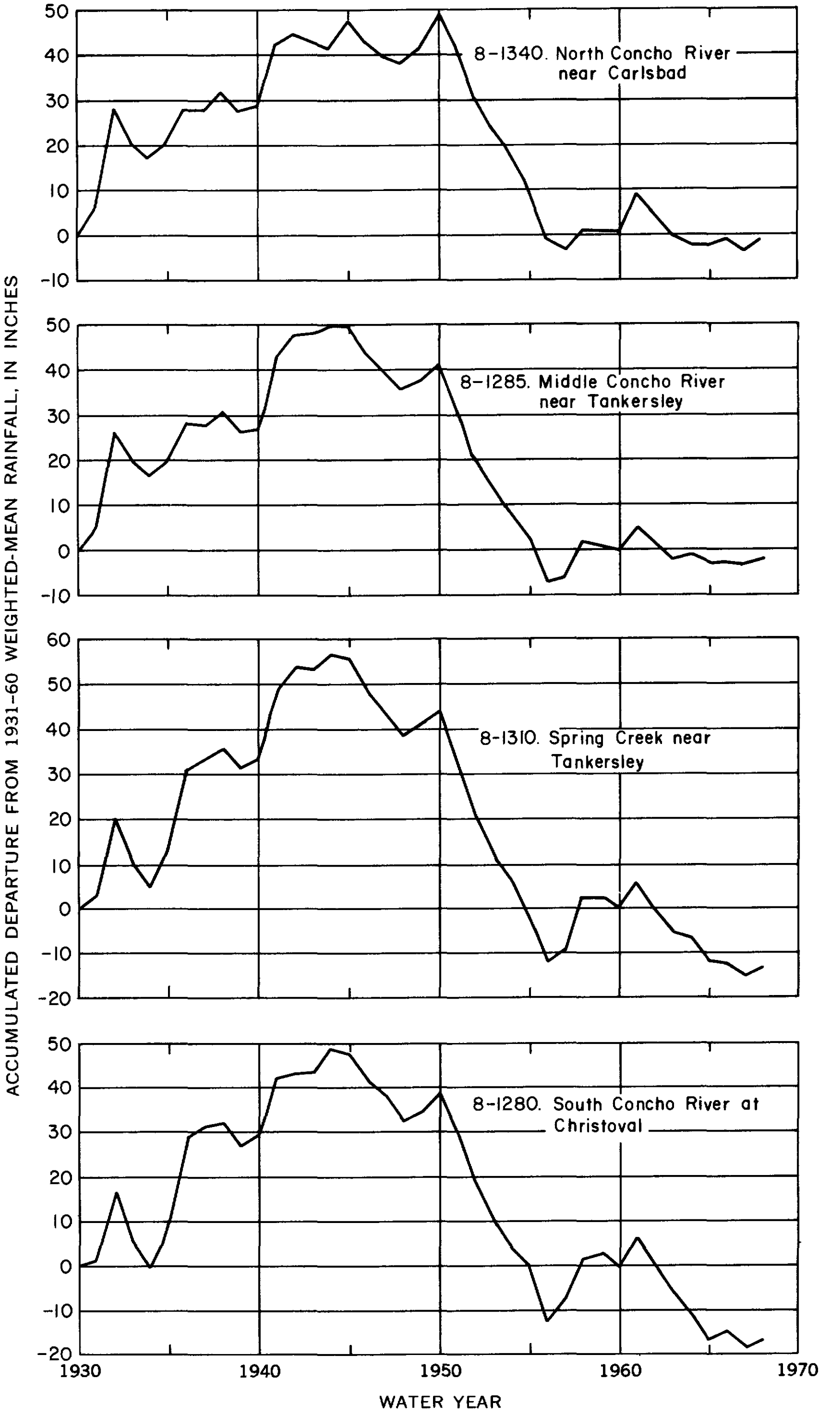


FIGURE 8.—Three-year moving averages of weighted-mean rainfall above selected stream-gaging stations, water years 1931–68.


8-1340. North Concho River near Carlsbad
8-1285. Middle Concho River near Tankersley
8-1310. Spring Creek near Tankersley
8-1280. South Concho River at Christoval
ACCUMULATED DEPARTURE FROM 1931-60 WEIGHTED-MEAN RAINFALL, IN INCHES
WATER YEAR
1930
1940
1950
1960
1970
50
40
30
20
10
0
-10
60
-20

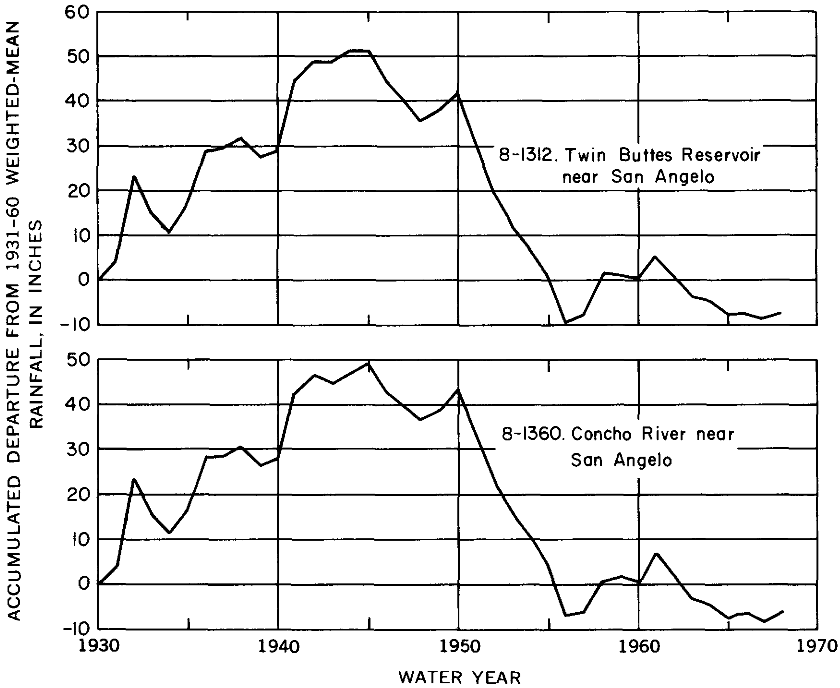


FIGURE 9 (left and above).—Accumulated departures of annual weighted-mean rainfall from 1931–60 mean for various areas in the Concho River basin.

FREQUENCY DISTRIBUTION OF MONTHLY RAINFALL

To properly analyze the changes in rainfall characteristics, as they relate to runoff, records from a network of recording rain gages would be required. This type of rainfall data generally is not available in the Concho River basin. As an alternative, monthly weighted-mean rainfall was analyzed. The reasoning here is that although a month with relatively large rainfall does not assure runoff if the rainfall is spread over a number of days, it may be assumed that a month with relatively low rainfall will not produce significant runoff.

Some of the results of the study of monthly rainfall are illustrated in figures 10 and 11. Each of these figures illustrates clearly a significant decrease in frequency of monthly rainfall exceeding 2 inches during the period 1943–68 and 1962–68. This decrease is probably sufficient to account for the decrease in runoff.

ANALYSES OF RUNOFF DATA

AVAILABLE DATA

Records of streamflow and reservoir content have been collected in the Concho River basin for a relatively long time. Stream-gaging

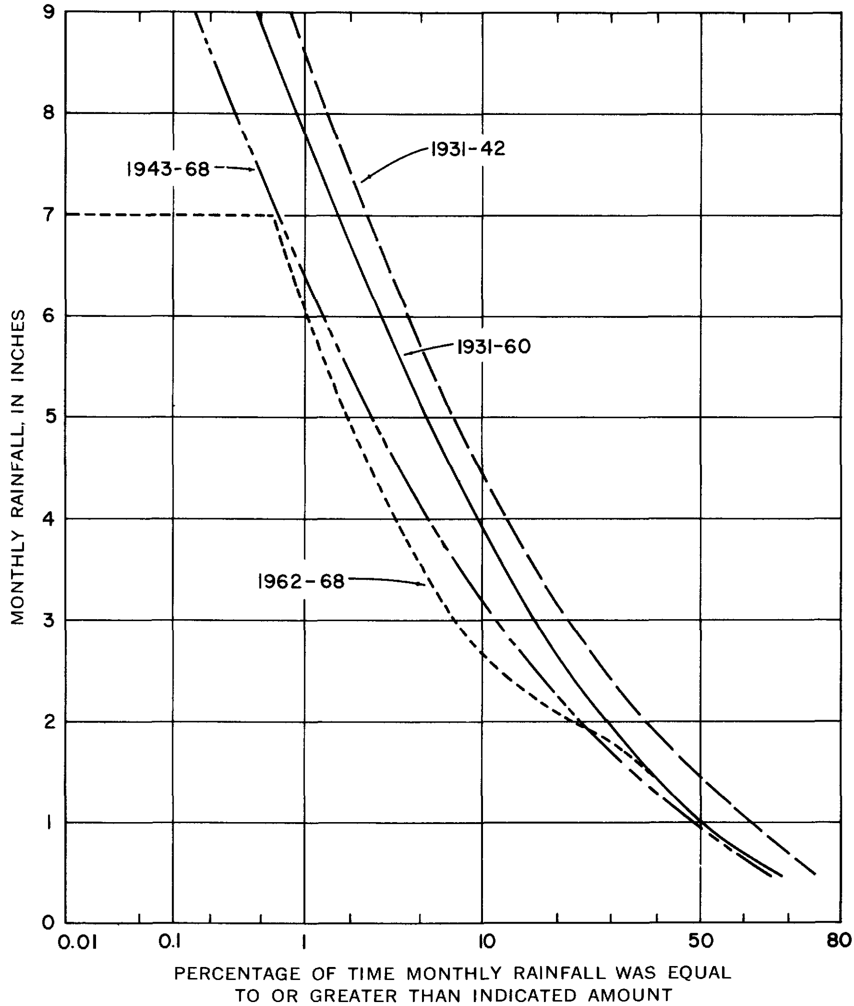


FIGURE 10.—Frequency distribution of monthly rainfall at San Angelo.

stations established on the North Concho and Concho Rivers in 1915 were part of the early Geological Survey effort to establish a data-collection network in the State. Additional gaging stations were established later for water management purposes and for defining the characteristics of surface runoff in the area. As a result, considerable information was available for use in planning and designing the major multipurpose reservoirs now in the basin. A description of locations and periods of record for all streamflow and reservoir-content stations in the basin is given in table 5. Locations of these stations are shown in figure 1. Streamflow records for various locations in the adjacent basins were also available for analysis.

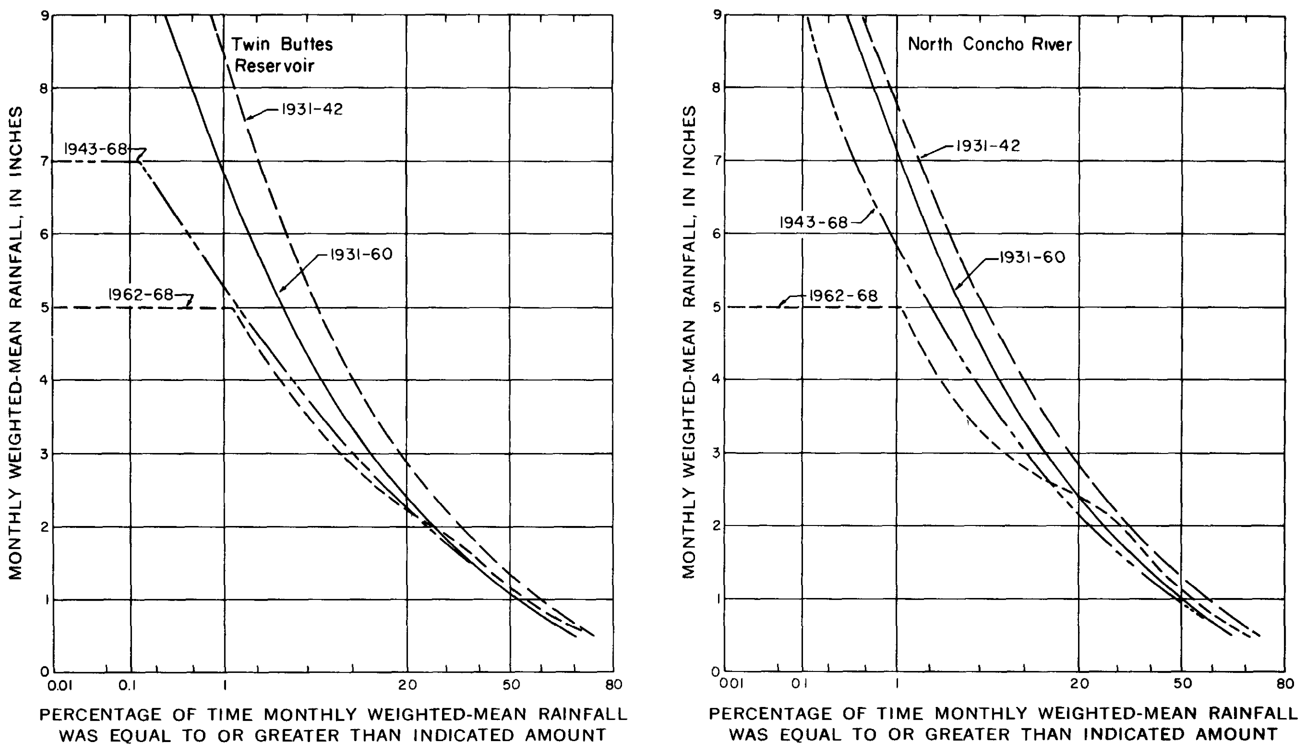


FIGURE 11.—Frequency distribution of monthly weighted-mean rainfall at station 8–1312, Twin Buttes Reservoir, and at station 8–1340, North Concho River near Carlsbad.

TABLE 5.—*Description of stream-gaging and reservoir-content stations*

Station		Period of record	Drainage area (sq mi)		Remarks
			Contributing	Total	
8–1275.	South Concho Irrigation Co's. Canal at Christoval.	1939–68	------	------	Irrigation diversion. Unused diversion returns to South Concho River below station 8–1280. Periodic discharge measurements available 1930–38.
1280.	South Concho River at Christoval	1930–68	344	409	
1284.	Middle Concho River above Tankersley.	1961–68	1,381	2,436	
1285.	Middle Concho River near Tankersley.	1930–61	1,444	2,509	
1290.	Spring Creek Springs near Mertzon.	1943–44, 1948–52, 1955–64	------	------	Springflow partial-record station.
1293.	Spring Creek above Tankersley	1960–68	396	424	Flow affected by irrigation diversion.
1295.	Dove Creek Springs near Knickerbocker.	1944–68	------	------	Springflow only; partial record since 1959.
1305.	Dove Creek near Knickerbocker	1960–68	198	229	Flow affected by irrigation diversion.
1310.	Spring Creek near Tankersley	1930–60	641	700	Flow affected by irrigation diversion.
1312.	Twin Buttes Reservoir near San Angelo.	1963–68	2,546	3,724	
1314.	Pecan Creek near San Angelo	1961–68	84.9	84.9	
1320.	Lake Nasworthy near San Angelo	1930–68	2,655	3,833	
1325.	South Concho River at San Angelo.	1931–53	2,688	3,866	Flow affected by irrigation and municipal diversions and regulation by Lake Nasworthy.
1335.	North Concho River at Sterling City.	1939–68	539	605	
1340.	North Concho River near Carlsbad.	1924–68	1,144	1,249	
1345.	San Angelo Reservoir at San Angelo.	1952–68	1,383	1,488	
1350.	North Concho River at San Angelo.	1915–28, 1929–31, 1947–68	1,402	1,507	Flow controlled by San Angelo Reservoir since 1952.
1360.	Concho River near San Angelo	1915–68	4,097	5,380	Flow affected by irrigation and municipal diversion and by upstream reservoirs.

ADJUSTMENTS TO HISTORICAL RUNOFF FOR WATERSHED DEVELOPMENT

In this study, the statistical samples of runoff data are considered as a discrete time series, with 1-year time increments. The samples are a non-stationary time series because of the effects of man's activities in the basin. Most standard statistical tests and analyses require a stationary time series. In this study, the time series of observed runoff plus all depletions is considered to be first-order stationary. The variable runoff plus all depletions has been given various designations, such as virgin flow, natural runoff, and undepleted flow. Regardless of designation, it is an attempt to adjust the observed sample of runoff to a common base. For this study, the quantity is termed "adjusted runoff."

There are several advantages in analyzing a stationary time series. The primary advantage is that if a mathematical or probability model can be derived for the stationary time series, new sets of data can be generated by using the appropriate statistics.

The causes of depletion of surface runoff are numerous, and as a rule, the depletions increase with time. The primary causes of depletion of surface runoff in the Concho River basin, although the relative magnitude of each item varies from place to place, are as follows:

1. Irrigation diversions.
2. Diversions for municipal and industrial use.
3. Evaporation from channel reservoirs.
4. Evaporation from major reservoirs.
5. Evaporation and seepage losses from stock ponds.
6. Reduction in storm runoff due to land use and land-treatment practices such as terracing and contour farming.

The most comprehensive study regarding the effects of land use, land treatment, and stock ponds on runoff was made by the U.S. Bureau of Reclamation (1960) for use in the report by the U.S. Study Commission–Texas (1962). The procedure used was similar in some respects to one later presented by Sharp, Gibbs, and Owen (1966). Depletions of runoff were estimated on the basis of number, capacity, and surface area of stock ponds, annual runoff, and type and magnitude of land treatment. Annual net evaporation rates were taken into account, as was the probable average contents and surface area of the stock ponds. The Bureau of Reclamation, Austin Development Office, has continued to compute the annual depletions. These subsequent computations were obtained from the Austin office files.

Data on runoff depletions are shown in figure 12. The relationships of depletion to annual unit runoff for the various time periods

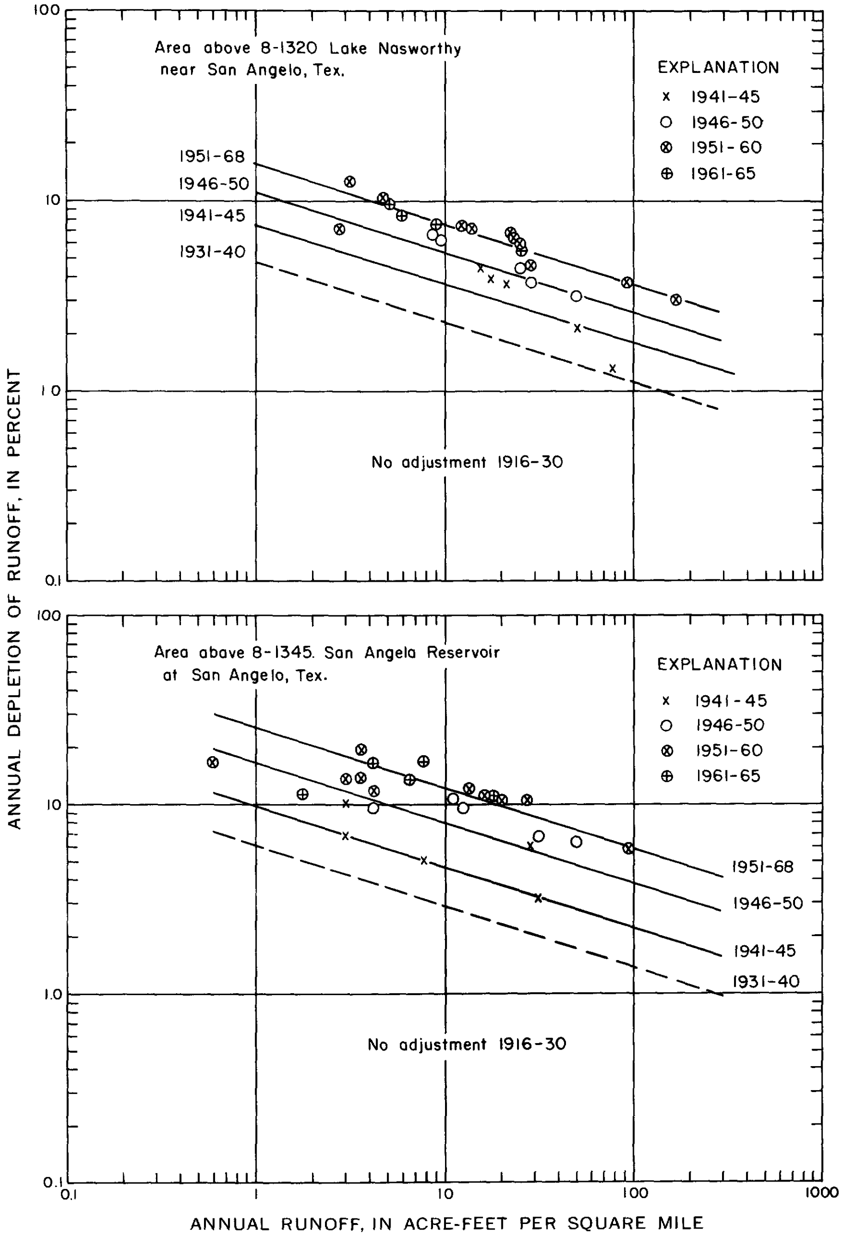


FIGURE 12.—Relationship of annual runoff to estimated annual depletion of runoff, Nasworthy and San Angelo damsites.

were fitted graphically. No adjustments were necessary for the period 1916–30; the relationship for the 1931–40 period was estimated. The watershed condition during the 1916 water year is used as the base condition because this is the first year of runoff record. Relationships of depletion to runoff were developed for each of the long-term stream-gaging stations in the basin. These relationships, which were used to adjust observed (measured) runoff in the basin for the effects of stock ponds and land use, are shown in figure 13.

Other depletions of surface runoff were estimated as follows:

1. Irrigation diversions were assumed to be constant in all except the North Concho River basin, where a number of permits have been cancelled. The assumption of constant irrigation diversion was made on the basis of data shown in table 1.
2. Diversions for municipal and industrial use were estimated from records of the city of San Angelo.
3. Evaporation losses from small channel reservoirs were estimated on the basis of evaporation data and estimated surface areas. Evaporation rates were based on data for the Spur Experiment Station (Texas Agricultural Experiment Station, 1954), data from Kane (1967), and on data collected by the Corps of Engineers at San Angelo Dam.
4. Evaporation losses from major reservoirs were based on surface areas as computed from Geological Survey records and evaporation data as outlined above.
5. Changes in storage in major reservoirs above stream-gaging stations were taken from records at reservoir-content stations.

A summary of observed runoff, estimated depletions, and change in storage above long-term stream-gaging stations in the Concho River basin is given in table 6. Basinwide weighted-mean rainfall is included for comparison. From the table, it may be seen that depletion by irrigation diversions and by evaporation from channel-dam impoundments was relatively constant. Diversions for municipal and industrial use have been increasing at a fairly uniform rate. Depletions due to land use and treatment have been increasing, but they have remained relatively constant for the past 20 years. Figure 13 shows that runoff depletion due to land use and treatment is proportionately greater during years of below average runoff.

Evaporation losses from major reservoirs increased greatly with the construction of San Angelo Dam in 1952 and Twin Buttes Dam in 1963. These losses will be considerably larger when both major reservoirs have significant storage. If the three major reservoirs are maintained at or near the level of conservation storage, evaporation losses will be on the order of 100,000 acre-feet per year.

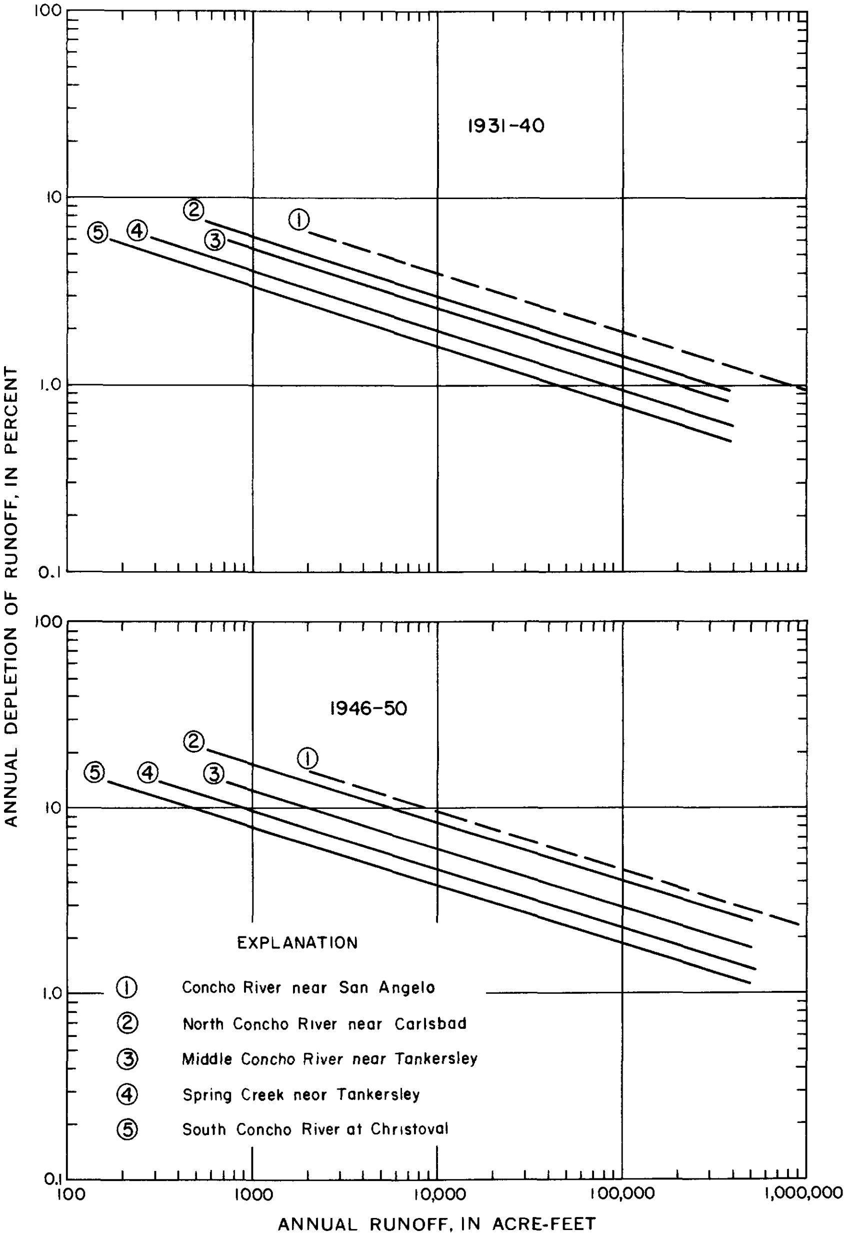
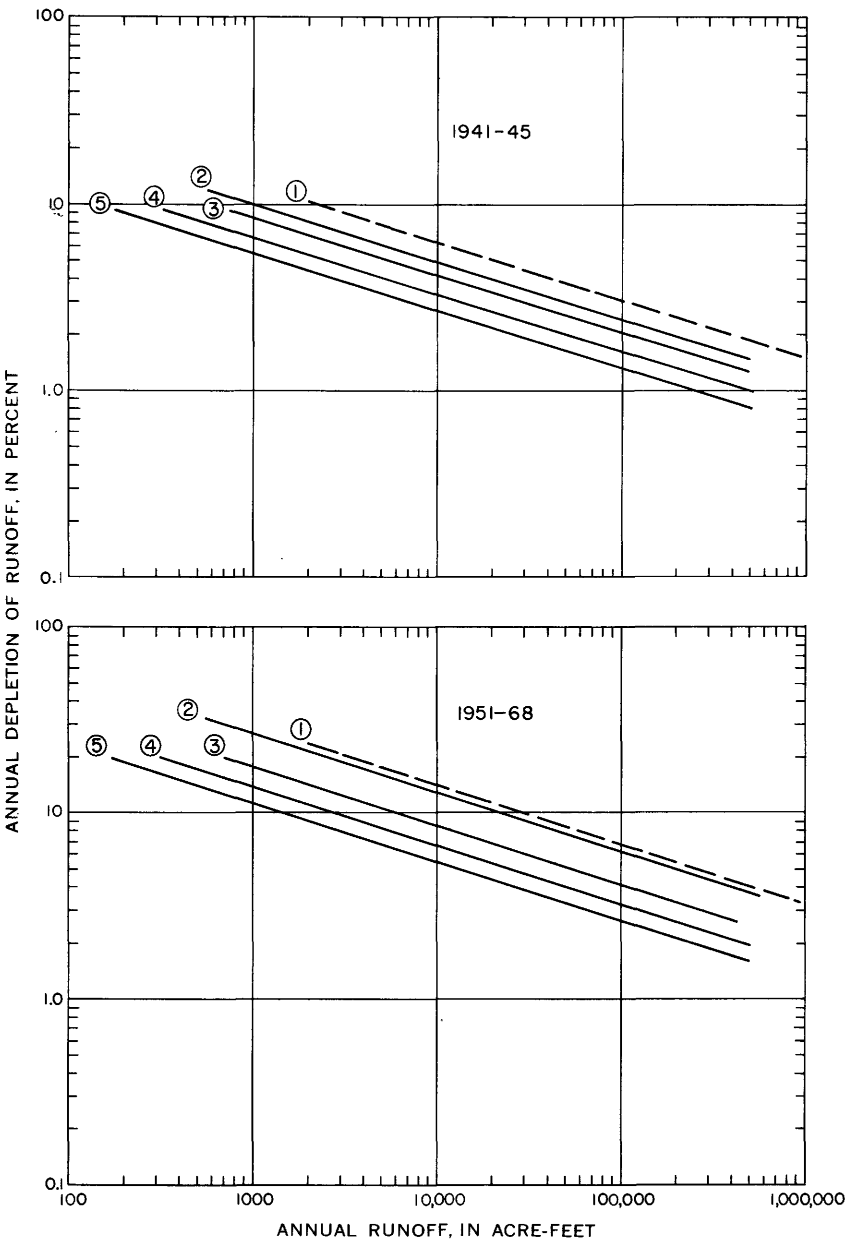


FIGURE 13.—Estimated annual depletion of runoff due to land



treatment and stock ponds above selected stream-gaging stations.

TABLE 6.—*Annual runoff at stream-gaging stations, 1916–68, adjusted for rainfall,*

[Streamflow (A) for station 8–1280 includes flow recorded at station 8–1275, South Concho stations above respective gaging points beginning in 1961. Data for station 8–1312 was

Water year	Basinwide weighted-mean precipitation (in.)	8–1280. South Concho River at Christoval			8–1285. Middle Concho River near Tankersley			8–1310. Spring Creek near Tankersley				
		A	F	H	A	F	H	A	B	D	F	H
1916....	12.33	....	....	....	....	....	....	....	....	....	....	....
1917....	8.63	....	....	....	....	....	....	....	....	....	....	....
1918....	7.91	....	....	....	....	....	....	....	....	....	....	....
1919....	34.22	....	....	....	....	....	....	....	....	....	....	....
1920....	23.43	....	....	....	....	....	....	....	....	....	....	....
1921....	15.20	....	....	....	....	....	....	....	....	....	....	....
1922....	19.29	....	....	....	....	....	....	....	....	....	....	....
1923....	18.77	....	....	....	....	....	....	....	....	....	....	....
1924....	18.75	....	....	....	....	....	....	....	....	....	....	....
1925....	23.86	....	....	....	....	....	....	....	....	....	....	....
1926....	22.36	....	....	....	....	....	....	....	....	....	....	....
1927....	21.61	....	....	....	....	....	....	....	....	....	....	....
1928....	22.82	....	....	....	....	....	....	....	....	....	....	....
1929....	19.44	....	....	....	....	....	....	....	....	....	....	....
1930....	13.56	....	....	....	....	....	....	....	....	....	....	....
1931....	22.53	76.7	0.7	77.4	14.5	0.3	14.8	26.1	5.0	0.8	0.4	32.3
1932....	37.92	27.9	.3	28.2	69.9	1.0	70.9	59.2	5.0	.5	.7	65.4
1933....	10.35	24.7	.3	25.0	8.5	.2	8.7	21.8	5.0	1.1	.3	28.2
1934....	14.47	17.1	.2	17.3	2.2	.1	2.3	8.8	5.0	1.2	.2	15.2
1935....	23.65	35.2	.4	35.6	44.1	.7	44.8	33.3	5.0	.7	.4	39.4
1936....	29.66	159.5	1.1	160.6	114.8	1.4	116.2	47.5	5.0	.5	.6	53.6
1937....	18.87	33.3	.4	33.7	26.4	.5	26.9	16.4	5.0	.8	.3	22.5
1938....	20.69	121.6	.9	122.5	11.7	.3	12.0	33.3	5.0	.8	.4	39.5
1939....	13.94	25.5	.3	25.8	10.3	.3	10.6	17.7	5.0	1.1	.3	24.1
1940....	19.67	24.1	.3	24.4	6.7	.2	6.9	15.0	5.0	.8	.3	21.1
1941....	33.13	28.2	.6	28.8	90.2	1.9	92.1	43.8	5.0	.8	.9	50.5
1942....	22.53	35.1	.6	35.7	29.2	.9	30.1	67.2	5.0	.9	1.2	74.3
1943....	17.68	25.9	.1	26.4	7.7	.3	8.0	23.3	5.0	1.2	.6	30.1
1944....	19.34	18.5	.4	18.9	14.3	.5	14.8	17.6	5.0	1.1	.5	24.2
1945....	20.69	22.2	.5	22.7	8.8	.4	9.2	18.0	5.0	1.2	.5	24.7
1946....	12.41	21.5	.6	22.1	17.8	.9	18.7	15.6	5.0	1.3	.7	22.6
1947....	14.50	17.7	.6	18.3	17.3	.9	18.2	5.3	5.0	1.2	.4	11.9
1948....	15.32	11.9	.4	12.3	40.5	1.9	42.4	15.4	5.0	1.3	.7	22.4
1949....	20.65	20.4	6	21.0	52.4	2.3	54.7	29.1	5.0	1.0	1.0	36.1
1950....	23.14	20.6	.6	21.2	14.7	.8	15.5	8.6	5.0	1.1	.5	15.2
1951....	9.21	10.7	.6	11.3	4.4	.5	4.9	1.0	5.0	1.2	.2	7.4
1952....	7.25	6.5	.4	6.9	2.5	.3	2.8	2.0	5.0	1.4	.3	8.7
1953....	11.78	7.7	.5	8.2	23.7	1.6	25.3	13.2	5.0	1.3	.9	20.4
1954....	13.20	6.5	.4	6.9	47.5	2.5	50.0	11.6	5.0	1.3	.8	18.7
1955....	11.72	13.2	.7	13.9	18.1	1.3	19.4	18.1	5.0	1.5	1.1	25.7
1956....	7.32	7.3	.4	7.7	11.6	1.0	12.6	7.5	5.0	1.7	.6	14.8
1957....	19.43	108.6	2.8	111.4	102.6	4.2	106.8	119.3	5.0	1.3	3.7	129.3
1958....	24.94	33.3	1.3	34.6	42.1	2.3	44.4	27.8	5.0	1.0	1.4	35.2
1959....	18.94	14.5	.7	15.2	23.9	1.5	25.4	16.2	5.0	1.1	1.0	23.3
1960....	17.56	43.0	1.5	44.5	30.6	1.8	32.4	94.2	5.0	1.2	3.1	103.5
1961....	24.62	25.0	1.0	26.4	6.1	.7	6.8	22.9	5.0	1.0	1.2	30.1
1962....	13.27	27.8	1.1	28.9	.0	.0	.0	9.1	5.0	1.4	.7	16.2
1963....	13.87	11.7	.6	12.3	.3	.0	.3	3.7	5.0	1.3	.4	10.4
1964....	16.84	15.8	.7	16.5	11.2	.9	12.1	3.0	5.0	1.4	.4	9.8
1965....	15.93	12.7	.6	13.3	9.3	.8	10.1	3.4	5.0	1.2	.4	10.0
1966....	18.92	6.3	.4	6.7	19.7	1.4	21.1	4.1	5.0	1.0	.4	10.5
1967....	16.78	7.5	.5	8.0	3.9	.4	4.3	14.5	5.0	1.2	.9	21.6
1968....	20.56	9.5	.5	10.0	.3	.0	.3	3.7	5.0	.7	.5	11.9

A. Recorded streamflow at station.
B. Estimated irrigation diversions above station.
C. Estimated diversions for municipal and industrial use.
D. Estimated evaporation depletions due to channel dams.

runoff depletions, in thousands of acre-feet, and basinwide weighted-mean in inches

Irrigation Co. Canal at Christoval. Data for stations 8–1285 and 8–1310 was estimated from estimated as 1.04 times the sum of adjusted annual runoff at stations 8–1280, 8–1285, and 8–1310]

8–1340. North Concho River near Carlsbad				8–1360. Concho River near San Angelo								8–1312. Twin Buttes Reservoir site near San Angelo
A	B	F	H	A	B	C	D	E	F	G	H	H
....	....	....	....	46.9	8.0	0.0	1.6	0.0	0.0	....	55.7	....
....	....	....	....	27.1	8.0	1.0	1.9	.0	.0	....	38.0	....
....	....	....	....	34.4	8.0	.9	2.1	.0	.0	....	45.4	....
....	....	....	....	221.0	8.0	.9	.5	.0	.0	....	230.4	....
....	....	....	....	109.0	8.0	.9	1.1	.0	.0	....	119.0	....
....	....	....	....	24.7	8.0	1.2	1.4	.0	.0	....	35.3	....
....	....	....	....	360.0	8.0	1.5	1.7	.0	.0	....	371.2	....
....	....	....	....	43.0	8.0	1.3	1.4	.0	.0	....	53.7	....
....	....	....	....	117.0	8.0	1.3	1.6	.0	.0	....	127.9	....
133.3	0.5	0.0	133.8	186.6	8.0	1.5	1.4	.0	.0	....	197.5	....
33.4	.5	.0	33.5	132.9	8.0	1.7	1.0	.0	.0	....	143.6	....
13.1	.5	.0	13.6	44.6	8.0	2.0	1.6	.0	.0	....	56.2	....
28.5	.5	.0	29.0	84.0	8.0	2.2	1.4	.0	.0	....	95.6	....
11.5	.5	.0	12.0	42.0	8.0	2.4	2.3	.0	.0	....	54.7	....
32.3	.5	.0	32.8	65.7	8.0	2.7	2.9	.9	.0	+3.0	83.2	....
5.2	.5	.2	5.9	118.0	8.0	2.3	2.0	4.5	2.4	+6.2	143.4	129.5
60.9	.5	1.0	62.4	238.1	8.0	1.8	1.2	2.8	3.7	+.8	256.4	171.1
5.9	.5	.2	6.6	52.0	8.0	2.1	3.0	6.7	1.4	—3.9	69.3	64.4
11.4	.5	.4	12.3	28.6	8.0	2.4	3.3	5.5	1.0	—1.3	47.5	36.2
80.0	.5	1.3	81.8	195.1	8.0	2.3	1.8	3.4	3.1	+5.1	218.8	124.6
243.6	.5	2.7	246.8	821.6	8.0	2.7	1.4	2.7	8.2	—8.9	835.7	343.6
25.1	.5	.6	26.2	110.1	8.0	2.7	2.0	3.5	2.2	+6.7	135.2	86.4
27.6	.5	.6	28.7	218.9	8.0	2.6	2.2	4.4	3.4	+.8	240.3	181.0
4.9	.5	.2	5.6	47.8	8.0	3.3	3.0	6.0	1.3	—1.6	67.8	62.9
10.3	.5	.3	11.1	71.7	8.0	2.8	2.4	4.4	1.7	+1.0	92.0	54.5
41.8	.5	1.3	43.6	201.7	8.0	2.9	2.1	4.3	5.1	+1.1	225.2	178.3
9.7	.5	.5	10.7	155.0	8.0	3.8	2.4	4.8	4.3	+.5	178.8	145.7
4.6	.5	.3	5.4	51.0	8.0	5.1	3.3	6.0	2.2	—3.4	72.2	67.1
3.9	.5	.3	4.7	29.3	8.0	4.3	3.1	5.6	1.7	+1.5	53.5	60.2
52.4	.5	1.6	54.5	87.8	8.0	4.9	3.5	6.2	3.1	—.3	113.2	58.9
2.2	.5	.3	3.0	52.1	8.0	6.9	3.6	5.8	3.5	+.9	80.8	65.9
21.2	.5	1.4	23.1	55.7	8.0	6.9	3.3	5.3	3.3	—4.6	77.9	50.3
79.9	.5	3.5	83.5	123.0	8.0	8.4	3.9	4.8	6.0	+9.5	163.6	80.2
37.9	.5	2.1	40.5	148.1	8.0	7.9	2.8	6.6	6.3	—4.6	175.1	116.3
14.5	.5	1.1	16.1	46.2	8.0	8.8	3.2	7.4	3.5	+4.6	81.7	54.0
4.7	.3	.8	5.8	11.8	8.0	10.0	3.3	5.8	2.5	—6.9	34.5	24.5
1.2	.3	.3	1.8	1.2	8.0	5.2	4.2	3.2	1.3	—4.6	18.5	19.1
28.4	.3	2.8	31.5	36.3	8.0	6.5	3.9	4.8	6.6	+42.6	108.7	56.1
23.3	.3	2.3	25.9	60.4	8.0	9.0	4.0	25.1	7.3	+11.2	125.0	78.6
5.0	.3	.8	6.1	36.5	8.0	9.6	4.5	22.2	5.0	—7.6	78.2	61.4
10.2	.3	1.3	11.8	9.9	8.0	11.9	5.1	28.1	3.9	—11.1	55.8	36.5
70.2	.3	4.9	75.4	368.8	8.0	7.7	3.7	24.2	18.9	+57.2	488.5	361.4
94.9	.3	6.0	101.2	156.0	8.0	9.2	2.9	28.5	11.2	+11.2	227.0	118.8
8.5	.3	1.1	9.9	52.8	8.0	9.6	3.1	27.0	5.9	—10.2	96.2	66.5
15.7	.3	1.7	17.7	197.8	8.0	9.8	3.5	30.0	11.9	—11.4	249.6	187.6
31.8	.1	2.8	34.7	34.4	8.0	9.9	2.9	23.7	6.1	+16.3	101.3	65.8
.5	.1	.2	.8	26.7	8.0	10.5	4.1	32.1	3.8	—31.7	53.5	46.9
3.1	.1	.6	3.8	4.9	8.0	10.7	3.8	22.5	2.2	—22.1	30.0	23.9
9.2	.1	1.2	10.5	1.5	8.0	11.3	4.1	20.9	3.8	+5.0	54.6	39.9
8.3	.1	1.1	9.5	3.3	8.0	11.7	3.4	22.3	2.7	—14.4	37.0	34.7
9.5	.1	1.2	10.8	2.8	8.0	12.2	3.0	18.7	4.0	+9.2	57.9	39.8
.9	.1	.3	1.3	2.5	8.0	13.0	3.5	21.0	2.8	—11.9	38.9	35.3
2.6	.1	.5	3.2	2.2	8.0	10.8	2.0	11.2	2.0	—8.6	27.6	23.1

E. Estimated evaporation depletions from impoundments in major reservoirs.
F. Estimated depletions due to land treatment and stock ponds.
G. Change in storage in major reservoirs above station.
H. Runoff adjusted for depletions.

TABLE 7.—*Estimated depletions of runoff at long-term stream-gaging stations, 1962–68*

[Figures shown are totals for the 7-year period, 1962–68]

Station	Actual streamflow		Estimated diversions		Estimated evaporation depletions by channel dams		Estimated depletions due to land treatment and stock tanks		Change in contents in major reservoirs		Total adjusted runoff (1,000 acre-ft)
	1,000 acre-feet	Percent adjusted runoff	1,000 acre-feet	Percent adjusted runoff	1,000 acre-feet	Percent adjusted runoff	1,000 acre-feet	Percent adjusted runoff	1,000 acre-feet	Percent adjusted runoff	
8–1280. South Concho River at Christoval (includes station 8–1275)	91.3	95.4	*	----	*	----	4.4	4.6	----	----	95.7
1285. Middle Concho River near Tankersley	44.7	92.7	*	----	*	----	3.5	7.3	----	----	48.2
1310. Spring Creek near Tankersley	43.5	48.1	35.0	38.7	8.2	9.1	3.7	4.1	----	----	90.4
1340. North Concho River near Carlsbad	34.1	85.5	.7	1.8	*	----	5.1	12.8	----	----	39.9
1360. Concho River near San Angelo	43.9	14.7	136.2	45.5	23.9	8.0	21.3	7.1	—74.51	—24.91	299.5

* Less than 0.1.

The effects of man's activities in the basin are most apparent at station 8–1360, Concho River near San Angelo, which is downstream from all major reservoirs and diversions. At this station, flow during the past 8 years has been severely diminished. The depletions for the period 1962–68 are tabulated in table 7. For the period 1963–68, depletions are proportionately greater and actual streamflow amounts to only 7.0 percent of the adjusted runoff.

The effect's of man's activities are least apparent above the stream-gaging stations 8–1285, Middle Concho River near Tankersley, and 8–1280, South Concho River at Christoval. It should be noted that water for irrigation is diverted immediately above the South Concho River stream-gaging station for use below the station and above Twin Buttes Reservoir. This diverted water is measured at station 8–1275, South Concho Irrigation Company's canal at Christoval and is added to the observed flow at station 8–1280, South Concho River at Christoval. Irrigation diversions significantly reduce the flow of Spring Creek. In all cases, effects of man's activities are proportionately greater during periods of low runoff such as 1962–68. Estimated effects on runoff for the period 1962–68 for the long-term stream-gaging stations in the basin are given in table 7.

As stated previously, there are additional depletions below the South Concho River, Middle Concho River, and Spring Creek gaging stations and above Twin Buttes Reservoir, particularly on the South Concho River. These depletions are included with totals for Concho River near San Angelo. Average total water use for irrigation above Twin Buttes Reservoir is estimated to be 6,400 acre-feet per year. Depletions due to land use and treatment, stock ponds, and evaporation from channel reservoirs are in proportion to those estimated for the South Concho River, Middle Concho River, and Spring Creek. Annual adjusted runoff at Twin Buttes Reservoir was estimated on the basis of drainage area ratio.

A summary of the effects of land and water use on streamflow in the Concho River basin is given in table 8. Totals are given for various selected time periods, including the periods used in the rainfall-frequency analysis and the total period of record for each location.

A measure of the variation of runoff with rainfall is shown in figure 14. This plot is an indication of the general relationship of runoff to rainfall in the Concho River basin, but also illustrates the tremendous variance of the relationship. From this plot, it may be seen that annual rainfall alone is not sufficient for development of a rainfall-runoff relationship. The plot also indicates that runoff experienced during the period 1962–68 was not unusually low for the amount of rainfall occurring when compared to previous experience.

TABLE 8.—*Summary of effects of*

Streamflow site	Average annual runoff for indicated period in 1,000 acre feet					
	1916–68		1925–68		1931–68	
	Actual	Adjusted	Actual	Adjusted	Actual	Adjusted
8–1280. South Concho River at Christoval[1]	----	----	----	----	30.0	30.5
1285. Middle Concho River near Tankersley	----	----	----	----	25.3	26.2
1310. Spring Creek near Tankersley	----	----	----	----	23.7	30.5
1312. Twin Buttes Reservoir site[2]	----	----	----	----	82.0	90.8
1340. North Concho River near Carlsbad	----	----	30.1	31.5	28.2	29.8
1360. Concho River near San Angelo	101.9	[3]130.5	100.4	132.8	101.6	137.1

[1] Includes flow at station 8–1275.
[2] Estimated from streamflow records above site.

STATISTICAL CHARACTERISTICS OF ADJUSTED ANNUAL-RUNOFF DATA

The design of a water-resource system must be based on the mean, variability, frequency distribution, and degree of persistence of runoff. These parameters are statistically defined by the mean, variance or coefficient of variation, skewness or coefficient of skew, and the serial correlation. For annual runoff data, usually only the first-order serial correlation has any significance.

Monthly flows are generally used in designing water-resource systems, with the standard design procedure being to route monthly historic flows through a proposed reservoir in order to achieve the optimum size and design yield. The use of monthly time periods is necessary in much of the United States because storage is required for the yearly cycle, that is, to augment flow during peak-demand periods or dry periods each year. In areas where annual or seasonal runoff fluctuates within narrow limits, this procedure may be used. In the Southwest, where runoff is highly variable, carryover storage is required for years rather than months. For complete utilization of the water resource, storage may be required for 5 or more years to supply water during extended periods of drought. Therefore, the statistics of monthly runoff have less significance.

land and water use on runoff

Average annual runoff for indicated period in 1,000 acre feet—Continued							
1931–60		1931–42		1943–68		1962–68	
Actual	Adjusted	Actual	Adjusted	Actual	Adjusted	Actual	Adjusted
34.1	34.6	51.0	51.2	20.2	21.0	13.0	13.7
30.3	31.4	35.7	36.4	20.4	21.6	6.4	6.9
27.8	34.6	32.5	38.8	19.6	26.7	6.2	12.9
95.7	104.7	124.0	131.5	62.5	72.0	26.6	34.8
33.5	35.3	43.9	45.1	20.9	22.8	4.9	5.7
126.1	160.3	188.2	209.2	61.6	103.9	6.2	42.7

[3] Adjusted for depletions of runoff due to diversions, reservoir evaporation, land use and treatment, and reservoir storage.

In this study, the statistics of annual adjusted runoff were computed. Because runoff was adjusted for depletions, the statistical samples should be relatively stationary. The statistics were computed both for annual runoff and the logarithms of annual runoff. The statistics were computed for several time periods, including 1943–68, 1931–60, and for the period of record. A summary of these statistics is given in table 9.

For the different time periods, the principal variation in statistics is in the mean. In other respects, they are quite similar. The serial correlation coefficient of the runoff in acre-feet is generally low, but it is consistently positive. Yevdjevich (1963), in a study of 140 runoff records from the entire world, found similar results. The statistics of the 1962–68 time period were not computed because of the small sample size. A comparison of the mean for the 1962–68 period with long-term means will be given in the section on drought frequency.

The time series of adjusted annual flows is reasonably well described as being log-normally distributed; that is, the logarithms of annual discharges are normally distributed. The adjusted runoff values were plotted on log-probability paper. All stations showed similar characteristics. A sample of the plot is shown in figure 15.

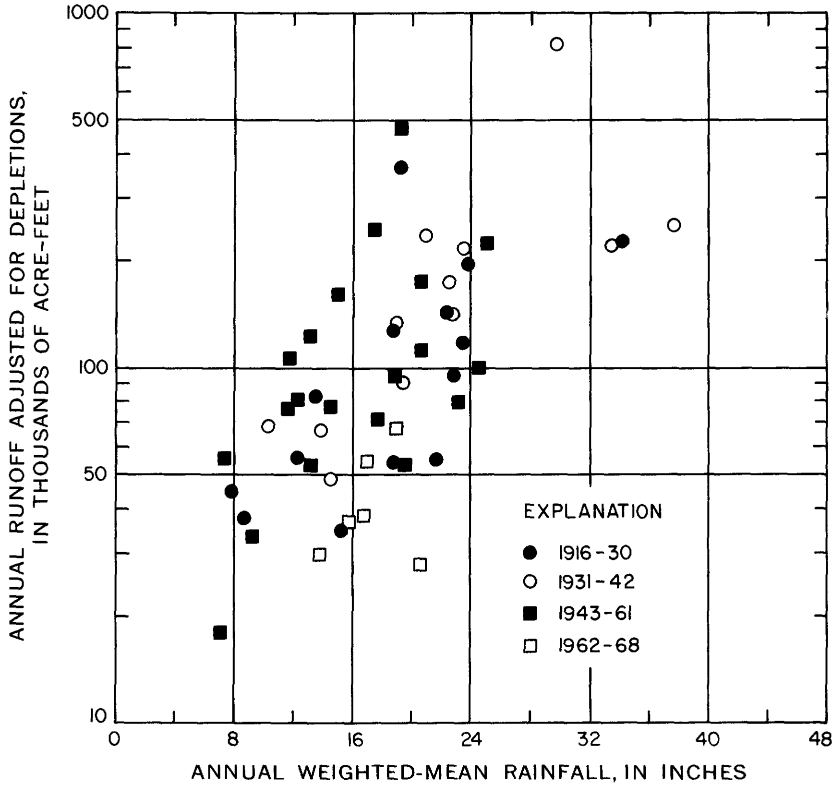


FIGURE 14.—Annual weighted-mean rainfall and annual runoff adjusted for depletion, 1916–68 water years, station 8–1360, Concho River near San Angelo.

The solid line is shown to facilitate comparison of the plotted points with a log-normal distribution. The formula used for plotting position was:

$$P=\frac{M}{N+1}\times 100,$$

where

P=percent of time runoff is equal to or less than the indicated amount,

M=order of observed variable, and

N=number of observations.

The log-normal probability distribution has been found by numerous investigators to describe adequately the frequency distribution of annual flows. This is reasonable because annual precipitation is normally distributed and runoff is logarithmically related to pre-

TABLE 9.—*Statistics of annual adjusted runoff for selected time periods*

[s_x, standard deviation; C_v, coefficient of variation; C_s, coefficient of skew; r_1, first-order serial correlation coefficient]

Station	Period (water yr)	Annual runoff in 1,000 acre feet					Log10 annual runoff (1,000 acre-ft)			
		Mean	s_x	C_v	C_s	r_1	Mean	s_x	C_s	r_1
8–1280. South Concho River at Christoval	1943–68	21.0	20.7	0.98	3.61	0.11	1.21	0.29	0.86	0.33
	1931–60	34.6	36.3	1.05	2.38	.06	1.39	.35	.60	.34
	1931–68	30.5	33.3	1.09	2.70	.11	1.33	.34	.71	.42
1285. Middle Concho River near Tankersley	1943–68	21.6	23.3	1.08	2.22	.28	1.01	.72	—1.47	.51
	1931–60	31.4	30.3	.96	1.59	.02	1.31	.44	—.22	.16
	1931–68	26.2	28.8	1.10	1.82	.13	1.11	.67	—1.40	.43
1310. Spring Creek near Tankersley	1943–68	26.7	27.9	1.04	2.99	.08	1.30	.30	1.10	.33
	1931–60	34.7	27.3	.79	2.14	.01	1.44	.28	.37	.23
	1931–68	30.5	25.7	.84	2.37	.10	1.38	.29	.51	.36
1312. Twin Buttes Reservoir near San Angelo	1943–68	72.0	69.1	.96	3.31	.12	1.75	.28	.86	.35
	1931–60	104.7	82.5	.79	1.94	.04	1.92	.30	.22	.22
	1931–68	90.8	78.2	.86	2.17	.13	1.84	.31	.44	.37
1340. North Concho River near Calsbad	1943–68	22.8	27.3	1.20	1.71	.24	1.05	.56	—.13	.18
	1931–60	35.3	48.7	1.38	3.12	.15	1.26	.51	.18	.10
	1925–68	31.5	44.5	1.41	3.16	.18	1.16	.55	—.10	.20
1360. Concho River near San Angelo	1943–68	103.9	98.2	.94	2.72	.25	1.89	.32	.40	.41
	1931–60	160.3	159.5	.99	3.03	.08	2.07	.34	.18	.23
	1916–68	130.5	134.7	1.03	3.31	.10	1.97	.34	.43	.24

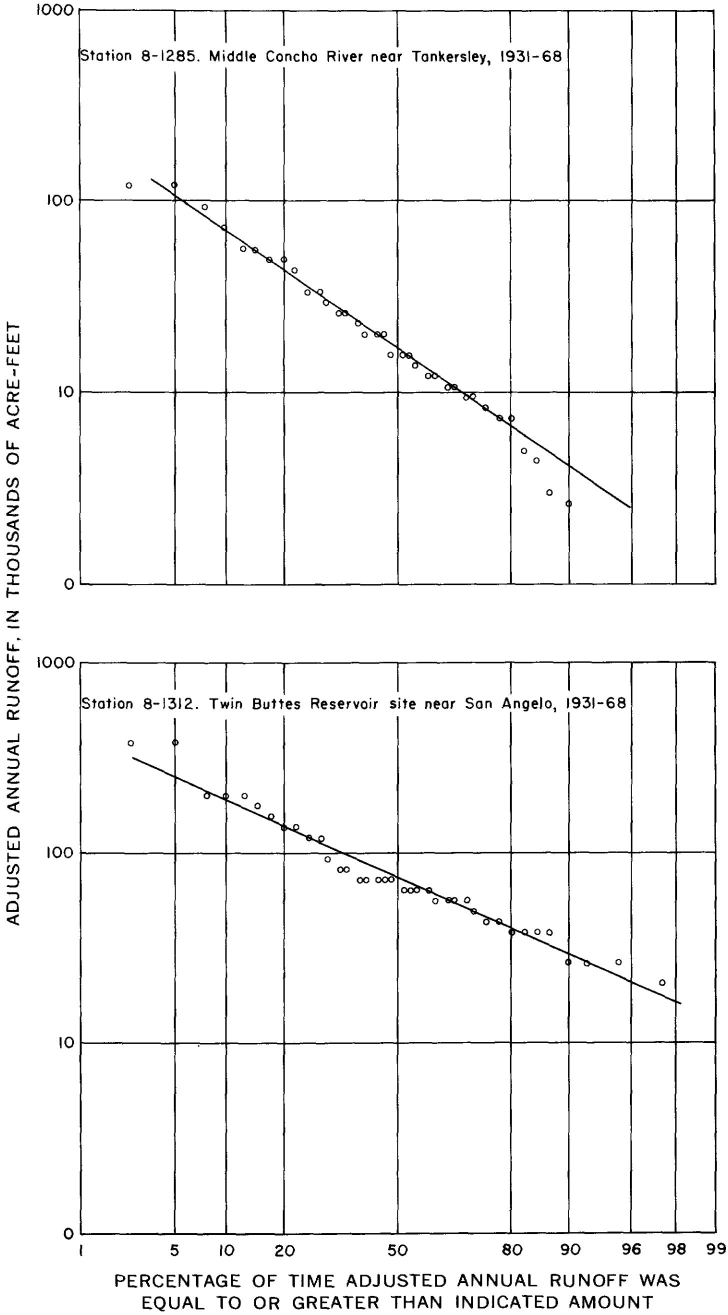
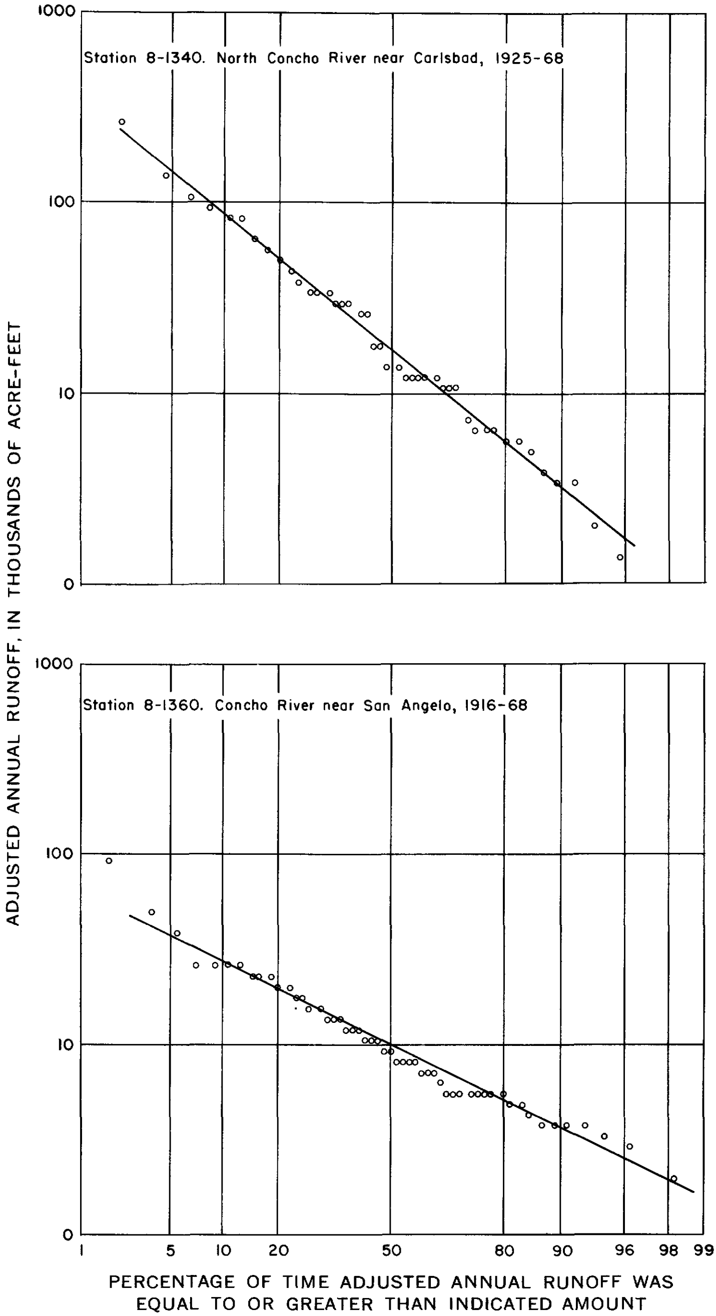


FIGURE 15.—Frequency distribution of adjusted annual



runoff at selected stream-gaging stations.

cipitation. Markovic (1965) in a statistical analysis of records from 446 stream-gaging stations found the two-parameter log-normal probability distribution to describe annual runoff adequately.

DROUGHT-FREQUENCY ANALYSIS

It is generally recognized that the low amounts of runoff generated in the Concho River basin from 1962 to 68 represent a severe drought condition. For water planners and water managers, the important question is "How often may a drought of this severity be expected to recur?" or "What is the probability that a drought of greater severity will occur?" Two approaches may be taken to answer these questions. The preferred method is analytical. The alternative is to simulate long sequences of record by using the statistics of the observed sample.

ANALYTICAL APPROACH

Multiyear flows are combinations of random variables; hence, they are also random variables and have a frequency or probability distribution. Distributions of multiyear flows may be developed by combining the distributions of single-year events. Much of the analysis in this section is drawn from Hardison (1961, 1966, and written commun. 1969).

For this study, distributions of independent multiyear means were developed for log-normally distributed annual flows for several values of the standard deviations of logarithms and for serial correlation of annual flows of 0.0, 0.1, 0.3, and 0.5. The serial correlations are for the logarithmically transformed variable. Distributions were computed for 1, 2, 4, and 8-year means; distributions for other lengths may be interpolated. From these distributions, the distributions for 7-year means were interpolated. The results are shown in figure 16. These graphs, which are for log-normally distributed annual flows, are applicable when a record is divided into $N/7$ parts, where N = number of years in sample. Similar graphs could be prepared for any length of time interval.

To determine the probability of a given 7-year mean, it is necessary to adjust the runoff for the effect of selecting the time period rather than using independent periods. Hardison (1961) has evaluated the difference between the lowest moving average and the lowest independent multiyear mean. According to Hardison, the adjustment required is as follows:

Years in multiyear mean	$\Delta Q/C_v$
2	0.13
4	.21
10	.18
20	.14

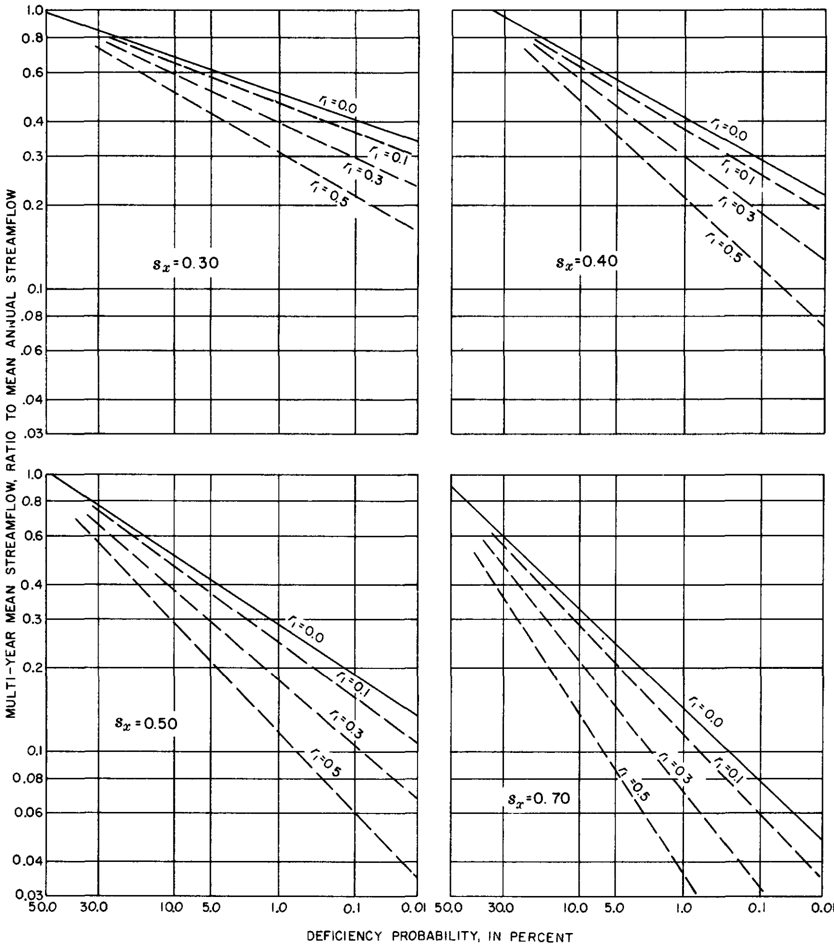


FIGURE 16.—Probability distribution of independent 7-year means in ratio to mean-annual flow. s_x = standard deviations of logarithms of annual streamflow; r_1 = first-order serial correlation of logarithms of annual streamflow.

where

ΔQ=upward adjustment of discharge for using frequency distribution of independent multiyear means and

C_v=coefficient of variation of annual runoff.

For a log-normal distribution, ΔQ is in log units and the standard deviation of the logarithms is used in place of C_v.

The distribution curve of multiyear means gives the expected lowest t-year mean in a group of n t-year means at a deficiency probability given by the relation from Beard (1962),

$$P=1-0.5^{t/n}.$$

Independent means for multiyear periods require that the full period be divided into N/t parts, where N is equal to the number of years in the full period. Then for multiyear periods,

$$n=N/t$$

and

$$P=1-0.5^{t/n}$$

from which

$$N=\frac{-0.301t}{\log(1-P)},$$

where N as computed is an estimate of the recurrence interval of an independent t-year low, equal to or less than that given by the t-year distribution curve at probability P.

In statistical analysis, the statistics of the largest sample are usually the best estimators of the population statistics. In sampling streamflow data, each year is considered to add to the accuracy of estimating the true or population statistics. For drought analysis, the mean, variance, and serial correlation are the most important statistics to consider. It must be recognized that much larger samples (longer periods of streamflow records) are required to give a reliable estimate of the mean in an area of large variation (coefficient of variation). The standard error of the mean in percentage of mean is given by the equation

$$E=\frac{100C_v}{\sqrt{N}},$$

where

E=standard error of estimate, percentage of mean,
C_v=coefficient of variation, and
N=number of years of record.

The coefficient of variation of annual runoff in the Concho River basin ranges from 0.84 to 1.41. For a C_v of 1.1, the standard error of the mean based on 25 years of record would be approximately

TABLE 10.—*Recurrence interval of the*

	Station	Period of record	Mean runoff (1,000 acre ft per yr)	1962–68 adjusted runoff (ratio to mean annual flow	Standard deviation of logs of runoff
8–1312.	Twin Buttes Reservoir near San Angelo	1931–68	90.8	0.38	0.31
1340.	North Concho River near Carlsbad	1925–68	31.5	.18	.55
1360.	Concho River near San Angelo	1916–68	130.5	.33	.34

22 percent. Because the ratio to the mean flow is the parameter used for drought frequency, the estimate of the mean runoff is all important (fig. 16).

For this study, the recurrence interval of the 1962–68 drought was computed for the stations Twin Buttes Reservoir, North Concho River near Carlsbad, and Concho River near San Angelo, using the mean of the adjusted runoff for the entire period of record. The results of this study are given in table 10.

It is obvious that if the mean for the period 1943–68 were used as the population mean, the computed recurrence interval would be less; conversely, use of the 1931–60 mean would result in a larger computed recurrence interval. On the basis of information given in table 10, it is estimated that the 1962–68 drought has a recurrence interval of about 200 years. This is for adjusted runoff. Obviously as depletions increase, the actual available streamflow during a similar drought in the future would be less than during 1962–68.

SIMULATION APPROACH

The use of simulation of hydrologic records has received considerable emphasis by researchers in recent years. By using random numbers and appropriate transformations, very long periods of hydrologic record can be generated, and the use of computers makes this a relatively easy task.

The summary of techniques for generating synthetic hydrologic records is given by Maass and others (1962), Fiering (1966), and Matalas (1967). The general approach is to generate numbers having statistics similar to the observed records. Generally, it is sufficient to achieve similarity in the mean, variance, and serial correlation. The observed sample of runoff is generally small (small time period) and therefore subject to sizable sampling errors. The probability that an observed sample of runoff will be exactly repeated is practically nil. Although the mean, variance, and serial correlation

1962–68 drought at selected stations

First-order serial correlation coefficient of logs of runoff	ΔQ Adjusted (percent)	Adjusted ratio to mean of 1962–68 runoff	Deficiency probability (percent)	Recurrence interval (yr)
0.36	14	0.43	2.6	185
.20	25	.22	3.0	160
.24	15	.38‘	1.0	480

may be the same, the sequence of events is invariably different.

For water resources design, the probability of various sequences of events is very important (such as, the probability that a 10-year period with runoff ≦50 percent of the mean will occur, and so on). Streamflow records in general are of insufficient length to draw general conclusions about the distribution of multiyear means.

For the simulation study, a log-normal first-order Markovian generating process was used. It was assumed that a log-normal probability function, with only first-order serial correlation, adequately described the time series of annual runoff. The general recursion equation for a first-order lag-one Markov process (Matalas, 1967) is:

$$(x_i - \overline{x}) = r_1 \ (x_i - \overline{x}) + (1 - r_1^2)^{1/2} \ s_x \varepsilon_{i+1}$$

where

x_i and x_{i+1} denote values of events at time i and $i+1$,
$\overline{x}$=mean of x,
s_x=standard deviation of x,
r_1=first-order serial correlation of x, and
ε is a random independent variable with zero mean and unit variance.

For this study, computer-generated log-normally distributed numbers were used with the appropriate transformation to simulate annual runoff. The statistics from the sample of runoff (period of record) were used in generating the simulated data. Transformations used in the generating process were as outlined by Matalas (1967).

TABLE 11.—*Summary of results of simulation study*

Station	Base period used for sample statistics	Length of each generated record (yr)	Total number of years of generated record	1962–68 mean adjusted average annual runoff (1,000 acre-ft)	Statistics of 7-year minimum flows in simulated record: Number of periods where 7-year minimum was ≦ 1962–68	Minimum 7-year mean (1,000 acre-ft)	Mean (1,000 acre-ft)	Coefficient of variation
8–1312. Twin Buttes Reservoir near San Angelo	1931–68	38	11,400	30.8	19	23.5	50.1	0.22
1340. North Concho River near Carlsbad	1925–68	44	13,200	5.7	10	4.0	11.3	0.32
1360. Concho River near San Angelo	1916–68	53	15,800	42.8	29	24.7	60.1	.23

For stations 8–1312, Twin Buttes Reservoir near San Angelo; 8–1340, North Concho River near Carlsbad; and 8–1360, Concho River near San Angelo, 300 sets of data equal in length to the period of record were generated with the mean, variance, skewness, and serial correlation comparable to the statistics of the sample. For each of the sets of data, the minimum 7-year flow was computed. The statistics of the 7-year minimum flows were then computed. The results of the simulation study are shown in table 11. The results indicate that a 7-year minimum that is less than or equal to the 1962–68 mean is relatively rare and that the variation about the 7-year minimum is much less than the variation of annual runoff about the mean. The number of simulated drought conditions worse than the 1962–68 event ranged from 10 to 29 out of 300 samples equal in length to the period of record.

ANALYSIS OF RAINFALL INTENSITY AND RUNOFF

The determination of a rainfall-runoff relation generally requires extensive instrumentation and analysis before significant results can be obtained. The extent of the analysis depends primarily upon the available data, the climatic conditions, and the required accuracy. Because the amount of rainfall-runoff data available is limited, only cursory analysis of the relationship in the Concho River basin area was attempted. The main objective of this part of the study was to find probable reasons for the lack of significant runoff during the period 1962–68.

Rainfall records of the U.S. Weather Bureau for the period 1953–68 were used to provide an indication of the total amount of rainfall in the Concho River basin for each storm analyzed in this study. Rainfall intensity and duration and the 48-hour antecedent rainfall were tabulated for Weather Bureau stations recording hourly data. The total rainfall and its duration were computed for 36 storms during the period 1953–68, of which 14 were selected for more extensive study. The 14 storms studied occurred on the following dates: March 8, 1953; July 16, 1955; April 26, 1957; May 8–9, 1957; October 13, 1958; May 13, 1958; September 30, 1959; October 3, 1960; September 4, 1961; May 19, 1963; September 23, 1964; June 4–5, 1965; September 8, 1966; October 4, 1967. This study included tabulating 6-, 12-, 18-, 24-, and 48-hour antecedent rainfall and the 1-, 2-, 3-, 4-, 5-, and 6-hour cumulative rainfall for each Weather Bureau station that provided hourly precipitation data. The resulting storm runoff at each of the four gaging stations that monitor unregulated discharge in the Concho River basin was also tabulated.

Analysis of the tabulated data lead to the following conclusions about the intensity and duration of rainfall and the resulting storm runoff:

1. Rainfall in the basin is extremely varied both in areal distribution and amount.
2. Point rainfalls of at least 1.3 inches per hour occur regularly but usually have little or no antecedent rainfall.
3. Since 1961, high-intensity and long-duration rainfall has not occurred frequently, and when it did occur, it was generally preceded by small amounts of antecedent rainfall.
4. Storm runoff results from high-intensity and long-duration rainfall preceded by moderate amounts of antecedent rainfall. High-intensity rainfall of short duration and little antecedent rainfall generally produce only token amounts of runoff.
5. No substantial storm runoff occurred in the Concho River basin during the period 1962–68 due to the lack of high-intensity and long-duration rainfall either at designated points or basinwide. The two storms during this period that had recorded initial point intensities of at least 1.5 inches per hour both had short duration and little antecedent precipitation; this resulted in minimal runoff.

A study conducted by Hershfield (1961) provides an indication of the expected probability of annual occurrence of maximum rainfall in the Concho River basin. There is 2 percent probability that in any one year a rainfall of 1.9 inches per hour or more will occur at any one point, or that a 1.2-inch-per-hour rainfall will occur over an area greater than 300 square miles. The probability of the annual maximum 1-hour rainfall equal to or greater than 1.9 inches covering an area greater than 300 square miles is 2 percent.

SUMMARY AND CONCLUSIONS

Although cultivation of land in the Concho River basin has increased since the collection of streamflow records began, the proportion of the basin under cultivation was estimated at less than 3 percent in 1968. Other practices such as terracing and stock-pond construction have changed little since the early 1950's. Land-use and treatment practices are estimated to have reduced the 1962–68 runoff from the entire basin by about 7 percent from the 1916 undeveloped condition.

Irrigation practices in the basin have changed little since 1900. Most of the base flow of the spring-fed streams is fully utilized for irrigation, and these diversions have a proportionately greater effect on streamflow during periods of low runoff. Irrigation diversions are estimated to have reduced the runoff from the basin by about 19 percent during the period 1962–68.

Diversions of water for municipal and industrial use have been increasing steadily in response to the growing population of the city of San Angelo. As a result, flow during the period 1962–68 was reduced by about 27 percent at the station measuring outflow from the basin.

Ground-water use has not affected streamflow to any significant extent. Springflow from streams in and adjacent to the basin continues to respond directly to annual rainfall.

Evaporation from channel-dam impoundments has not changed appreciably since the 1930's and is estimated to have reduced the 1962–68 runoff by 8 percent. Evaporation losses from major reservoirs are estimated to have equaled approximately 50 percent of the 1962–68 adjusted runoff, of which about one-half was derived from change in storage in reservoirs in the basin. The remaining 15 percent of 1962–68 adjusted runoff appeared as outflow from the basin. The depletions of flow varied in various parts of the basin, depending upon the degree of development.

In the analysis of long-term rainfall, the period 1943–68 exhibits statistical characteristics different from those prior to that time. Annual rainfall averaged 10–30 percent less during this period, and the frequency distribution of monthly rainfall indicates a significant decrease in monthly rainfall above 2.0 inches, especially during the period 1962–68.

The analysis of runoff data indicates that runoff has responded directly to the deviations in rainfall. Statistical analysis of adjusted annual runoff data shows the runoff to be highly variable, with coefficients of variation ranging from 0.8 to 1.4. Annual flows were not highly correlated; the first-order serial correlation ranged from 0.01 to 0.28. The annual runoff is shown to be log-normally distributed.

Drought frequency analysis indicates a drought of severity equal to the 1962–68 period may be expected on the average once every 200 years. As depletions of runoff continue to increase, the relative severity of a given level of drought will increase.

An analysis of rainfall intensity and runoff indicate the basic cause of the unusually low runoff during the period 1962–68 has been a lack of long-duration, high-intensity rainfall.

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