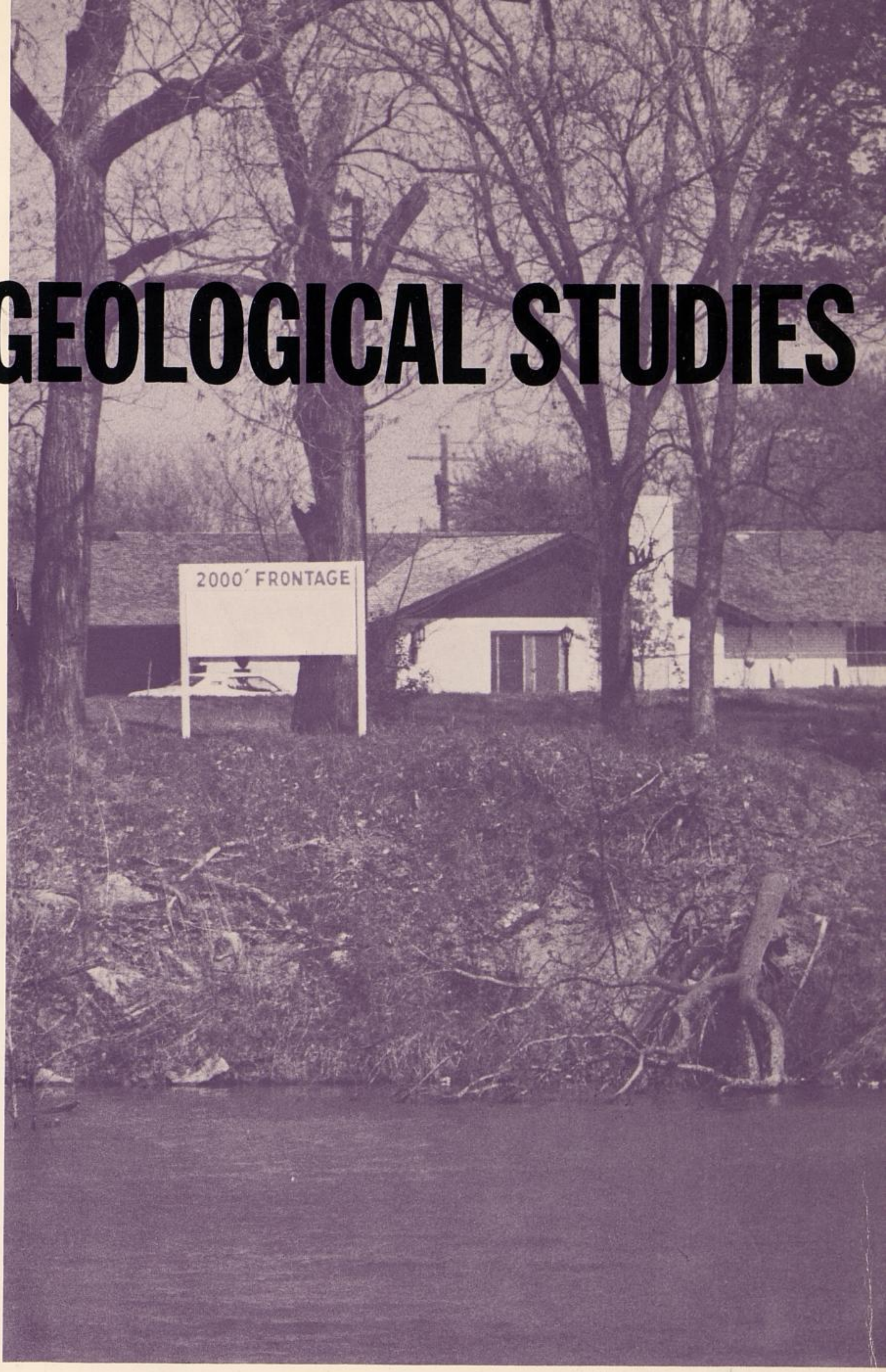
BAYLOR GEOLOGICAL STUDIES



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Probable Maximum Flood on the Brazos River in the City of Waco

EDWARD DALE LEACH

"Creative thinking is more important than elaborate equipment--"

Frank Carney, Ph.D.
Professor of Geology
Baylor University
1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

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Edward Dale Leach

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
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Probable Maximum Flood on the Brazos River in the City of Waco

Edward Dale Leach

ABSTRACT

This report summarizes an investigation of probable maximum flooding of the Brazos River in the City of Waco. The Brazos River basin above Waco, Texas, has approximately 19,000 square miles contributing runoff to the Brazos River, and therefore could influence probable maximum flooding in Waco.

Several interrelated physical factors (area, shape, slope, topography, etc.) and climatic factors (easterly wave, storm transposition, moisture maximization, etc.) influence runoff volume and rate in the Brazos basin. Due to the inverse relationship between rainfall depth-duration and area, those factors which affect runoff were emphatically analyzed for the local "uncontrolled" portion of the Brazos basin. Both physical and climatic factor controls are reflected in subbasin flood hydrographs.

Flood-control structures have little effect on probable maximum flooding, but improper urban flood-plain use will increase flood stage, peak discharge, and flow velocities.

River-routing procedures and surface-water profile calculation contributed to exact delineation of the developed hypothetical probable maximum flood. This report contains maps and cross sections that indicate the extent of flooding that might occur in the future. Photographs are included to show typical Brazos flood-plain development within the City of Waco.

NONTECHNICAL SUMMARY*

One of the earliest "recorded" intense rainfalls on the Brazos River occurred in the 1870's. Little is actually known about the storm, but the recollection of an old inhabitant (Vance, 1934, p. 7) gives the following account:

> A few days before the rains began to fall a band of Tonkawa Indians that were camped in the river valley just below old Fort Griffin moved their camp to the top of one of the near by hills. After the flood, on being asked why they moved to the top of the hill, the chief answered that when the snakes crawl toward the hills, the prairie dogs run toward the hills and grasshoppers hop toward the hills, it is time for the Indian to go the hills.

Staying above water has always been a problem for people of Waco who live near the Brazos River. The days have long passed when Waco citizenry can take their possessions and move to high ground. Each year a greater portion of the Waco urban population is concentrated on or near the Brazos flood plain. No one now living has experienced a probable maximum flood on the Brazos. Because of the enormous economic risk, as well as the potential loss of life, there is a need to make the general public aware of areas subject to flood. We can not afford to wait until snakes, prairie dogs and grasshoppers begin scurrying uphill before people are warned of impending flood danger.

The effects of urbanization in Waco have increased the potential for flooding in areas that were not previously in danger. As asphalt, concrete, and buildings replace natural soil covering, and as drainage networks are streamlined and made smooth, rainfall runoff is conveyed more efficiently, therefore greater volumes of water can accumulate more quickly. Given identical rainfall, a 1980

*A thesis submitted in partial fulfillment of the Master of Environmental Science degree, Baylor University, 1978.

flood in Waco will be far greater than was a 1970 flood. The 1977 Kansas City flood is an example of this problem facing urban Waco. In terms of probability, the rainfall intensity of the Kansas City flood had a probability of occurring each 15-20 years, yet it produced a flood which had a probability of occurring under natural conditions each 750-1,000 years. The tributary which caused the Kansas City flood, Brush Creek, has an area of only 30 square miles but is completely urbanized.

Tributary flooding within urban Waco is a significant problem; however, this paper addresses a problem of far greater magnitude—the probable maximum flood of the Brazos River in the City of Waco. Probable maximum flood determination is based upon the consideration of several climatic and physical factors. Waco is located in a physiographic region which experiences all air mass movements known to cause great storms in the southwest United States. If a storm occurs in one river basin of a given physiographic region, it is reasonable to assume the same storm could occur in any basin within that region. For example, Austin and Waco have similar climates, both are about the same distance from the Gulf Coast, both have the same topography, and both experience weather phenomena associated with the same air mass movements. Flood discharges on the Colorado River at Austin could therefore occur on the Brazos River at Waco. The record flood at Waco had a peak flow of 246,000 cfs while the record flood at Austin had a peak flow of 803,000 cfs.

That the flood of record for the Brazos River at Waco is well below the probable maximum flood is obvious. Studies accomplished on probable maximum flooding make this fact even more obvious. Peak discharge greater than 1,000,000 cfs and rainfall depths of near 40 inches in 48 hours are estimated for areas of 1,000 square miles. It should also be apparent that probable maximum flooding may result from a storm covering only a small portion of the Brazos River basin. Two of the worlds greatest observed point rainfalls have occurred in Texas and are considered "transposable" to the Brazos basin. Twenty-two inches of rain fell near D'Hanis in 2 hours, 45 minutes, and 36 inches of rain fell at Thrall in a period of 18 hours. These storms could just as well have been centered over the City of Waco.

Construction of Whitney Dam gave the people of Waco assurance that they will be protected from Brazos River flooding. The new Lake Waco Dam increased confidence to the point that few businessmen would hesitate to develop the Brazos flood plain in Waco. Now, with construction progressing on Aquilla Dam, the Waco citizen may believe nature has been harnessed, when in fact these structures only set the stage for a great flood disaster. Under meteorological conditions of probable maximum flooding it is reasonable to assume a flood, producing sufficient runoff volume to fill all lakes, has recently occurred. If the lakes are full at the beginning of a storm, then the flood retarding effects of those lakes are insignificant.

At one point during 1957 Lake Whitney reservoir was full and flood releases could not be made because of general rains over the basin and flooding downstream. Conditions were right at that time for the beginning of the probable maximum flood at Waco. Those conditions will some day coincide with a great storm, and a great flood will occur on the Brazos River in Waco. This flood will have a peak discharge greater than 900,000 cfs and a flood stage greater than 68 feet, compared to 246,000 cfs flood flow and 40.9 feet stage of the flood of record for the Brazos River at Waco. There will be channel velocities near 30 fps (20 mph) and overbank flow velocities near 8 fps. Waco City Hall will be under 9 feet of water and the County Courthouse will be on the edge of the Brazos River. There will not be a square foot of Baylor University campus that is not inundated, and all bridges crossing the Brazos River will be either washed away or covered by floodwater. Hundreds of houses will be flooded and many washed away. There is no method of estimating loss of life.

Great floods have occurred on the Brazos River, but not during recorded times. Great floods have occurred during recorded history in areas which could have, but for chance, occurred on the Brazos River in Waco. Few known floods have reached probable maximum discharge rates or volumes. This is not to say greater floods will not occur, but rather that our records are so limited that we cannot predict their occurrence. However, in time the correct sequence of variables will combine, and Waco will experience flooding far greater than anyone ever imagined.

INTRODUCTION

PURPOSE

Whether living on the Brazos River bank or on top of a hill in downtown Waco, everyone in the city has an interest in Brazos River flooding and flood control. The big multipurpose dam at Whitney, the damaged levee system in Waco, the small upstream dams along the Brazos River and its tributaries, and the land management programs in the Brazos basin constitute some of the largest activities of the Federal Government in the area. Due in part to our desire not to worry, the average citizen of Waco has some unrealistic ideas about Brazos River flooding.

The channel and flood plain of the Brazos River were constructed by the river and are an expression of the river's natural process of accommodating excess rainfall. During most of the year, water seldom covers more than the bottom of the river channel. The Brazos River flows bankfull only about twice each year, on the average, and only infrequently do floods spread out over the flood plain. It is on the flood plain that nearly all flood damage occurs (Leopold and Maddock, 1954, p. 9).

While determining an annual flood, the so-called 100-year flood, or the even greater Standard Project Flood is a necessary and valuable activity. A more logical method of flood-plain management is to delineate the probable maximum flood water level along the Brazos River. Making this fact of flooding a matter of public information gives the individual citizen the choice of living or working at a location completely safe from the threat of rising water, or knowingly accepting a greater degree of risk with each lower elevation increment.

Floods kill and floods destroy and floods are certain. Our only real protection from great floods is to remain out of their path. Therefore, the purposes of this investigation are (1) to determine the magnitude of probable maximum floods of the Brazos River at Waco, and (2) to show on maps the extent and depth of water over potentially floodable areas.

LOCATION

Drainage area of the Brazos River (above the U.S. Geological Survey gage located 2.2 miles downstream from La Salle Avenue, at river mile 400.7) is approximately 28,531 square miles, of which approximately 9,240 square miles on the high plains are classified as noncontributing drainage area (Patterson, 1965, p. 193). The basin has a maximum width of about 120 miles, bounded on the east by the Red and Trinity River basins and on the west by the Colorado River basin (Fig. 1). The study area lies within two physiographic provinces of the United States: (1) the Great Plains physiographic province (from the upper limits of the basin in New Mexico to the Caprock escarpment near Post and Crosbyton) and (2) the Central Lowlands province (from the Caprock escarpment to the Balcones escarpment, a series of low escarpments near Waco, Texas).

METHOD

Using topographic maps, U.S. Geological Survey flow records, and historical hydrometeorological data, an analysis of the Brazos River basin above Waco was made for physical and climatic factors that affect rainfall and runoff. A more detailed study of the Waco portion of the Brazos basin gives special attention to the effect basin geometry had on a composite flood hydrograph. Cross-valley profiles were prepared for critical points downstream from Aquilla Creek, and for each of these the cross-sectional area was determined for use in calculating flow volumes, depths, and velocities. Vegetation and floodway developments were studied for stream flow formula modification. Hydrographs were developed for each contributing watershed in the uncontrolled area between Lake Whitney and Waco. Using U.S. Weather Service procedures, flow volumes indicated by these hydrographs were routed through Waco, and a probable maximum flood peak discharge was determined for the Waco gage. Given this peak discharge at the gage point, a water surface profile for the probable maximum flood level was calculated, using a computer program developed by the Hydrologic Engineering Center, Davis, California. This water surface profile made it possible to delineate the flood stage at all points along the river within the Waco region and, using these data, to prepare a large scale flood map of the City of Waco.

PREVIOUS WORKS

Previous works of specific value to this study can best be divided into six categories: (1) studies specifically related to experienced and expected flooding on the Brazos River in central Texas, (2) hydrologic studies of small watersheds within the Brazos River and adjoining river basins, (3) studies of previous weather phenomena and historical flooding, (4) reports of probable maximum rainfall experienced and predicted for central Texas, (5) factors affecting runoff, and (6) tools used in the study of surface water hydrology and hydraulics.

Studies Specifically Related to Experienced and Expected Flooding on the Brazos River in Central Texas

Several specific studies have been accompanied by federal and state agencies. The U.S. Army Corps of Engineers made extensive flood studies of the Brazos River basin for the design of Whitney Dam (1946) and of the Bosque River for the design of Waco Dam (1957).

The Corps of Engineers (1970) report relates to the flood situation along the Brazos and Bosque Rivers in the vicinity of Waco. The Corps of Engineers (1974) made another extensive flood study for the design of Aquilla Creek Dam. Bishop (1976) studied the flood potential of the Bosque River. A flood insurance study (HUD, 1977) investigated the severity of flood hazards in Waco and provided information for sound flood-plain management within the urban area.

Hydrologic Studies of Small Watersheds Within the Brazos and Adjoining River Basins

Patterson (1965) described peak gage heights and discharges for gaging stations of rivers flowing into the western Gulf of Mexico. This publication was valuable through all phases of this study. The Texas Water Development Board prepared several hydrologic studies of small watersheds throughout Texas. Hydrologic data compiled and analyzed in these studies were useful in understanding and relating watershed processes common in all watersheds, and in determining processes unique to the central Texas portion of the Brazos basin. Mills, McGill and Flugrath (1965) and Sauer (1965) studied small watersheds in the Colorado River basin; Smith and Welborn (1967) studied a small watershed in the Trinity

River basin; Mills (1969) and Hampton (1972) studied watersheds of the Brazos River basin.

Studies of Previous Weather Phenomena and Historical Flooding

Historical flooding prior to 1934 is documented by Vance (1934). In this study he also included rainfalls noted in unofficial records. Breeding and Dalrymple (1944) describe some notable storms in Texas. For specific weather phenomena which influence flooding in the Brazos River basin, Byers (1951) discussed the thunderstorm, and Riehl (1951) described tropical storms. Breeding and Montgomery (1952) also described notable storms in Texas, and Yost (1963) gave an account of the April-June 1957 flooding on the Brazos and adjacent basins. A general description of Texas climate by Orton (1964) included the important Gulf coastal waters, the source of moisture for central Texas; Orton (1966) also discussed easterly waves in much the same manner as Carr (1966) discussed weather associated with hurricanes. In addition to this Carr (1967) described the climate and physiography of Texas. Another specific study of weather phenomena that influence flooding in the Brazos basin was by Schoner (1968) who discussed weather associated with hurricanes. Petterssen (1969) described in very general terms global meteorology. Newspaper accounts from the *Waco-Times Herald* provided details of specific floods in the City of Waco.

Reports of Probable Maximum Rainfall Experienced and Predicted for Central Texas

An early attempt to approximate the probable maximum rainfall was that by Jarvis (1936). Commons (1945) developed a probable maximum "rainfall envelope" from all storms that had occurred in the four physiographic regions identified in Texas. A relationship between maximum observed point rainfall and areal rainfall values was developed by Fletcher (1950), who also developed a formula for estimating probable maximum rainfall. The Corps of Engineers' probable maximum storm calculation in design of major water projects is explained by Cochran (1975). Schreiner and Riedel (1976) described probable maximum precipitation estimates for the United States east of the 105th meridian and in this study included areas up to 20,000 square miles and durations to 72 hours.

Factors Affecting Runoff

The relationships between runoff and basin morphology were first described by Robert E. Horton (1914), in a study in which runoff estimates were derived from rainfall data. Later Horton (1932) defined drainage basin characteristics. This paper is still useful as is his 1935 discussion of factors affecting surface runoff. Horton (1945) described a hydrophysical approach to quantitative basin morphology. Langbein (1947) described in greater detail many topographic characteristics of drainage basins previously identified by Horton. Leopold and Maddock (1953) addressed the effect of channel roughness and slope on surface runoff, and Schumm (1956) related slope development to drainage systems. In a 1956 study Leopold and Miller described relationships of stream order to stream number, length, and drainage area. Boyer (1957) compared characteristics of great storms and examined the association of area, precipitation, and duration. Strahler (1957) and Morisawa (1959) made quantitative analyses of geomorphic factors and their impact on stream flow, describing such factors as length, order, bifurcation ratio, area, slope, drainage density and drainage texture. Benson (1962 a,b), in two studies employing statistical multiple-regression techniques, examined the relationships between peak discharge and topographic and climatic factors. In these studies he selected one area in a humid region with diverse terrain and the second area in the arid Southwest. In an analysis of some variables which affect sediment transport, Guy (1964) related seasonal influences to flood hydrograph. Bowden and Wallis (1964) compared various stream ordering techniques with special emphasis on those developed by Horton (1945) and Strahler (1957). Work by Hare (1970) on the effects of urbanization on storm runoff rates, together with other studies from Beard (1970) on urban areas, was of considerable use in this work.

Tools Used In The Study Of Surface Water Hydrology And Hydraulics

The synthetic unit hydrograph was described by Snyder (1938) and by Langbein (1940) who also explained the movement of flood waves through channels. Methods of flood routing and a method for developing a flood hydrograph were described by Commons (1945). These simple methods appear to be relatively accurate for Brazos basin streams chiefly because Commons' studies were made in Texas. Johnston and Cross (1948) gave several methods of analyses of the unit hydrograph and also provided information on flood routing. Chow (1959), in his study of open channel hydraulics, discussed factors influencing hydrograph peak and shape, such as channel storage, types of stream flow, and resistance and retardation of flow. A helpful explanation of hydrologic terminology was developed by Langbein and Iseri (1960). The definitions in this study are those commonly used in field investigations of hydrologic problems. Searcy (1960) presented a procedure for graphically correlating gaging station records, and Searcy and Hardison (1960) described the development of a double mass curve for flood routing. Dalrymple (1960), in an excellent study, analyzed flood frequency, and Court (1961) compared and examined six different area-depth rainfall formulas. Statistical methods used in this paper were derived primarily from a study by Beard (1962) in which both analytical and graphical methods of frequency determination were discussed. The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California, has completed a number of flood studies. Those most useful in the current investigation were Hydrologic Engineering Center (1973), a study on hydrograph analysis; Thomas' (1975) description of water surface profile calculation; and a study by Davis (1975) on flood frequency analysis.

In addition to the above were a series of general hydrologic studies and, among these, those most useful in the current investigation were by Wisler and Brater (1959), Chow (1964), U.S. Department of Agriculture (1971) and Gregory and Walling (1973).

ACKNOWLEDGMENTS

Recognition is given to those who have contributed to the accomplishment of this study. My appreciation is expressed to Dr. O. T. Hayward, Department of Geology, Baylor University, first, for sharing his understanding of natural processes, and second, for his advice and manuscript suggestions. Dr. Merle Alexander, Director, Institute of Environmental Studies, Dr. Robert Font and Dr. G. A. Morales, Department of Geology, Baylor University, provided advice, encouragement, and critical review. Warren Hatch, National Weather Records Center, Asheville, North Carolina, assisted in obtaining critical out-of-print publications, and John Miller, National Weather Service, Silver Spring, Maryland, provided advice on various meteorological subjects. Special thanks to Colonel John F. Wall, Jr., District Engineer, U.S. Army Corps of Engineers, Fort Worth District, for making available the resources of his office. Doyle D. Harris, Hydrology Division, spent many hours answering questions related to general hydrology and explaining procedures and techniques employed by the Corps of Engineers. Dennis Barnabus, Hydraulics Division, assisted in developing specific data on the Brazos River floodway and provided unpublished Corps of Engineers studies for my purusal. Murray Huffman, Chief ADP Section, and Larry Dacus, Hydraulics Division, furnished computer application support for the backwater study. Jerry Nunn, National Weather Service River Forecast Center, Fort Worth, provided computer support for river routing procedures. Austin Bricker, Hydrologic Studies Branch, U.S. Geological Survey, Austin, explained hydrograph calculation and routing methods used by the survey and recommended alternate sources of information. Charlotte D. Friebele, U.S. Geological Survey Librarian, Austin, and Barbara Luedecke, Texas Water Development Board Librarian, Austin, assisted in my initial literature search, and Bob Crittendon, Director of Surface Water Division, Texas Water Development Board, gave special guidance for additional research. Mr. Harlen C. Johnston, Soil Conservation Service, Temple, furnished soil maps and a useful hydrology manual for the study. J. Leon Curtis, U.S. Army Corps of Engineers Division Office, Dallas, also gave his time discussing the procedure for developing a probable maximum storm, and provided hydrologic data and studies that would have otherwise been unavailable. Special recognition goes to Viola Shivers for her advice on format and for typing the manuscript, to George Harris for processing photographs, and to Tom French for drafting assistance.

PHYSIOGRAPHY

The eastern portion of the study area lies in the western edge of the Blackland Prairies (Fig. 1) of east-central Texas. The general surface relief is undulating to gently rolling. The west-facing White Rock Prairie is to the west. Native grasses and fertile soils of the Blackland Prairie are utilized for farming and ranching.

Just west of the Blackland Prairie lies the Grand Prairie, covered largely in grass, with high rolling, well-dissected limestone areas with moderate to rapid surface drainage. A small wooded area that extends southward on the east side of the Grand Prairie is the Eastern Cross Timbers. West of the Grand Prairie is the Western Cross Timbers, much larger than the Eastern Cross Timbers and with well-dissected surface relief ranging from gently to strongly rolling. Trees consist mainly of post oak and blackjack oak.

The North Central Prairie occupies about 6,000 square miles of the Brazos basin and lies between the Western Cross Timbers and the Rolling Plains to the west. It is well dissected with an undulating to gently rolling surface. Drainage is moderate to rapid in all but a few small areas. Native vegetation is mainly post oak and blackjack, but in places grasses and mesquite trees form a thick ground cover. It is used, almost entirely, for row crops and cattle raising.

The Rolling Plains is a lower extension of the High Plains. The well-dissected surface has some large, level undissected areas and severely eroded sloping areas adjoining streams. The most westwardly contributing tributaries of the Brazos basin head in the western portion of the Rolling Plains, and characteristically have deep valleys with strongly sloping and gullied side slopes. Some of the level areas are devoted to cultivation but this area is largely cattle country.

The Caprock escarpment divides the Rolling Plains and the High Plains to the west. This east-facing escarpment, formed by erosion, rises 200 to 500 feet above the Rolling Plains. From the escarpment, the High Plains slopes gradually upward from about 2,200 feet to over 4,000 feet in eastern New Mexico. Surface area is flat with little stream dissection. In recent history it has not contributed runoff to the Brazos River (Godfrey, McKee, Oakes, 1973, p. 1-2).

FACTORS AFFECTING RIVER FLOW

Stream flow, the result of runoff, is determined by two sets of factors: (1) precipitation and (2) the physical characteristics of the drainage basin. Evaporation and transpiration commonly enter into the rainfall-runoff relationship. However, under specific climatic conditions of probable maximum flooding of the Brazos River at Waco, evaporation and transpiration are of such limited significance that they are not here considered.

After rainfall reaches the ground its rate of runoff is influenced by (1) meteorologic factors which affect the amount of runoff (2) the topographic characteristics of the drainage basin, either surface or subsurface. Topographic factors of area and slope are constant; others such as vegetation, ground cover, and condition are variable (Benson, 1962a, p. 16).

There is no exact agreement on significance of factors affecting runoff because so many of them are interdependent. However, in the hydrologic problem-solving process, consideration is normally given to: (1) type of precipitation, (2) intensity of precipitation, (3) duration of precipitation, (4) distribution of precipitation, (5) frequency of precipitation, (6) direction of movement of storms, and (7) antecedent moisture conditions of the ground (Chow, 1964, p. 14-15).

In the general discussion which follows, those factors that will affect the flow of the Brazos River under the worst probable flooding conditions are given maximum emphasis.

TYPES OF WEATHER DISTURBANCES

While there are innumerable types of weather that cause rainfall within the study area, this discussion is limited to those considered probable producers of excessive precipitation: (1) easterly waves, (2) decadent tropical storms, and (3) thunderstorms.

An easterly wave is a weak trough of low pressure which occurs in the easterly wind currents as they flow in an anticyclonic direction. Breeding and Dalrymple (1944, p. 24) describe one as follows:

> The causes of this prolonged and torrential downpour are not readily discernible on the surface weather maps—no strongly developed center of disturbance crossed the country during this period; no tropical storm moved inland from the Gulf or was present on the Gulf; pressure gradients were for the most part very flat.
>
> However, from July 18 to 22 a broad, rather shallow depression trough extended from the Middle Atlantic States southwestward across Texas into northern Mexico. At the same time a field of high pressure made its appearance in the Canadian northwest and moved slowly southward along the eastern slope of the Rocky Mountains. This combination set in motion one of the most effective processes for the condensation and precipitation of atmospheric moisture about which anything is known—the raising of a mass of moisture-laden air and thus indicates a persistent flow of tropical air for the period of July 18-25, and soundings of the upper air show that this air was moist and convectively unstable.

Upper air observations were not available until after 1930 (Petterssen, 1969, p. 17). Many storms occurring prior to 1940 were described only as general rains; the origin and cause appeared mysterious since easterly waves are so difficult to detect. The only evidence of the existence of an easterly wave may be a slight poleward bulge of the weather map isobar (Fig. 2).

Fair weather prevails in front (west) of the trough because air is subsiding; therefore, the moist layer is thin and stable. Behind the trough (east) horizontal convergence forces the moisture-laden air upward, thickening the layer of moist air and causing instability.

Most easterly waves lose intensity shortly after moving inland and only produce precipitation along the Gulf Coast. Occasionally a combination of climatic conditions intensifies an easterly wave, causing it to move inland to the Balcones escarpment or even farther north. The Coriolis effect causes the vorticity of the air mass to increase as it moves toward higher latitudes, thus increasing the instability. Orographic lift provided by the Balcones escarpment may trigger tremendous rainfalls as horizontal convergence feeds a continuing source of warm moist air from the Gulf of Mexico.

Some external orographic or meteorological influence is necessary to transform a stable easterly wave into a large storm. In addition to those processes already mentioned, two other combinations of factors are potential storm producers: (1) an easterly wave approaching a trough in the westerlies circulation belt will cause both air masses to intensify, and (2) colder air of a southward-pushing polar air mass may intensify an easterly wave by forcing a more cyclonic curvature of the flow into the wave trough, thus increasing its instability (Orton, 1966, p. 11).

Tropical storms, which cause excessive precipitation in the study area during their decadent stage, originate in the same area as the easterly waves. Tropical storms which intensify to hurricane force are rare phenomena. They develop out of a preexisting disturbance only when a triggering mechanism is adequate to initiate vertical circulation through a major part of the troposphere (Petterssen, 1969, p. 239). High surface temperatures, above 26.6° C (80° F), are necessary to produce the steep lapse rate that is needed to maintain vertical circulation in a hurricane. Preexisting disturbances in which hurricanes

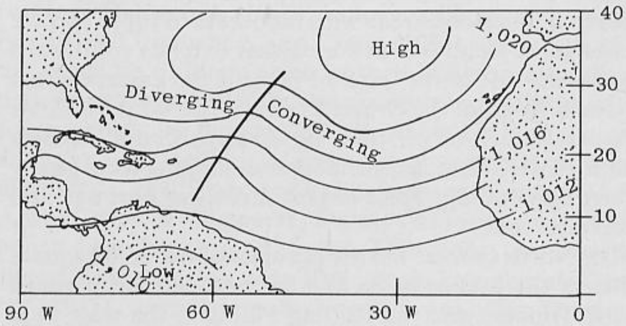


Fig. 2. Sea-level isobars with an easterly wave shown as a slight poleward bulge. Air currents are converging east of the wave and diverging to the west. *After* Petterssen, 1969, p. 238.

may develop are the easterly waves (Carr, 1966, p. 21) in the intertropical convergence zone, and occasionally in the trailing southerly portion of old polar troughs (Riehl, 1951, p. 894).

Generally the most intense rainfalls cover small areas and occur as the result of thunderstorms. Thunderstorms occur over all parts of the Brazos basin. They develop when large amounts of condensed water are being carried upward to heights where the ambient temperature is less than about -20° C (-4° F). Only under conditions of moderate to high temperature and moisture can large amounts of water accumulate in the atmosphere below the -20° C (-4° F) isotherm. Because of this, thunderstorms occur most often in summer when above freezing temperatures exist through a large portion of the lower atmosphere. Areas that provide thermal or geographic lifting of warm moist tropical air such as the Balcones fault zone or the Caprock escarpment are most likely to experience thunderstorms.

GENERAL CLIMATOLOGY

In general the climate in the study area is continental, characterized by rapid changes in temperature, conspicuous extremes, and large temperature range. Central Texas is easily accessible to warm, moist air moving northward from the Gulf of Mexico. This causes greater precipitation in the eastern part of the study area than in the western part. Rainfall decreases from about 35 inches annually at Waco to about 16 inches annually in extreme west Texas (Fig. 3).

SEASONAL VARIATION

In summer, daytime temperatures often exceed 37.7° C (100° F). The warmest weather occurs in June, but it is not unusual to have 37.7° C (100° F) temperatures from May through September. The High Plains area has moderately high daytime temperatures and cool nights. Summer weather in the study area is controlled by tropical maritime air from the Gulf of Mexico which flows all

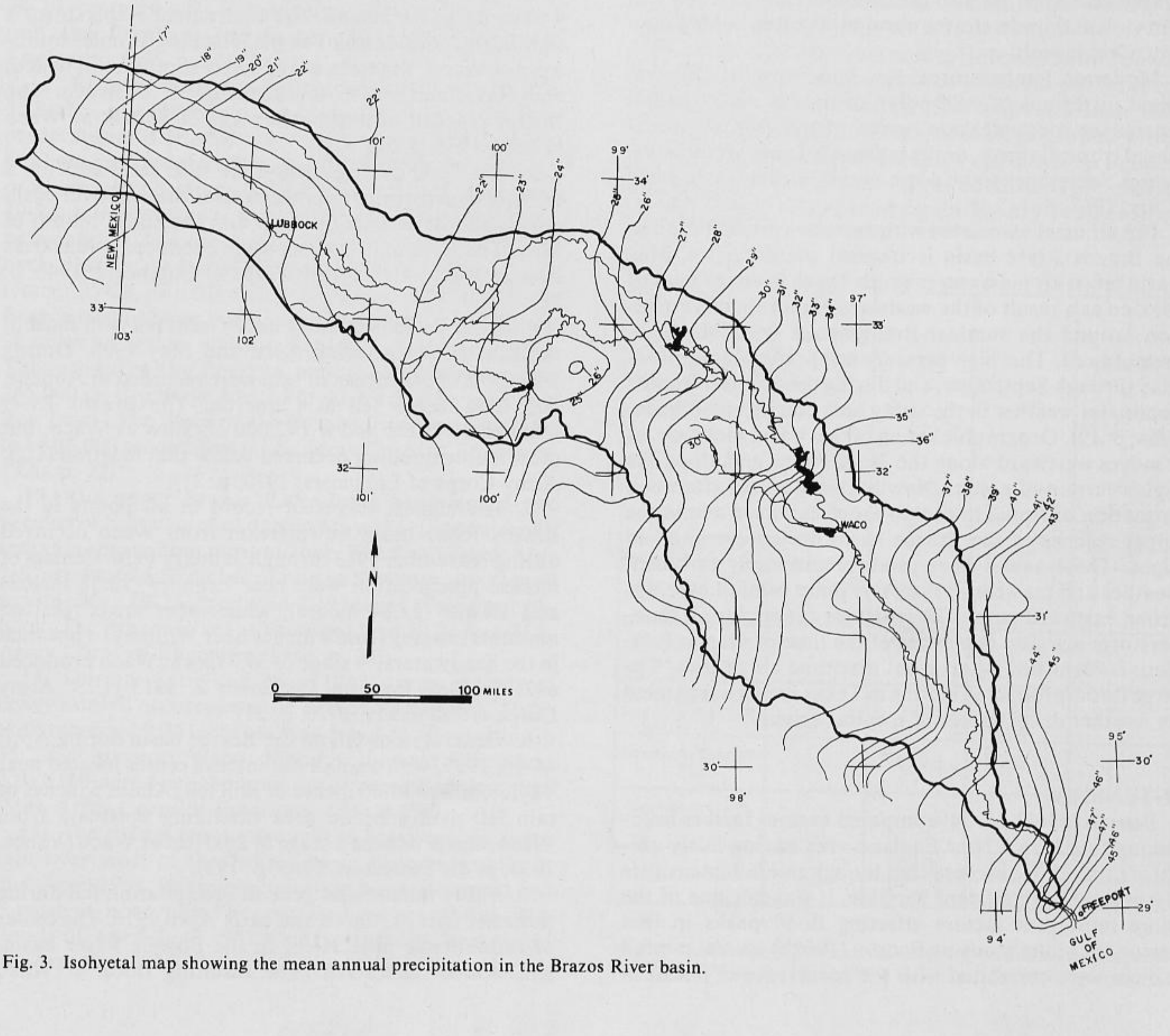


Fig. 3. Isohyetal map showing the mean annual precipitation in the Brazos River basin.

the way to the Rocky Mountains. Rainfall in the Brazos basin above Waco is heaviest through the late spring and early summer period; those summer rains are mostly brief, intense thunderstorms.

During the winter, that portion of the Brazos basin within the study area experiences frequent surges of cold continental air. These frequent fronts moving down across the High Plains are strong, but by the time they cross into Texas are usually moderate. January is the coldest month.

Winter precipitation generally occurs in connection with frontal activity associated with the west to east movement of air masses across the state of Texas. Moisture-laden air flowing from the Gulf of Mexico is cut off by the stronger west to east moving systems, resulting in dry winters. Snow is of little significance to the Brazos basin because very little accumulates in the contributing drainage area.

The spring season is a period of rapid and pronounced weather changes, especially during March and April. Short warm and cold periods follow each other in rapid succession, causing the most violent weather of the year. March and April are also the windiest months. Frequent and violent thunderstorms occur more often in May than any other month.

Moderate temperatures, low wind speeds, and frequent intrusions of mild polar air masses make the fall season the most pleasant period of the year. An occasional tropical storm, or the remnant of an easterly wave, causes September to be a wet month during some years (Carr, 1967, p. 11).

The air mass associated with excessive precipitation in the Brazos River basin is tropical maritime air. This warm moist air mass enters south Texas from the Gulf of Mexico as a result of the westward extension of circulation around the summer-strengthened Bermuda high-pressure cell. This high-pressure cell predominates from May through September, and during the summer months dominates weather in the study area completely (Orton, 1964, p. 19). Orographic lifting of this warm moist air, as it moves westward along the High Plains and along the higher terrain of eastern New Mexico, causes afternoon formation of squall lines that move eastward across the upper reaches of the Brazos basin during evening and night. These squall lines produce extremely turbulent weather and may cause excessive point rainfall over this broad eastward path. The moisture supply for all thunderstorm activity, regardless of the time of year or location, is furnished by tropical maritime air masses. The large flood-producing storms in Texas are also generated by weather disturbances of tropical origin.

INTENSITY

Benson (1962b, p. 54) compared various factors influencing floods in a New England area having fairly uniform rainfall. He showed that though rainfall intensity is a statistically significant variable, it was not one of the more important factors affecting flood peaks in that region. In a later study by Benson (1962b) several rainfall indices were correlated with the occurrence of floods in the Southwest. He noted that the outstanding characteristic of precipitation in the Southwest is its variability, and that rainfall intensity is an important variable. The only variable of more importance in affecting peak discharge is size of the drainage area (Benson, 1962a, p. 31).

In addition the impact of rainfall intensity on flooding varies with such factors as location, season, and area.

In the following short description, floods within the Brazos River basin above Waco are described in terms of rainfall intensity, location, time of year and resulting flood level.

Historic Floods

1. During September 20-24, 1900, heavy rains were centered over the Clear Fork of the Brazos River; 6.78 inches of rainfall fell at Abilene, and 8.85 inches fell at Haskell. This produced the maximum flood of record on the Clear Fork at Fort Griffin and near Crystal Falls. The estimated peak flow of the Brazos River was 79,500 second-feet at Waco (Vance, 1934, p. 34).

2. One of the longest storms in Texas meteorological records occurred during July 20-30, 1902. Nearly 17 inches of rain fell at Temple, 2.72 inches at Brazoria, and 4.67 inches at Rhineland. The areal extent of this storm is significant, considering Temple is located 35 miles southwest of Waco, Brazoria is 190 miles southeast of Waco, and Rhineland is 195 miles northwest of Waco. The Brazos reached an estimated stage of 35 feet at Waco (Vance, 1934, p. 35).

3. The flood during April-June 1905 resulted from a series of general rains over the central Brazos River basin during the latter part of April and the entire month of May. The resulting 32.5-foot stage produced a 96,300 cfs flow at Waco (U.S. Army Corps of Engineers, 1946, p. 22).

4. Three periods of fairly heavy rains fell over most of the Brazos basin during April and May 1908. During May 21-25, 7.18 inches of rain were recorded at Abilene, and 6.44 inches fell at Cameron. The Brazos River reached 36.7 feet and a 142,000 cfs flow at Waco, but most major flooding occurred below that location (U.S. Army Corps of Engineers, 1970, p. 21).

5. The highest stages of record at all points in the Brazos River basin downstream from Waco occurred during November 1913 through January 1914. Centers of intense precipitation were near Leander (13.58 inches) and Hewitt (11.84 inches), while other areas received amounts ranging from 9 inches near Whitney to one inch in the headwaters. A stage of 39.7 feet at Waco produced a 211,000 cfs flow on December 3, 1913 (U.S. Army Corps of Engineers, 1970, p. 21).

6. General rains fell on the Brazos basin during April 14-26, 1915, with a small but intense center located near Taylor, where 15.45 inches of rain fell. About 5 inches of rain fell over a broad area extending upstream from Waco, and produced a stage of 26.0 feet at Waco (Vance, 1934, p. 42; Patterson, 1965, p. 193).

7. Fairly intense and general precipitation fell during the latter part of March and early April 1916. The center of rainfall was near Hico, in the Bosque River basin, where 6.40 inches fell. The resulting flood at Waco

reached 33.8 feet and a flow 113,000 cfs on April 2, 1916 (U.S. Army Corps of Engineers, 1946, p. 23).

9. Heavy intermittent rains fell upstream from Waco during April and May 1922. Kopperl received 24.80 inches, and Cleburne received 22.29 inches. The flood produced the maximum known stage of 30.0 feet at Glen Rose. The Waco stage was 35.9 feet; flow equaled 122,000 cfs, and total flood volume was 2,176,900 acre feet. That volume is greater than total capacity of Lake Whitney. Estimated peak discharge at the Whitney Dam site was 214,000 second-feet (U.S. Army Corps of Engineers, 1946, p. 23; Patterson, 1965, p. 193).

10. The entire Brazos basin experienced light to heavy intermittent precipitation during the period May 1-18, 1930. Centers of rainfall greater than 11 inches were at Graham, Jarrell, and Mexia. Stage at Waco was 28.9 feet and discharge was 74,800 second feet (U.S. Army Corps of Engineers, 1946, p. 23).

11. The flood of May 1935, which crested at 34.9 feet and discharged 112,000 cfs, was the result of rains during two separate periods. The first light general rains occurred during May 2-5 and produced 4.88 inches at Hillsboro and 7.13 inches at Sealy. The second-period rainfall, May 14-20, centered near Putman and gave it 6.84 inches of rain and Brenham 7.59 inches (U.S. Army Corps of Engineers, 1946, p. 24).

12. Records show that during September 13-18, 1936, 30 inches of rain fell on the Colorado River basin and moderate rains fell over the upper Brazos River basin. Graham received 8 inches, but the Brazos River did not produce a flood of any importance. During September 19-24, rains covered a wide extent of the upper Brazos basin and caused the highest stage in 45 years at Lubbock. Rainfall at Lubbock was 8.32 inches. During September 25-28, rain fell over a relatively small area of the Brazos basin above Waco. The center was at Hillsboro, 30 miles upstream, which received 15.45 inches of rain. This produced the flood of record at Waco when the 246,000 cfs discharge crested at 40.9 feet. The peak outflow from Lake Waco on the Bosque River was estimated to be 96,000 second-feet (U.S. Army Corps of Engineers, 1970, p. 22).

13. The upper Brazos River basin experienced two periods of heavy rainfall during May 1941, and intermittent rain throughout most of June. The first period, May 2-5, produced 6.65 inches of rain at Seymour; the second period, May 19-25, produced 8.19 inches of rain at Lubbock. The Brazos River at Waco reached 29.34 feet (U.S. Army Corps of Engineers, 1946, p. 24).

14. During April and May 1942, three periods of heavy rainfall occurred on the Brazos River basin. Hillsboro recorded 9.26 inches during April 19-28 resulting in 35.7 feet stage at Waco. Flood volume at Waco was 2,547,100 acre-feet, the greatest of record at that time (U.S. Army Corps of Engineers, 1946, p. 25).

15. The change from a drought to heavy and frequent rain over most of the Brazos basin began abruptly in mid-April 1957. Heavy precipitation was widespread and consistent, not typified by centers of intense rainfall. The floods of April-June 1957 were outstanding because of the extent and the large volume of runoff produced. Although the runoff for this period was greater than any previous annual runoff, with the exception of 1941, only one stream had a peak discharge exceeding any previous known maximum (Yost, 1963, p. 1).

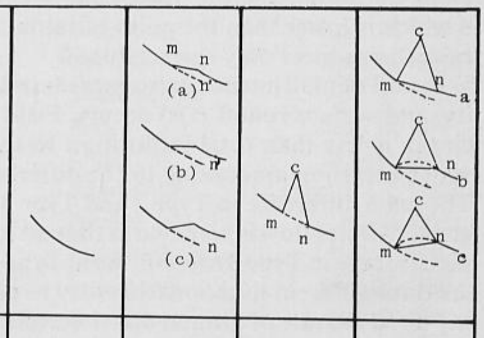
The preceding list of storms is restricted to those storms that caused flooding conditions at Waco. Because of the extent of the Brazos basin many record rainfalls occurred over the basin that did not cause flood stages at Waco. Excessive point rainfalls and storms of great areal extent may occur in west Texas, but because of impounding, infiltration, evaporation, or channel loss do not change significantly the stage at Waco.

The amount of rainfall received is but one of several variables controlling the extent of flooding caused by a particular storm. The volume of precipitation is not the most important determinant of flood potential.

Duration—Intensity Relationship

Storm effect upon stream flow depends upon the duration, distribution and intensity of that storm plus the physical characteristics of the basin. Intensity is normally measured in inches per hour. Horton (1914, p. 370) identified four storm-stream flow relationships related to rainfall intensity (Fig. 4).

For Type 0, rainfall intensity (p) is less than infiltration (f) capacity, therefore there is no surface runoff. Since the field moisture deficiency (FMD) is greater than total precipitation (P) there is no accretion to ground water. The soil moisture depletion curve continues its uninterrupted downward course. These conditions are characteristic of light rains occurring during dry weather when



Moisture Depletion Curve	(see figure above)			
Type	0	1	2	3
Rainfall Intensity(p)	f	f	f	f
Field-Moisture Deficiency(FMD)	P	P	F	F
Surface Runoff (Q)	None	None	Q=P	Q=P
Ground-water Accretion	None	P-FMD	None	F-FMD
Flow Increase	None	Ground Water Flow Only	Surface Runoff Only	Surface & Ground Water Runoff

Fig. 4. Classification of stream rises showing cross sections of surface runoff. *After* Horton, 1914, p. 370.

the soil has the maximum deficiency. Although Type 0 rainfall has no influence on stream flow, the cumulative effects of soil moisture accretion may cause surface runoff to occur from subsequent rainfall of comparable intensity.

Type 1 rainfall intensity is also less than the infiltration capacity, and no surface runoff occurs. Field moisture deficiency is less than total precipitation; therefore more water infiltrates than the soil can absorb, and ground-water accretion occurs.

Actually, three different situations may occur during Type 1 rainfall. In (a) the accretion to the water table, denoted by m-n, is less than the rate of normal ground-water depletion; n′ shows the stage had there been no ground-water accretion. Ground-water depletion continues, but at a reduced rate. In (b) the rates of depletion and accretion are the same and ground-water flow rate is momentarily stable. In (c) the ground-water accretion is greater than depletion, resulting in a water table rise and an increased ground-water outflow.

Stream rises from Type 1 rainfalls are minimal since the stream receives only ground-water flow. They are typical of light spring rains and of greater depth but low intensity rains during the summer and fall.

In Type 2 rainfall water accumulates on the ground at a rate greater than the absorption rate of the soil. This is typical of short, intense thunderstorms and occurs during the summer growing season when the soil moisture deficiency is so great that it is not restored by infiltration. Since the field moisture deficiency is greater than total infiltration (F), there is no accretion to the ground water and no change in ground-water flow. Although the stream rises, normal ground-water depletion continues along line m-n. After the rise to c the stream falls to stage n which is lower than the point of initial rise m. Type 2 rainfall produces only surface runoff.

Type 3 rainfall intensity also exceeds infiltration capacity, and surface runoff (Qs) occurs. Field moisture deficiency is less than total infiltration so there is ground-water accretion amounting to the difference in the two. The main difference in Type 2 and Type 3 is that normal ground-water flow is resumed at the end of the rise n, at a higher stage in Type 3 rainfall. As in Type 1 rainfall there are three different situations that may be present, depending upon the rate of ground-water accretion. In situation (a) and (b) the stage at n, where normal depletion flow resumes, will not be higher than m, the initial stage. In situation (c) n will be higher than m.

Intensity of Typical Storms

Rainfall intensity of typical meteorological conditions that produce excessive precipitation in the study area can be seen by examining individual storms. Thunderstorms are by far the most intense storm type in the study area. The abundant moist tropical air carried up slope by southeasterly winds is ready to be triggered into an unstable state by the time it reaches the study area. Orographic lifting, collision with a cold air mass, or convection may serve to initiate the release of latent energy. Thunderstorms occur separately, in clusters, or embedded in general storms of regional extent.

In May 1934, four local thunderstorms developed around Plainview. Each storm produced seven inches or more rain in two hours. A thunderstorm at Haskell on June 11, 1909, rained six inches in 30 minutes, plus so much hail that piles remained in fields for two days (Vance, 1934, p. 8). The world's greatest point rainfall for 2 hours, 45 minutes duration fell in 1935 when a thunderstorm dropped 22 inches near D'Hanis, Texas. An occurrence outside the study area that exemplifies the intensity of thunderstorms was the Holt, Missouri, storm of 1947, where 12 inches of rain fell in 42 minutes (Jennings, 1950, p. 4.).

The thunderstorm alone is capable of severe local flooding and of producing record tributary stages. However, because of climatic conditions, topography, and channel characteristics the stage of the Brazos River may not change. This is especially true in the western portion of the basin. The intense thunderstorm is an effective major flood producer only if coupled with another weather disturbance.

Hurricane intensity is measured by wind velocity, and wind velocity is a result of pressure differential. The lower the pressure the greater the wind velocity, and the greater the energy of the storm the greater the rainfall intensity. In a study of hurricane wind velocities the central pressure index has been used in conjunction with pressure-wind relationships to determine wind frequencies. Central pressure index is the estimated minimum sea level pressure for an individual hurricane. The index frequency for Texas is illustrated in Figure 5 (Davis, 1975, p. 8.03).

Some of the worst floods of record over the eastern and southern United States seacoasts have been caused by hurricane rains after landfall. A world's greatest observed point rainfall for 14-minute duration occurred at Galveston in 1871, when 3.95 inches fell during that short period (Cornthwaite, 1919, p. 302). The most intense rainfall associated with hurricanes usually ceases within 24 hours after landfall as the circulation dissipates over the inland

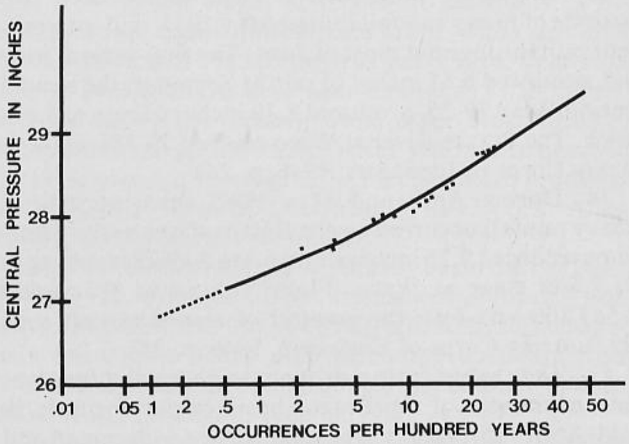


Fig. 5. Accumulated frequency of hurricane central pressures, as frequency per 100 years. *From* Davis, 1975, p. 8.04.

areas of Texas. Occasionally, a hurricane will establish a region of convergence during its decay stage. This converging warm moist maritime air, coupled with the orographic influence of the Balcones escarpment, will trigger torrential rains in the eastern portion of the study area (Schoner, 1968, p. 6).

Rainfall intensity associated with easterly waves is similar to that caused by decadent hurricanes. Both produce general rains of wide extent and torrential intensity, but because of the paths these weather systems take across Texas the easterly wave is more likely to cause excessive rains over the Brazos basin above Waco than is the decadent hurricane which tends to pass to the east.

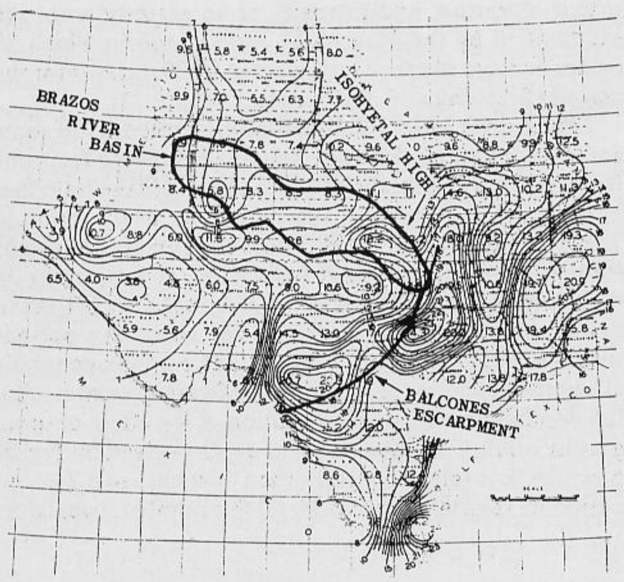
An easterly wave moved across central Texas in September 1952 causing flooding in the Colorado River basin that reached 803,000 cfs inflow at Lake Travis. Many stations reported 20 inches or more during 24 hours (Breeding and Montgomery, 1952, p. 1). The areal extent, duration, and intensity of an easterly wave are exemplified by the July 16-25, 1938, flood in which 20 inches or more of rain were reported by 70 stations for the period (Breeding and Dalrymple, 1944, p. 23).

Topography may compound rainfall intensity in some areas of the State of Texas. An area extending from the Rio Grande northeastward along the line of the Balcones escarpment is especially susceptible to heavy rainfall. There is evidence that the Balcones escarpment has significant effect on the paths of storms and consequently on their intensities. Table 1 shows isohyetal lines for maximum experienced precipitation for three-day periods through 1934. Notice the ridge that extends generally along the Balcones escarpment, indicating greater rainfall depths. Further documentation of the effect of topography on rainfall intensity and depth is given by Figure 6, which lists rains of greater than 10 inches in a 24-hour period in Texas through 1934. Of this number, twenty-six

Table 1. Rainfall, location, and date of all storms of ten inches or more in Texas.

Rainfall	Station	Date	Rainfall	Station	Date
24.00	Hearne	June 28, 1899	11.40	Austwell	July 22, 1919
23.11	Taylor	Sept. 9 & 10, 1921	11.30	Ricardo	June 21, 1924
20.60	Montell	June 29, 1913	11.05	Rockland	May 28, 1929
19.03	Austin	Sept. 9 & 10, 1921	11.00	Marble Falls	Sept. 10, 1921
18.00	Ft. Clark	June 15, 1899	11.00	Turnersville	June 29, 1899
16.02	Hills' Ranch	Sept. 10, 1921	11.00	Turnersville	June 30, 1899
15.71	Matagorda	May 1, 1911	11.00	Turnersville	July 1, 1899
15.00	Mercedes	Sept. 4 & 5, 1933	11.00	Waco	Oct. 2, 1913
14.28	Galveston	July 13 & 14, 1900	10.92	Matagorda	Oct. 24, 1914
14.22	Nacogdoches	June 28, 1902	10.89	Gainesville	July 19, 1919
14.21	Kaufman	Aug. 23, 1908	10.75	Midland	April 19, 1888
14.10	Galveston	Oct. 7 & 8, 1901	10.60	Marshall	April 26, 1921
13.85	Conroe	May 30, 1924	10.60	San Augustine	Aug. 18. 1915
13.54	Beaumont	May 18 & 19, 1923	10.50	Alice	Sept. 15, 1919
13.53	Uvalde	July 2, 1932	10.50	Arthur City	May 12, 1920
13.30	Bonham	July 3, 1903	10.44	Brownsville	Sept. 6 & 7, 1925
13.08	Brackettville	Oct. 1 & 2, 1881	10.43	Beeville	July 3, 1903
13.03	San Marcos	Oct. 2, 1913	10.35	Port Arthur	May 28, 1915
13.00	Georgetown	Sept. 10, 1921	10.32	Brownsville	Sept. 21, 1886
12.67	San Benito	Sept. 5, 1933	10.27	Galveston	June 12, 1925
12.45	Cameron	Sept. 10, 1921	10.10	Matagorda	June 22, 1921
12.43	Brackettville	May 28, 1880	10.07	Gainesville	July 2, 1903
12.35	Sinton	April 28, 1930	10.05	Orange	May 28, 1915
12.22	Port Lavaca	Aug. 10, 1903	10.05	Sabinal	April 20 & 21, 1926
12.19	Galveston	Oct. 22, 1913	10.02	Brenham	Oct. 3, 1902
12.00	Freeport	July 22, 1933	10.00	Austin	April 23, 1915
12.00	George West	Sept. 15, 1919	10.00	Brazoria	Sept. 8, 1900
12.00	Harlingen	Sept. 4 & 5, 1933	10.001	Brazos	May 8, 1922
11.96	Cuero	July 23, 1919	10.00	Brownsville	Sept. 4 & 5, 1933
11.91	Brownsville	Sept. 22, 1886	10.00	Edna	June 23, 1921
11.80	Mexia	Sept. 4, 1932	10.00	Fairfield	Sept. 4, 1932
11.60	Kerrville	Sept. 14 & 15, 1900	10.00	San Marcos	Oct. 19, 1909
11.40	Austin	Oct. 15, 1870	10.00	San Marcos	Dec. 4, 1913

From Vance, 1934, p. 83.



occurred along the coast; twenty-six along the Balcones escarpment or just below it; and the remainder were scattered over other areas of the state (Vance, 1934, p. 87). Figure 6 also displays another important fact concerning rainfall depth. The isohyetal high in the eastern portion of the Brazos basin indicates an experienced pattern of heavier rainfall nearly approximating the basin boundary. The relation of the Balcones escarpment to some individual storms is illustrated in Figure 7 which substantiates the belief that the Balcones escarpment triggers intense rainfall.

Fig. 6. Isohyetal pattern of maximum experienced three-day storms showing the relationship of the Brazos River basin and the Balcones escarpment to those storms. *From* Vance, 1934, p. 87.

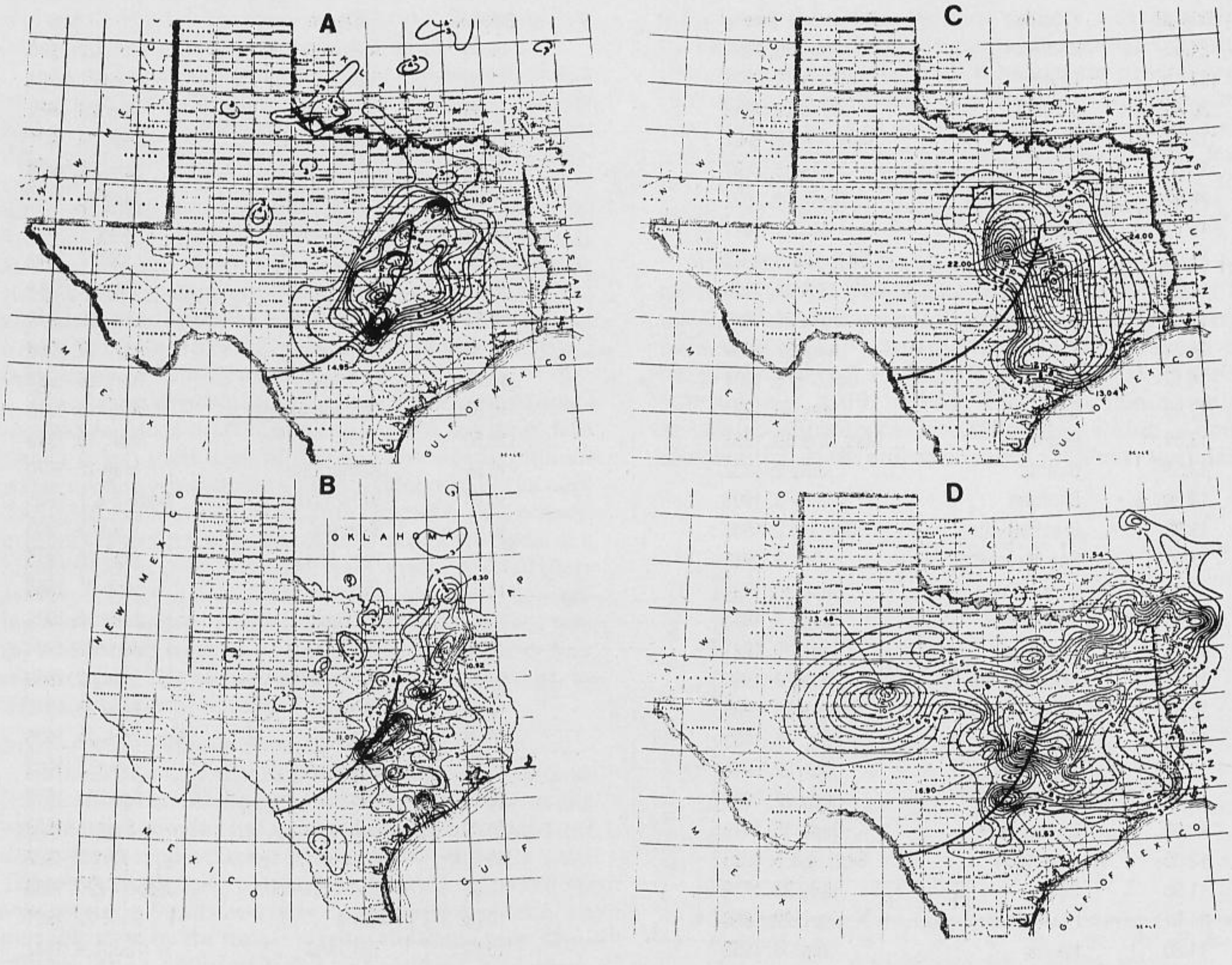


Fig. 7. Isohyetal maps showing the relationship of the Balcones escarpment to: (A) the Dec. 1913 storm, (B) the April 1915 storm, (C) the June 1899 storm, and (D) the July 1902 storm. Vance, 1934, p. 24, 30, 38, 43.

PROBABLE MAXIMUM STORM

Probable maximum precipitation (PMP) is defined by the American Meteorological Society as the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. Due to the limited knowledge of the complicated, interrelated processes in a storm, probable maximum precipitation values are termed generalized estimates. Probable maximum flood results from probable maximum precipitation and is defined as the most severe flood considered reasonably possible of occurrence. Derivation of the possible maximum flood is obtained by maximization of the meteorological and hydrological factors that combine to produce the maximum storm. This estimate is essential where complete protection against failure of a project, such as a dam, is mandatory because of potentially great loss of lives and property. Therefore, the estimates represent only the best judgement of the realistic upper limit of precipitation that can occur at a general location and time (Gilman, 1964, p. 9-62).

The basic approach used for determining the maximum probable storm for a non-orographic region, such as the Brazos basin, involves three operations: (1) moisture maximization, (2) transposition, and (3) envelopment (Beard, 1975).

MOISTURE MAXIMIZATION

Moisture maximization consists of mathematically increasing the rainfall depth to be expected from a given storm type to an amount considered the maximum possible for that location and time of year. This increase is determined by computing the maximum moisture that

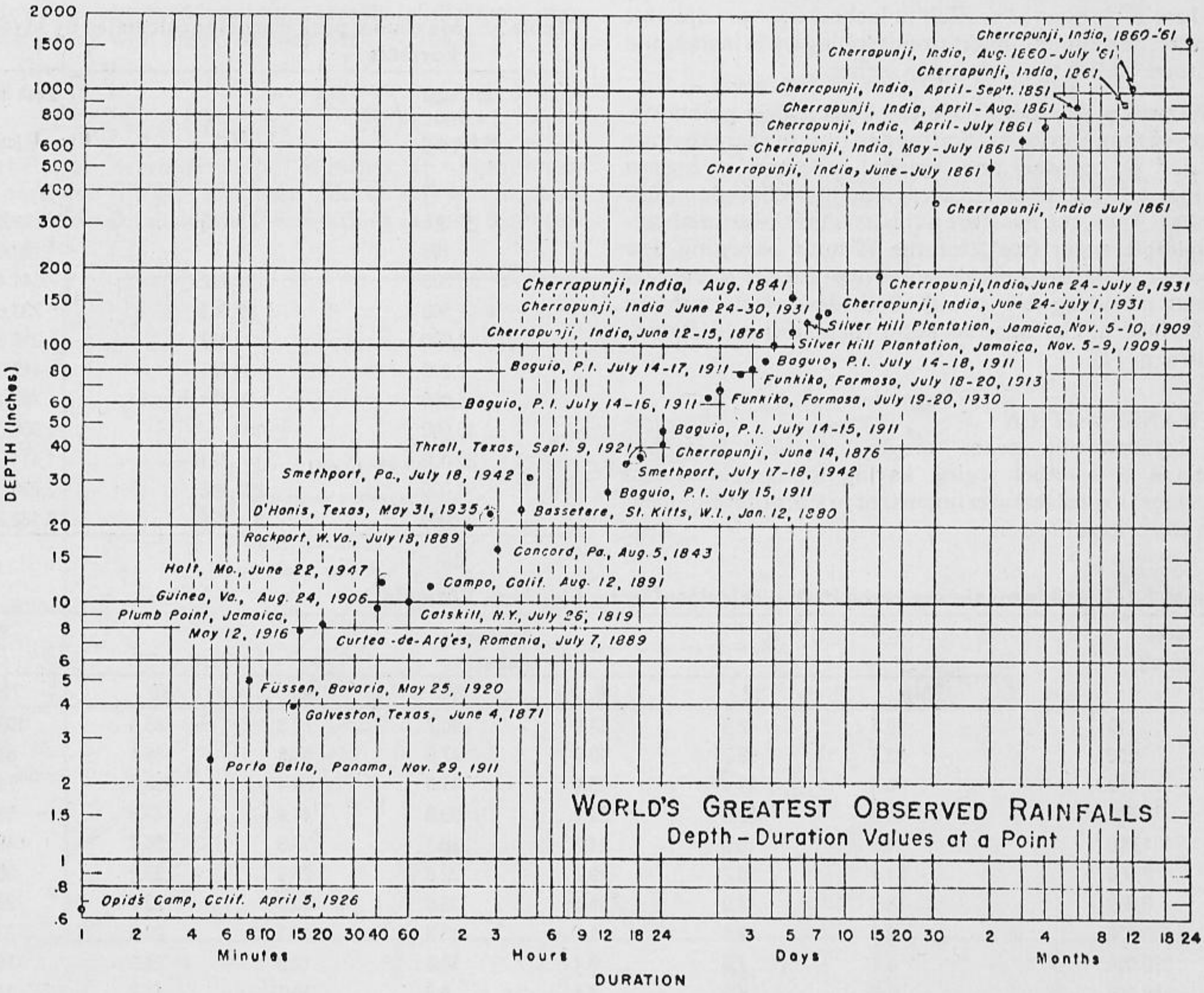


Fig. 8. World's greatest observed point rainfalls. *From* Jennings, 1950, p. 4.

could possibly occur in the atmosphere for location and season.

Attempts to model extreme rainfalls are hampered by the lack of data within storms to check such parameters as horizontal convergence and vertical motion. Since these cannot be readily measured, the practice has been to use recorded extreme rainfalls as an indirect measurement of those factors that influence excessive rainfall (Fig. 8).

Storms of record are adjusted to maximum moisture under the assumption that sufficiently large samples of extreme storms have been experienced so as to have produced near optimum storm efficiency (efficiency means a combined measure of all parameters, except moisture, that are important to rainfall production). Lifting of air masses by terrain slope is not normally considered for the Brazos basin.

Moisture is maximized by multiplying observed rainfall depths by the moisture adjustment. The mathematical expression is:

$$P \times wp\ maximum / wp\ storm = moisture\ adjusted\ rainfall \quad (1)$$

where P = observed rainfall in inches, wp = precipitable water, "maximum" refers to enveloping wp in inches, and "storm" refers to storm wp in inches.

Maximum dew points are the highest dew points observed for a particular location and time of year. They are based on seasonal and regional envelopes of highest observed 12-hour persisting dew points, reduced to 1,000 mbar. Thus, the moisture adjustment is the ratio of precipitable water (wp) (for the 12-hour persisting dew point) to the precipitable water (wp) for the storm (12-hour persisting dew point). Both dew points must be obtained at the same location (Schreiner and Riedel, 1976, p. 11).

TRANSPOSITION

Transposition means "moving" a storm from one region to another region having topographical and meteorological features important to storm development in the original region.

A principal factor which sets limits to storm transposition is topography. If storm patterns and locations correspond to underlying topography, transposition should be limited to areas of similar terrain. The Balcones escarpment has triggered several intense storms (Dorroh, 1946, p. 32), but due to its proximity to the eastern portion of the study area all storms occurring south of the Brazos basin should be transposable. This does not include storms caused by decadent hurricanes (Schoner, 1968, p. 23).

Studies indicate a decrease in areal rainfall to the western side of the study area. This is due to the gentle upslope of the terrain plus the increased distance from the moisture source area. However, this is true only for larger areas. Narrow bands of moist air are capable of feeding intense point storms of short duration.

Wide-scale meteorological features, such as surface and upper air high or low pressure centers that control or influence storms in one region, must be considered prior to transposing a storm from that region.

General guidelines given by Schreiner and Riedel

Table 3. Maximum peak discharge calculated by Myer's Formula.

Drainage area M (sq mi)	$\sqrt{M}$	Peak flow Q (cfs)
1		
10	3.163	31,630
100	10.	100,000
200	14.142	141,421
500	22.361	223,610
1,000	31.623	316,230
2,000	44.721	447,210
5,000	70.711	707,110
10,000	100.	1,000,000
20,000	141.421	1,414,210
50,000	223.606	2,236,060
100,000	316.228	3,162,280

Table 2. Possible maximum precipitation calculated using Fletcher's Formula.

Area (sq mi)	Duration (Hour)						
	6	12	18	24	36	48	72
10	30.4	42.9	52.9	60.7	74.3	85.8	105.1
100	23.5	33.3	40.7	47.0	57.6	66.5	81.4
200	20.8	29.4	35.6	41.5	50.4	58.7	71.9
500	16.9	23.9	29.2	33.8	41.4	47.8	58.5
1,000	14.0	19.9	24.3	28.1	34.3	39.7	48.6
2,000	11.4	16.2	19.7	22.8	27.9	32.2	39.5
5,000	8.5	11.9	14.6	16.9	20.7	23.7	29.5
10,000	6.7	9.5	11.5	13.3	16.3	28.9	23.1
20,000	4.1	7.5	9.1	10.5	12.9	24.9	18.2
50,000	3.9	5.9	7.1	8.2	10.1	11.7	14.3
100,000	3.2	4.5	5.4	6.3	7.7	8.9	10.9

(1976, p. 13) for storm transposition within the eastern two-thirds of the United States are:

1. Do not transpose across the Appalachian Divide.
2. Tropical storms transposed farther away from or closer to the coast require adjustment.
3. Storms transposed into regions of greater elevation differences are restricted to elevations within 1,000 feet of the original storm elevation.
4. Eastern limits are the western upslopes of the Appalachians.
5. Western limits are related to elevation and vary from storm to storm, but in most cases these coincide with the 3,000- to 4,000-foot contour.
6. Southern limits are not defined since storms located farther south provided greater rainfall values.
7. The Canadian border is the northern limit.

ENVELOPMENT

Using special graphs, moisture-maximized and transposed rainfall values obtained from various storms are smoothly "enveloped." Observed maximum point-rainfall depths tend to vary with the square root of duration. However, observed maximum areal rainfall depths vary excessively with area (Fletcher, 1951, p. 1042).

The equation

$$R = \sqrt{D}\left(0.5 + \frac{266}{19.2 + \sqrt{A}}\right) \qquad (2)$$

where R = depth of rainfall in inches, D = duration in hours, and A = area in square miles closely envelopes all observed rainfall depths for durations ranging from one minute to one year, and for areas of point rainfall to areas covering 200,000 square miles. Theoretically, this equation is correct for estimating possible maximum precipitation (Fletcher, 1950, p. 347). Table 2 gives calculated probable maximum precipitation depths for various area-duration combinations, using Fletcher's equation.

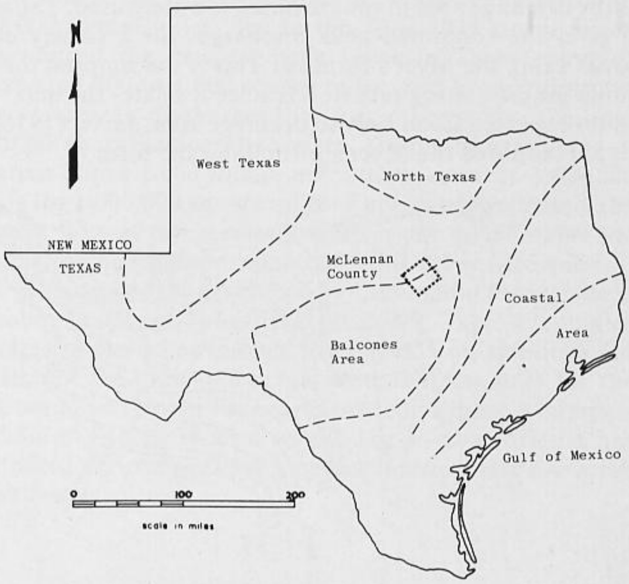


Fig. 9. Areas within the State of Texas classified by Commons for use in determining experienced maximum flood peak envelope. *From* Commons, 1945, p. 6.

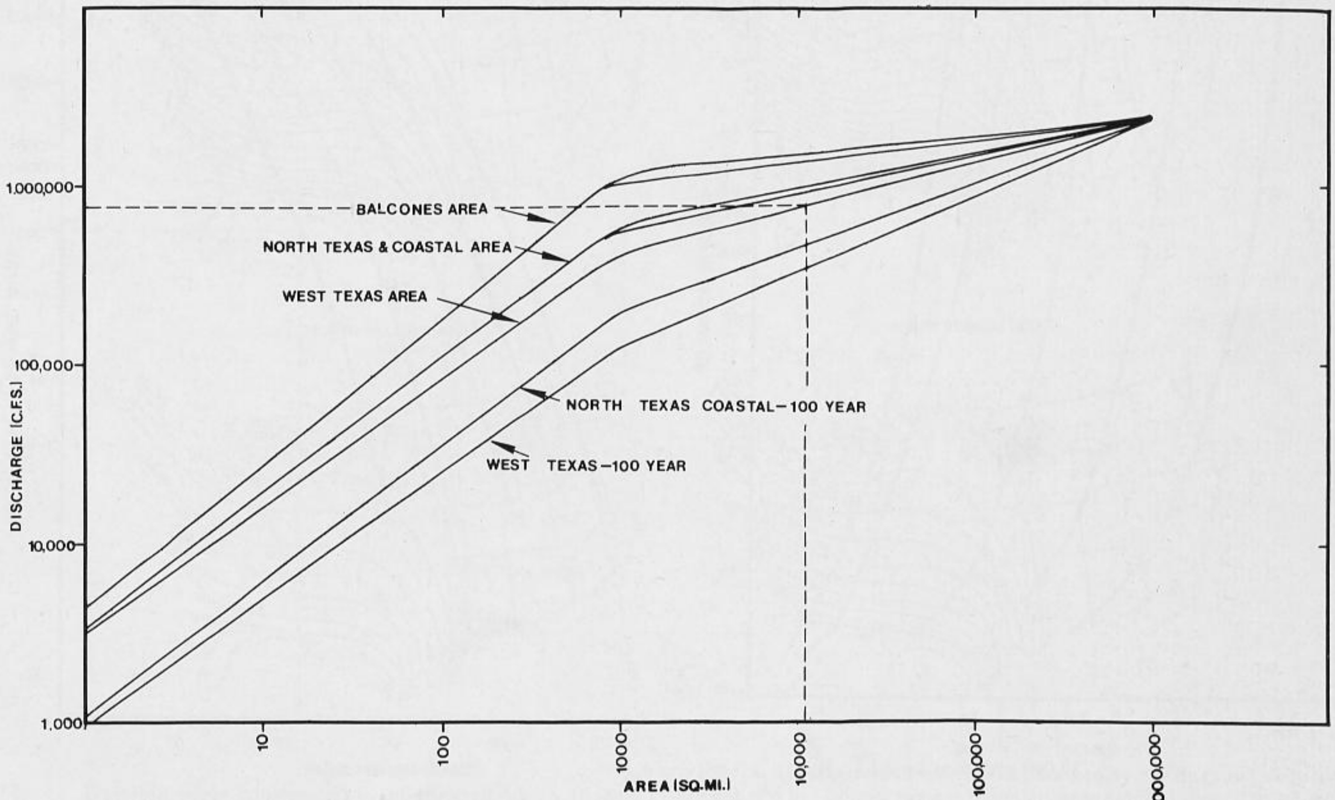


Fig. 10. Peak discharges enveloped by Commons. Commons, 1945, p. 6.

PROBABLE MAXIMUM PEAK FLOWS

Other methods have been proposed for enveloping observed peak flows to develop general estimates of probable maximum peak flows for various size drainage areas. The Myer's formula,

$$Q = 10{,}000 \quad \sqrt{M} \tag{3}$$

in which Q is the peak flow in cubic feet per second and M is the drainage area in square miles, is widely used. Table 3 gives the computed peak discharges for a variety of areas using the Myer's formula. This is the simplest formula for estimating rare floods since it relates the maximum expected flood only to drainage area. Jarvis (1936, p. 33) modified the Myer's formula to the form,

$$Q = 10{,}000 \quad p\sqrt{M} \tag{4}$$

where the coefficient p is a variable that relates the observed maximum peak flow of a stream to the assumed maximum possible peak flow of all streams. Consequently the Jarvis modification results in lower peak flow estimates than the original Myer's formula.

According to the Myer's formula (Table 3), an area of 400 square miles is capable of producing a peak flow of 200,000 cfs. In June 1935 the West Nueces River near Bracketville experienced a 580,000 cfs flow from 402 square miles of drainage area (Williams and Crawford, 1940, p. 136). The obvious disparity between Myer's estimated maximum and what actually occurred dramatically points out that the peculiar physiographic and

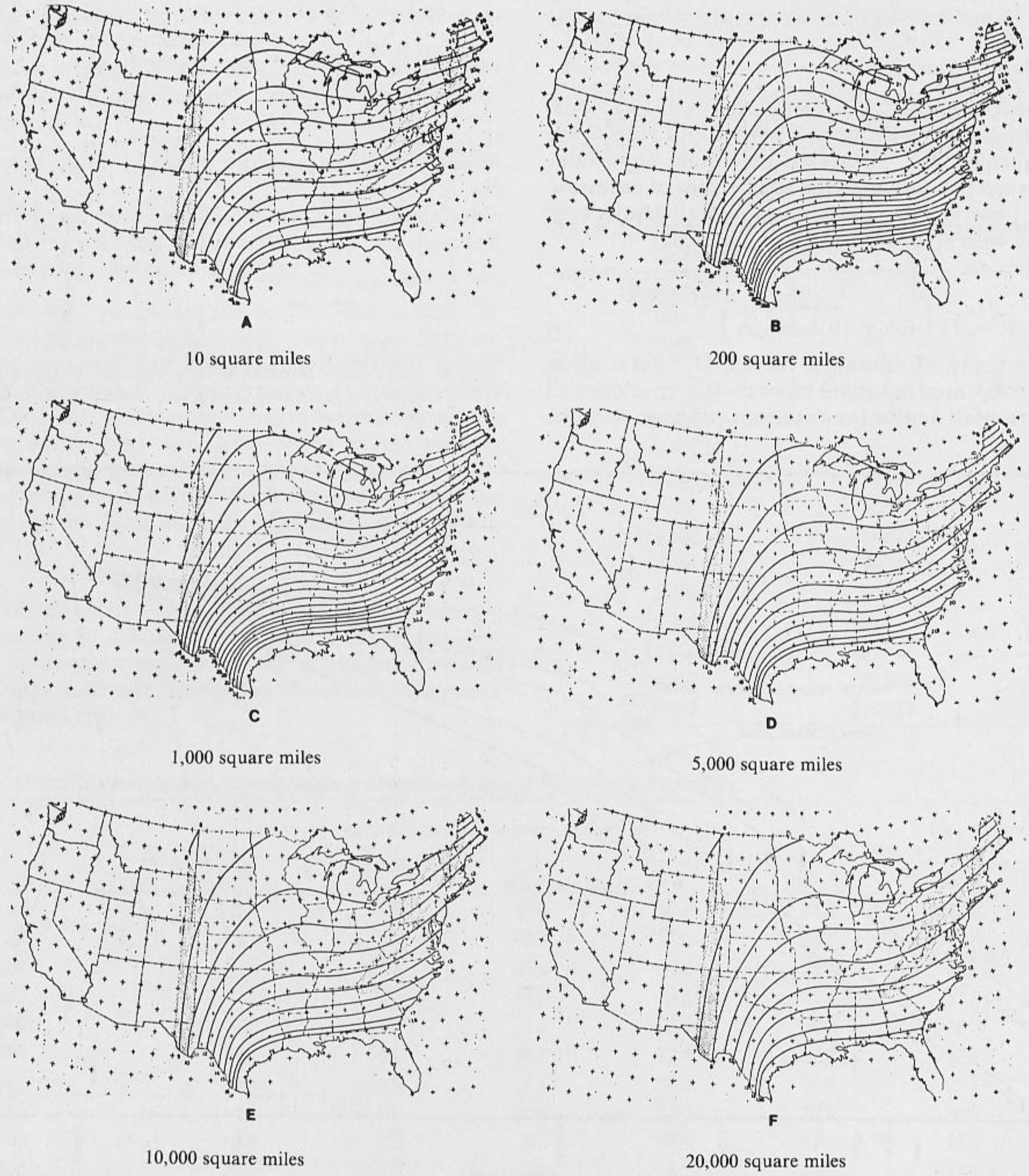


Fig. 11. Probable maximum 24-hour precipitation charts for areas of 10 to 20,000 square miles. *From* Schreiner and Riedel, 1976.

Table 4. Geographical areas-peak flow calculation using Commons' Method.

Size (sq mi)	Balcones	North Texas & Coast Area	West Texas
10	28,000	20,000	16,500
100	185,000	112,000	84,000
200	325,000	190,000	140,000
500	685,000	375,000	270,000
1,000	1,200,000	620,000	420,000
2,000	1,300,000	715,000	510,000
5,000	1,420,000	890,000	650,000
10,000	1,550,000	1,000,000	780,000
20,000	1,650,000	1,175,000	920,000
50,000	1,810,000	1,390,000	1,175,000
100,000	1,990,000	1,600,000	1,400,000

Flow in fps.

meteorologic characteristics of an area must be considered when more specific estimates are required.

In a study of flood peaks in Texas, Commons (1945a, p. 1) identified four areas in which floods have distinctive characteristics. The nature of flooding in each of the four areas differs because variable factors control or influence rainfall intensity and rainfall runoff. Distinctive character of an area is controlled by such factors as stream gradient, topographic dissection, slope steepness, soil permeability and distance from atmospheric moisture sources.

Commons (1945a) developed a maximum flood of record, peak flow-area envelope for each of the distinctive areas shown in Figure 9. By plotting the logs of about 500 flood peaks against the logs of net drainage areas, he was able to plot enveloping maximum peaks for each of the four areas (Fig. 10). Note the sharp break at 800 to 1,000 square miles, due to the June 1935 storm which produced the greatest peak flows in Texas. Since it covered 800 to 1,000 square miles, and produced by far greater peak discharges than any other storm, the lines break sharply rather than curve. The plotting trend for all areas above 1,000 square miles tends towards 2,400,000 cfs for 1,000,000 square miles. This is approximately the peak flow of the Mississippi River at a point where the area drained is approximately 1,000,000 square miles.

This procedure developed by Commons (1945a) is considered accurate for general estimates. Table 4 tabulates calculations of enveloped area-peak flow relations for each of the indicated areas. Note that the lines for the Coastal and North Texas areas are coincident. A comparison of Tables 3 and 4 reveals the Myer's formula has limited accuracy except for some intermediate size areas in Texas.

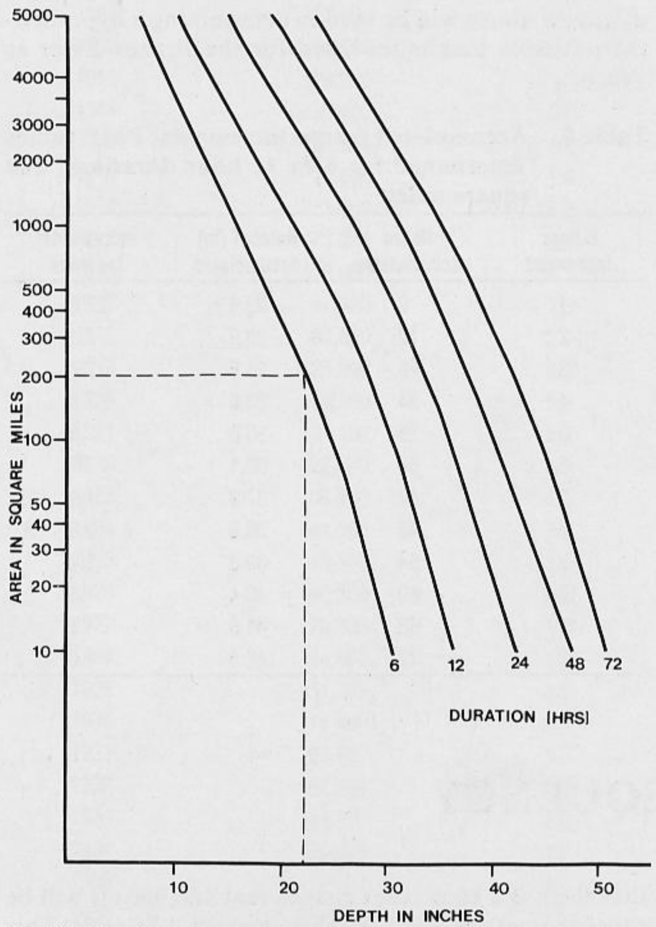


Fig. 12. Duration curve constructed by plotting all 10- to 10,000-square-mile basin areas against all 6- to 72-hour storm rainfall depths.

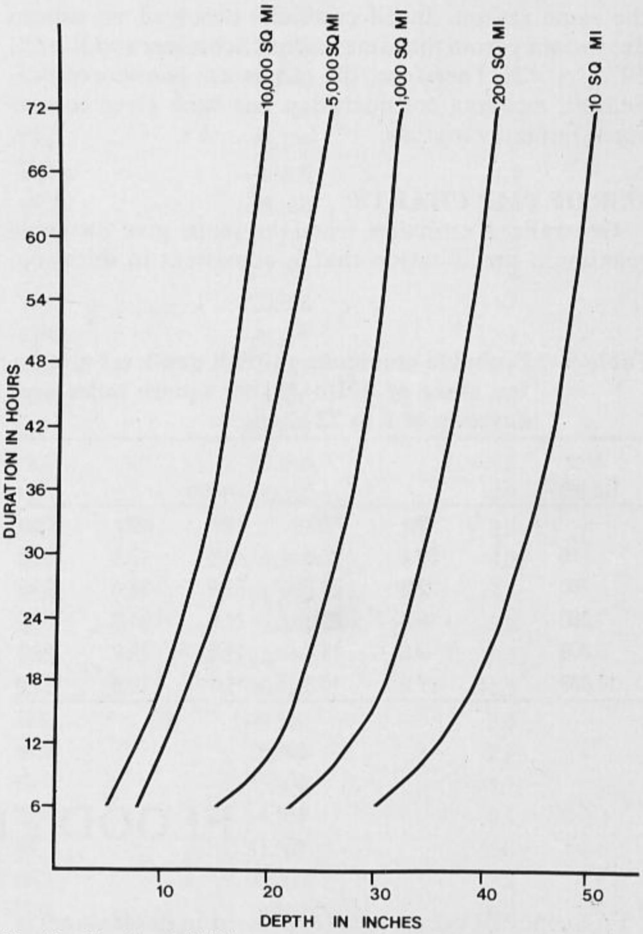


Fig. 13. Hourly rainfall increments obtained by plotting rainfall durations of 6 to 72 hours against rainfall depths for basins of 10 to 10,000 square miles for probable maximum storms.

PROBABLE MAXIMUM PRECIPITATION

The National Weather Service has compiled a set of generalized charts giving the level of Probable Maximum Precipitation for drainage areas from 10 to 20,000 square miles and durations from 6 to 72 hours (Fig. 11). The Brazos River basin lies within the set of charts covering the United States east of the 105° Meridian (Schreiner and Riedel, 1976, p. 70-99).

The basic data for developing these charts were observed maximum areal precipitation depths for various durations developed by a standardized depth-area-duration (D-A-D) analysis of point precipitation amounts. Over 500 storms were analyzed and the maximum areal depths calculated and published by the U.S. Army Corps of Engineers. Storm rainfalls from these published reports were augmented by numerous unofficial storm D-A-D values developed by the National Weather Services Hydrometeorological Branch.

The study region, east of the 105° Meridian, was divided into 7 zones and seasonal tests were performed. Within each zone the greatest observed rainfall depths for periods of 6, 24, and 72 hours, for areas of 10, 200, 1,000, 10,000, and 20,000 square miles were identified. If the second and third greatest rainfalls were within 10 percent of the greatest, they were also considered in the seasonal test. All rainfall values were checked for each area size to determine if the 6-, 24-, and 72-hour rainfalls came from the same season. In all cases the observed maximum depths came from the same season (Schreiner and Riedel, 1976, p. 42). Therefore, the charts are considered All-Season, meaning consideration has been given to seasonal rainfall variation.

USE OF PMP CHARTS

Generalized estimates from the maps give probable maximum precipitation that is consistent in duration, area, and location. PMP depths for any basin in the United States, east of the 105° Meridian, can be determined for areas of 10 to 20,000 square miles and durations of 6 to 72 hours. The procedure (Schreiner and Riedel, 1976, p. 45) is as follows:

1. Determine the geographic center in which the storm is to be located and the areal extent. (As an illustration I will consider a 200-square mile storm centered between Lake Whitney and Waco).
2. From the PMP maps covering those areas, determine the PMP rainfall depths at the center of the study area. (At least four of the six area sizes closest to the study area should be considered.) Tabulate the values for all durations as in Table 5.
3. Plot the PMP depths on semi-logarithmic paper and draw smooth rainfall duration curves through the plotted data points as shown in Figure 12. This completed graph is called a depth-area-duration graph.
4. Determine the PMP depths at the study area size (200 square miles) for each duration, 6 to 72 hours, from the D-A-D graph (see indicated line, Fig. 12).
5. Plot the study area PMP values and draw a smooth line connecting these points. From this curve, Figure 13, accumulated PMP values can be determined in 6-hour increments for durations of 6 to 72 hours (see Table 6).

The information listed in Table 6 and the procedure discussed above will be used in determining a hypothetical probable maximum flood for the Brazos River at Waco.

Table 5. Probable maximum rainfall depth tabulation for areas of 10 to 10,000 square miles and duration of 6 to 72 hours.

Area (sq mi)	Duration				
	6hr	12hr	24hr	48hr	72hr
10	30.4	36.6	42.3	47.9	50.0
200	22.8	28.9	33.9	38.0	42.5
1,000	16.6	22.8	27.2	31.8	35.3
5,000	9.5	13.4	18.5	23.2	26.5
10,000	7.2	10.8	15.1	19.5	23.9

Table 6. Accumulated 6-hour incremental PMP values determined for 6 to 72 hour durations, 200 square miles.

6-Hour Increment	Hours Accumulated	Rainfall (in) Accumulated	Incremental Increase
1	6	22.8	22.8
2	12	28.9	6.1
3	18	31.6	2.7
4	24	33.6	2.3
5	30	35.0	1.1
6	36	36.1	1.1
7	42	37.2	1.1
8	48	38.0	0.8
9	54	39.3	1.7
10	60	40.4	1.1
11	66	41.5	1.1
12	72	42.5	1.0

FLOOD FREQUENCY

Frequency of occurrence (expressed in percentage) is related to the probability of occurrence. If the probability is 0.10 that a flow of 100,000 cfs will be exceeded, it means that there is a 10 percent chance that 100,000 cfs will be exceeded, on the average, once in every 10 floods. This does not imply that 100,000 cfs will be exceeded exactly once in ten consecutive occurrences. Some sets of ten consecutive floods will have no peak flow greater than 100,000 cfs, while other sets will have more than one flood greater than 100,000 cfs.

Flood frequency curves are commonly used in design of local flood protection water projects and in studies to determine the economic value of flood control projects. There are two common frequency curves used in hydrologic analysis: (1) a curve which utilizes the maximum annual peak flow is used when the major concern is with very large floods (or when second largest events are of minor concern in the analysis), and (2) a partial-duration curve is ordinarily used in economic analysis of a water project since substantial economic losses can result from the second or third largest flood of an unusually wet year (the partial-duration curve considers the frequency of all events above a specific base flow). If five flood peaks above the base value occurred within the same year, all five would be considered when constructing the partial-duration curve (Davis, 1975, p. 4-15).

Only annual maximum events are considered in this study since second largest events are not capable of producing a probable maximum flood.

The two approaches to developing flood frequency

Table 7. Annual flood of record at Waco expressed as a percentage of the "curve-maximum."

Year	Peak Flow	% Curve Max	Year	Peak Flow	% Curve Max
1899	117,000	8.4	1938	88,400	6.3
1900	69,000	4.9	1939	43,500	3.1
1901	22,000	1.6	1940	38,500	2.8
1902	106,000	7.6	1941	68,800	4.9
1903	43,600	3.1	1942	126,000	9.0
1904	22,400	1.6	1943	67,400	4.8
1905	85,800	6.1	1944	137,000	9.8
1906	40,900	2.9	1945	144,000	10.3
1907	13,500	0.96	1946	37,600	2.7
1908	142,000	10.1	1947	29,600	2.1
1909	23,500	1.7	1948	36,800	2.6
1910	29,200	2.1	1949	71,400	5.1
1911	35,400	2.5	1950	16,700	1.2
1912	24,900	1.8	1951	18,300	1.3
1913	19,000	1.4	1952	25,500	1.8
1914	211,000	15.2	1953	61,700	4.4
1915	73,300	5.2	1954	22,600	1.6
1916	113,000	8.1	1955	23,600	1.7
1917	17,600	1.3	1956	46,100	3.3
1918	30,000	2.1	1957	101,000	7.2
1919	125,000	8.9	1958	70,600	5.0
1920	78,100	5.6	1959	10,600	0.8
1921	31,100	2.2	1960	80,900	5.8
1922	122,000	8.7	1961	62,800	4.5
1923	66,900	4.8	1962	35,400	2.5
1924	41,900	3.0	1963	16,300	1.2
1925	49,300	3.5	1964	49,500	3.5
1926	40,500	2.9	1965	45,800	3.9
1927	75,300	5.4	1966	33,700	2.4
1928	24,800	1.8	1967	18,800	1.3
1929	31,300	2.2	1968	39,000	2.8
1930	74,800	5.3	1969	38,600	2.7
1931	93,500	6.7	1970	15,100	1.1
1932	62,500	4.5	1971	4,950	0.4
1933	41,100	2.9	1972	17,500	1.3
1934	45,400	3.2	1973	32,000	2.3
1935	112,000	8.0	1974	9,600	0.7
1936	246,000	17.6	1975	40,000	2.9
1937	26,600	1.9	1976	17,800	1.3

curves are graphic and analytic. Beard (1962, p. 9) suggests that although results of frequency studies can be obtained entirely analytically, they should be plotted graphically so that observed data may be visually compared with the derived curve. Using the graphic method of frequency study, the derived curve is easily visualized, and the observed data may be compared with the computed results.

Graphic construction of a frequency curve consists of arranging the selected data in order of magnitude and plotting on a suitable coordinate system. Magnitude is plotted on the vertical scale against the frequency on the horizontal scale. A frequency curve is a best fit smooth line drawn through these plotted points (Davis, 1975, p. 4.04). The objective of the frequency analysis is to determine the magnitude of flood equaled or exceeded only once in a specified period of years. This period of year is known as the recurrence interval (Dalrymple, 1960, p. 5).

In constructing a frequency curve for the Brazos River at Waco, annual peak flood data were chosen. The annual peak flows for each year of record were determined and arranged by magnitude of flow (Table 7). It was then necessary to compute a measure of frequency so that a plotting position could be obtained for the frequency scale. This plotting position is in terms of years.

Plotting positions were derived from the Beard formula:

$$P = 1 - (0.5)^{1/n} \qquad (5)$$

(where N is the number of years of record) for the probability P of the largest event, and

$$P = (0.5)^{1/n} \qquad (6)$$

for the probability of the smallest event, with probabilities for the remaining events in the series determined by linear interpolation between probabilities for the extremes (USDA, 1966, p. 37). Recurrence interval for the flood of record on the Brazos River at Waco is 111 years (P = 0.896 percent), when N = 77 years. Using the same formula, probability of the smallest event is 99.1 percent, almost certain annual recurrence.

The formula used by the U.S. Geological Survey is:

$$T = \frac{N + 1}{M} \qquad (7)$$

where T = recurrence interval, in years; N = number of years of record; and M = magnitude of flood, the greatest being 1.

This formula applies to annual flood data as well as partial series. Results of this calculation conform with current theoretical treatments (Dalrymple, 1960, p. 16). Recurrence interval for the Brazos River flood of record, using the U.S. Geological Survey formula, is 78 years for the greatest flood and 1.01 years for the smallest.

In computing plotting positions by any formula there are situations when computations must be modified. For example, discharges at the Waco gage have been recorded since 1899, but historical records document the 1936 flood peak as the highest since at least 1847. Therefore, a more realistic number of years of record N for any formula would be 130 years. For example, using Beard's formula (5), assigning N a value of 130 years instead of 77 years, the recurrence interval (P = 0.527 percent) is 173 years for the greatest flow and a 99.5 percent annual recurrence probability for the smallest flow recorded. The same contrast can be seen using the U.S. Geological Survey formula (7), when N is increased from 77 years to 130 years. Calculations for the greatest flow, M-1, is:

$$T = \frac{130 + 1}{1}$$

giving a 131-year recurrence interval as opposed to T = 78 when N = 77.

PLOTTING GRID

Frequency data plotted on Cartesian coordinates portray a frequency relationship on a line that may curve abruptly at both upper and lower ends. Those parts of the curve of greatest interest, the extreme values, are those compressed into small areas making extrapolation of the curve difficult. Because of these shortcomings a probability grid has been developed, on which a series of values (such as river stage), which has a lower limit far removed from the range of experience, will yield an approximate straight-line frequency curve. A variable, such as stream flow, in which the lower limit of zero is often approached will generally yield a straight-line frequency curve only if plotted on a logarithm grid. The logarithmic probability grid used for Figure 10 has been developed so that flow can be plotted directly to yield a straight line (Beard, 1962, p. 13).

A flood frequency study by Commons (1945b, p. 1) has direct application in the current study. The basis for Commons' study is explained by this statement.

> The study of flood frequencies on a stream is only too often handicapped by a short time record, or by the absence of any record. Again, the period of record may contain no major flood, or it may contain one or more floods approaching the maximum. Floods of enormous magnitude have occurred on some streams in historic times, and there is no reason to believe that like floods cannot occur on other streams located in similar areas. Any method of computing or estimating flood frequencies that fails to take this into account is likely to give results that are much in error.

The use of a percentage of a maximum flood was adopted by Commons to put all stations on a common basis. This procedure made it possible to combine records. For example, flood records of a major river in one basin will be considered with those of a minor tributary in another basin. The procedure uses the curve of Maximum Flood Peaks Experienced in Texas (Fig. 10). Each of the 34 stations used in compiling the curve was assigned a "curve maximum" flood, which is the maximum flood for that drainage area and locality. An example of how the "curve maximum" for each station was determined is illustrated by calculating the "curve maximum" for the Brazos River at Waco.

The "curve maximum" of the Brazos River at Waco was obtained by first determining within which area the basin lies. Waco is in the northeastern tip of the Balcones area, (Fig. 9), but the contributing portion of the Brazos River is between the Balcones and north Texas areas. For localities lying between areas, values intermediate between the two areas and proportional to the distance from each are used. Emphasis should be placed on the location of the drainage basin rather than to the location of a particular point on the stream (Commons, 1945a, p. 2).

"Curve maximum" for the 19,000 square miles contributing runoff to the Brazos River ranges from 900,000 cfs to 1,600,000 cfs (see Figure 10 dashed line from 19,000 vertical to the west Texas curve, then horizontal to 900,000 cfs; and vertical to the Balcones curve then horizontal to 1,600,000 cfs). Since there is extreme variance in enveloped recorded flood peaks within the study area, judgement must be used in interpolation. Although approximately one-fourth of the contributing Brazos River is in the west Texas area, this was offset by the fact that only 700 square miles of Balcones area produced a flood peak equal to 20,000 square miles of west Texas area. A "curve maximum" of 1,400,000 cfs was selected for the Brazos River at Waco.

WEATHER PHENOMENA FREQUENCY

Flood frequency on the Brazos River at Waco (or recurrence interval) is a product of the occurrence frequency of weather phenomena that cause flooding in the Brazos River basin.

An easterly wave passes over the Eastern Caribbean about twice a week from June through September (Orton, 1966, p. 9). Such waves have an average velocity of about 5° longitude per day crossing the Gulf of Mexico and may affect weather in south Texas, but generally dissipate shortly after moving inland. An easterly wave that may cause flooding over the study area is such an unusual event that little is known concerning probable frequency.

The occurrence and frequency of hurricanes are well documented. For a 73-year period there were no hurricanes or tropical storms reported on the Texas coast during the periods from December through May. During this 73-year period 12 hurricanes were reported in June, and 8 in July. Sixteen hurricanes occurred during the period of record in August. Although September had the greatest occurrence of tropical storms in the Gulf of Mexico, they began to migrate east by that time of year, and the Texas coast reported only 14 for the Septembers of record. Only 6 were reported during the Octobers, and for the Texas coast the tropical storm and hurricane season is over by November (Orton, 1964, p. 167). Tropical storms and hurricanes actually cross the Texas coastline at a frequency of 0.67 storms per year (Hayes, 1967, p. 1). Several variable conditions must exist coincidentally for flood-producing, hurricane-derived storms to

Table 8. Mean number of thunderstorm days in the middle and upper Brazos River basin.

STATION	MONTHS												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
El Paso	*	*	1	1	3	5	10	11	3	2	*	*	36
Amarillo	*	*	1	4	9	9	11	9	4	3	*	*	50
Lubbock	*	*	1	3	9	9	8	5	3	3	*	*	41
Midland	*	1	1	3	6	5	8	6	3	2	1	1	37
Abilene	*	2	3	5	8	6	5	5	3	3	1	1	42
San Angelo	*	1	2	4	7	4	6	4	4	3	1	*	36
Wichita Falls	1	2	3	5	10	7	7	4	4	3	2	1	49
Fort Worth	1	2	4	6	7	6	6	4	3	3	2	1	45
Dallas	1	3	4	6	7	5	4	4	3	3	2	1	43
Texarkana, Ark.	2	3	6	7	9	7	9	7	5	3	3	2	63
Waco	2	3	4	6	8	5	5	5	4	3	2	2	49
Austin	1	2	3	5	7	4	4	5	3	3	2	1	40

From Orton, 1964, p. 151.

move across the study area. This is true for any meteorological condition causing flood-producing storms. Figure 14 shows the paths of hurricanes that have caused excessive rainfall in the eastern portion of the study area.

Since thunderstorm development depends upon the vertical mass movement of moisture-laden air by convection, it occurs most frequently during the warm months. Heat not only provides lifting energy, but warm air has a higher saturation point than does cold air; therefore, more moisture per unit of air is available for lifting.

The probable maximum storm for small areas (less than 10 square miles) is likely to result from a thunderstorm, or a cluster of thunderstorms. They occur during every month of the year in the Waco area but are more frequent in April and May. Table 8 shows the mean number of thunderstorm days in the central and western parts of Texas (Orton, 1964, p. 165). Thunderstorms are significant to the study of probable maximum flooding at Waco because they occur in conjunction with other weather phenomena capable of producing a probable maximum storm over a major portion of the Brazos basin.

INFILTRATION

The ability of a drainage basin to absorb, therefore detain, the precipitation that falls, determines the character of the resulting hydrograph. The maximum rate at which the soil, in a given condition, can absorb falling rain is the infiltration capacity (Horton, 1935, p. 2).

The soil layer is of fundamental importance in the functioning of a drainage basin. Precipitation may collect on the surface in depressions, but as the amount of detention increases it will either run off or infiltrate into the soil. The proportion of runoff versus infiltration depends upon the soil character at a particular time, as well as upon the land use, topographic character such as slope, and upon the amount and intensity of rainfall (Gregory and Walling, 1973).

TEXTURE AND STRUCTURE

Two soil characteristics that influence infiltration are texture and structure. Sand, silt and clay are the primary particles of soil which form its texture. Structure refers to the general division of soils into horizons. Figure 15 illustrates these soil horizons.

Texture and structure of soil control capillary porosity, soil wetness, and the degree of compaction caused by rainfall impact. A coarse texture or well-aggregated soil may allow water to infiltrate so rapidly that runoff does not occur, even during heavy downpour. Table 9 shows some typical infiltration capacities. The other extreme may be a bare clay soil that soaks up the initial precipitation then swells and becomes a waterproof layer that sheds all subsequent rainfall. Exposed clay soils can also form impermeable conditions through mechanical compaction by raindrops, whereas the infiltration capacity of a clean sandy soil is affected very little by rain compaction (Wisler and Brater, 1959, p. 105).

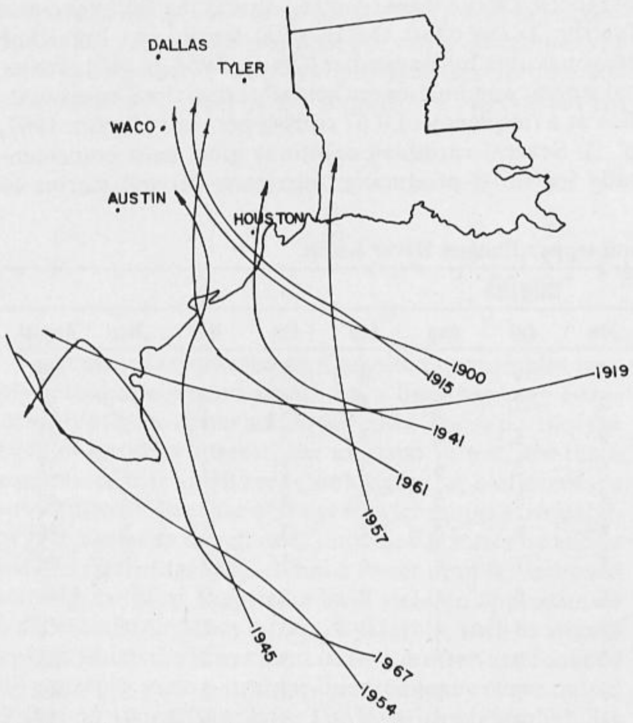


Fig. 14. Paths of major hurricanes affecting the Texas coast. *After* Hayes, 1967, p. 1.

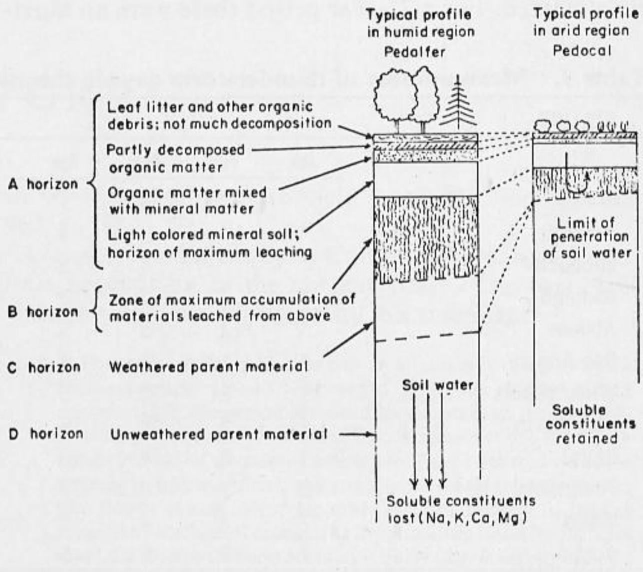


Fig. 15. A typical soil profile. *From* Hunt, 1967, p. 92.

Table 9. Typical Infiltration Capacities.

Clay Loam	0.1 -	0.2 in/hr
Silt Loam	0.3 -	0.6 in/hr
Loam	0.5 -	1.0 in/hr
Loam Sand	1.0 -	2.0 in/hr

When soil becomes very dry, as during a drought, the surface accumulates a thin layer of dustlike particles. These particles are carried into the soil when subsequent precipitation begins to infiltrate and are deposited in the interstitial spaces, reducing soil infiltration capacity (Wisler and Brater, 1959, p. 105). If the soil is bare clay and compaction also occurs, the runoff rate from intense rainfall could well approach 100 percent.

VEGETATION

Vegetative cover is related to those factors that affect infiltration. A dense cover of vegetation promotes rapid infiltration of water into the soil, by slowing the runoff velocity, therefore, allowing more time for infiltration. Decaying roots provide tunnels through which the water can flow, and the cover protects the soil from rainfall compaction. The layer of decaying matter covering a soil also promotes the activity of burrowing insects and animals (Wisler and Brater, 1959, p. 106).

ANTECEDENT MOISTURE

One of the most significant factors affecting the infiltration capacity of soil is the amount of soil moisture present at the start of the rainfall. This soil moisture measurement is expressed as an antecedent precipitation index and relates the existing soil moisture to the time since last precipitation and the amount of rainfall during that period. Table 10 shows infiltration and runoff data compiled during the design phase of Lake Waco Dam and illustrates the impact of conditions preceding a storm on resulting runoff. Notice that storms having the lowest infiltration index were preceded by light rain. Again the factor of intensity is seen to be significantly interrelated to both infiltration and runoff. This suggests that the conditions most conducive to excessive runoff would be an intense, long-duration storm preceded by light general precipitation.

QUANTITATIVE DESCRIPTION OF THE BRAZOS RIVER BASIN ABOVE WACO

The probable maximum flood at Waco will be determined, in part, by the volume of flood water that has passed through Lake Whitney. The Brazos River system and its subsystems vary in efficiency as means for collecting and conveying water. In some tributaries surface waters are quickly accumulated and the discharge is directly influenced by rainfall amounts. In other tributaries surface flow is delayed; therefore, discharge is more evenly distributed over time. The rainfall and volume discharged may be the same for two tributaries of the same size, yet one may experience far greater flooding than the other. The efficiency of the Brazos drainage

Table 10. Infiltration and runoff data—Bosque River watershed.

Date of storm	Rainfall (inches)	Runoff (inches)	Runoff (percent)	Initial loss (inches)	Infiltration index (in./hr)	Conditions preceding storm
North Bosque River near Clifton (Drainage area = 1,015 sq mi)						
26-27 Sep 1936	4.85	1.38	28.5	1.75	0.30	Heavy rain 14-18 Sep; light rain 25 Sep.
22-23 Jan 1938	3.23	1.08	33.4	0.62	0.16	No rain 14-19 Jan; light rain 20-21 Jan.
4-5 May 1941	1.92	0.90	46.9	0.84	0.04	Light rain 26 Apr - 3 May.
6-8 Sep 1942	4.69	0.91	19.4	1.75	0.30	Heavy rain 3 Sep.
South Bosque River near Speegleville (Drainage area = 380 sq mi)						
21 Apr 1926	2.15	1.04	48.4	0.50	0.07	Moderate rain 10 Jun; light rain 14-15 Jun.
5 Jun 1927	1.69	0.48	28.4	0.90	0.11	Heavy rain 12-13 May; moderate rain 24 May.
13-14 Jun 1927	4.00	2.15	53.8	0.73	0.12	Heavy rain 12-13 May; moderate rain 24 May; heavy rain 5 Jun.
21 Jun 1927	2.57	0.75	29.2	1.00	0.15	Moderate rain 24 May; heavy rain 5, 13-14 Jun.
Bosque River at Lake Waco (Drainage area = 1,666 sq mi)						
26-27 Sep 1936	5.96	2.15	36.1	1.35	0.38	Heavy rain 14-18 Sep; moderate rain 25 Sep.
30 Apr 1944	2.45	0.94	38.4	1.00	0.15	Light rain 22 Apr; heavy rain 29 Apr.
1-2 May 1944	2.43	1.02	42.0	0.88	0.10	Heavy rain 29-30 Apr.
21-22 Apr 1945	3.91	2.74	70.1	0.41	0.06	Moderate rain 11 Apr; light rain 15-16 Apr.
12 May 1953	1.80	0.66	36.7	1.00	0.06	Light rain 4 and 10 May; moderate rain 11 May.

From U.S. Army Corps of Engineers, 1957, p. 8.

system above Lake Whitney will determine the volume of water passing through that reservoir preceding the probable maximum flood at Waco.

Many stream flow characteristics of the Brazos basin are related either directly or indirectly to topographic features of the various watersheds. Each individual tributary basin is a natural hydrologic unit. Within each basin the runoff follows watercourses in which the flow undergoes retardation, acceleration, or other changes related to the physical characteristics of the basin (Langbein, 1947, p. 131). The characteristics of the Brazos basin are defined by morphology and form process relationships that influence runoff. These interrelationships describe the drainage basin in quantitative terms (Gregory and Walling, 1973, p. 37) and will therefore offer evidence as to the influence the Brazos basin above Whitney Dam will have on probable maximum flooding at Waco.

TOPOGRAPHIC FACTORS AFFECTING RUNOFF

The unit hydrograph is a quantitative measure of a drainage basin and is a function of watershed topography (Langbein, 1947, p. 128). The relationship between peak discharge and length of the base of unit hydrographs in terms of area, mean slope, and stream pattern, for application to flood control design, has been described by McCarthy (1938). Morgan and Hullinghorst (1939, p. 6) stated that the discharge characteristics of a watershed can be attributed to three fundamental watershed characteristics: (1) area of the watershed, (2) mean length of travel, and (3) mean height of watershed above the outflow station. Wisler and Brater (1959, p. 42) added a shape factor to the list of characteristics contributing to hydrograph shape.

The relationship between time distribution of discharge during a flood, and the size, shape, and gradient of a drainage basin has long been recognized by hydrologists. Therefore, to understand the Brazos River as a potential flood producer at Waco, those topographic factors are described. The complexity of relationships within a drainage basin is graphically illustrated by Figure 16 (Gregory and Walling, 1973, p. 85).

AREA

Basin size influences the amount of water produced; therefore, it is considered the most important factor. Basin area is the characteristic most easily related to basin processes, but because it is influenced by other factors, its importance is not easy to quantify. A basin of homogeneous rock type, soil cover, vegetation type and topographic character, receiving uniform precipitation, should experience streamflow that varies according to watershed area. However, such overall uniformity is rare, and it is difficult to determine the hydrologic response attributable solely to area (Gregory and Walling, 1973, p. 267).

Runoff volume under conditions of probable maximum precipitation is most directly related to area; but area is inversely related to relative peak flow. This inverse relationship is due to rainfall intensity increasing toward the center of a storm and decreasing outward. The larger the basin the more variation in precipitation across the area.

To experience maximum peak flow on a stream, the duration of intense rainfall must equal the time of concentration. Time of concentration, Tc, is the time it takes water to travel from the farthest point of a watershed to the watershed outlet. An estimated time of concentration for stream basins having average roughness values and hydrologic radius can be obtained using the formula

$$Tc = L^{1.15}/7700\ H^{0.38} \qquad (8)$$

where Tc is the time of concentration in hours; L is the length of the watershed along the main stream, in feet; and H is the total relief along the stream, in feet (Ogrosky and Mockus, 1964, p. 21-10). A small basin such as Kickapoo Creek, Figure 18B, having a 20-mile stream length and 420 feet of relief has a 7-hour time of concentration. So, in order for Kickapoo Creek to experience its maximum peak flow, a probable maximum storm of seven hours' duration centered over the basin would be required.

Both storm intensity and duration are inversely related to area; therefore, small basins are more likely to experience probable maximum flows. This does not imply that only small basins produce maximum flooding, but that under high antecedent moisture conditions resulting from normally experienced meteorological conditions over a large contributing area the probable maximum flood could be produced from a relatively small area.

Tributaries of the Brazos River, upstream from Waco,

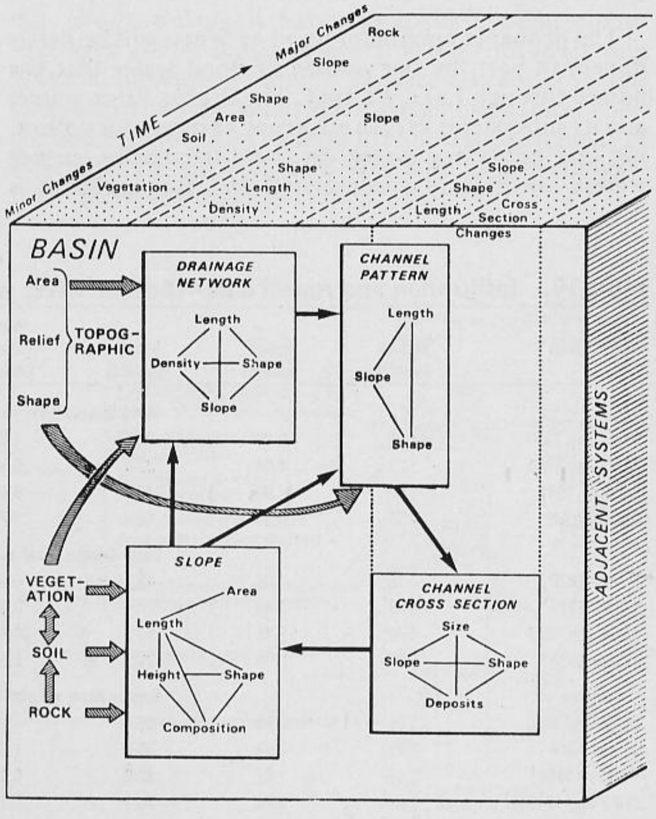


Fig. 16. Major interrelationships in a drainage system. *From* Gregory and Walling, 1973, p. 85.

are illustrated in Figures 17 through 21. Area was determined by planimeter from a 1:250,000 scale map, and is indicated on each figure. Because of its relationship with other basin factors, area receives additional comment in describing other factors.

SHAPE

The shape of a drainage basin influences the rate at which water is supplied to the main stream. To what extent shape influences flood dynamics is not clearly understood because those processes depend partly upon the shape of the basin and partly upon the dependent network shape (Gregory and Walling, 1973, p. 271). For example, compare the shapes of Palo Pinto Creek, Figure 18D, and Croton Creek, Figure 20E. Palo Pinto Creek is more efficient with respect to both shape and network, and will produce a slower rise but a higher peak, whereas the attenuated shape-network of Croton Creek will produce a quick rise but a lower hydrograph peak with a broader base.

Basin shape exerts an effect on the flood hydrograph

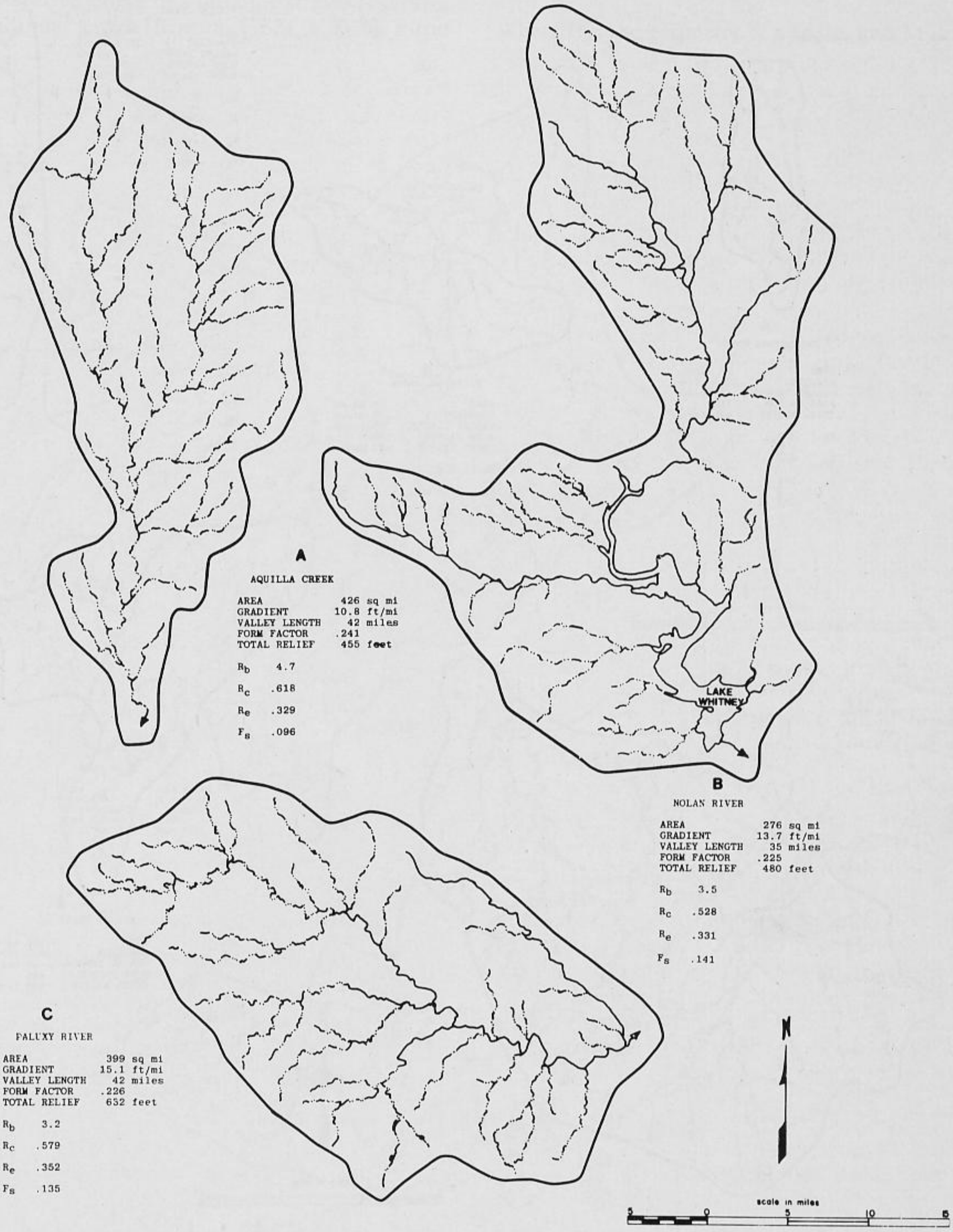


Fig. 17. Major tributaries of the Brazos River above Waco. See Table 11 for key to indices.

and it determines both time of rise and lag time. Lag time is the time between center of mass of surface-runoff-producing rain of a storm and the occurrence of the resulting peak discharge at a specific location (Snyder, 1938, p. 448). Since rainfall patterns are generally circular rather than elongate, and since maximum peak flows occur when the time of concentration of intense rainfall is equal to or greater than lag time, the impact of basin shape on flooding is important. It is difficult to express by a numerical index the effect of basin shape on stream hydrology, but several indices have been developed in an attempt to quantify this factor. Each is a measure of departure from circular shape. Indices calculated for the Brazos River basin are listed in Table 11.

Form Factor

This represents the ratio of the width of a drainage basin to its length. The length is measured from a point on the watershed line opposite the head of the main stream. This length is not necessarily the maximum basin

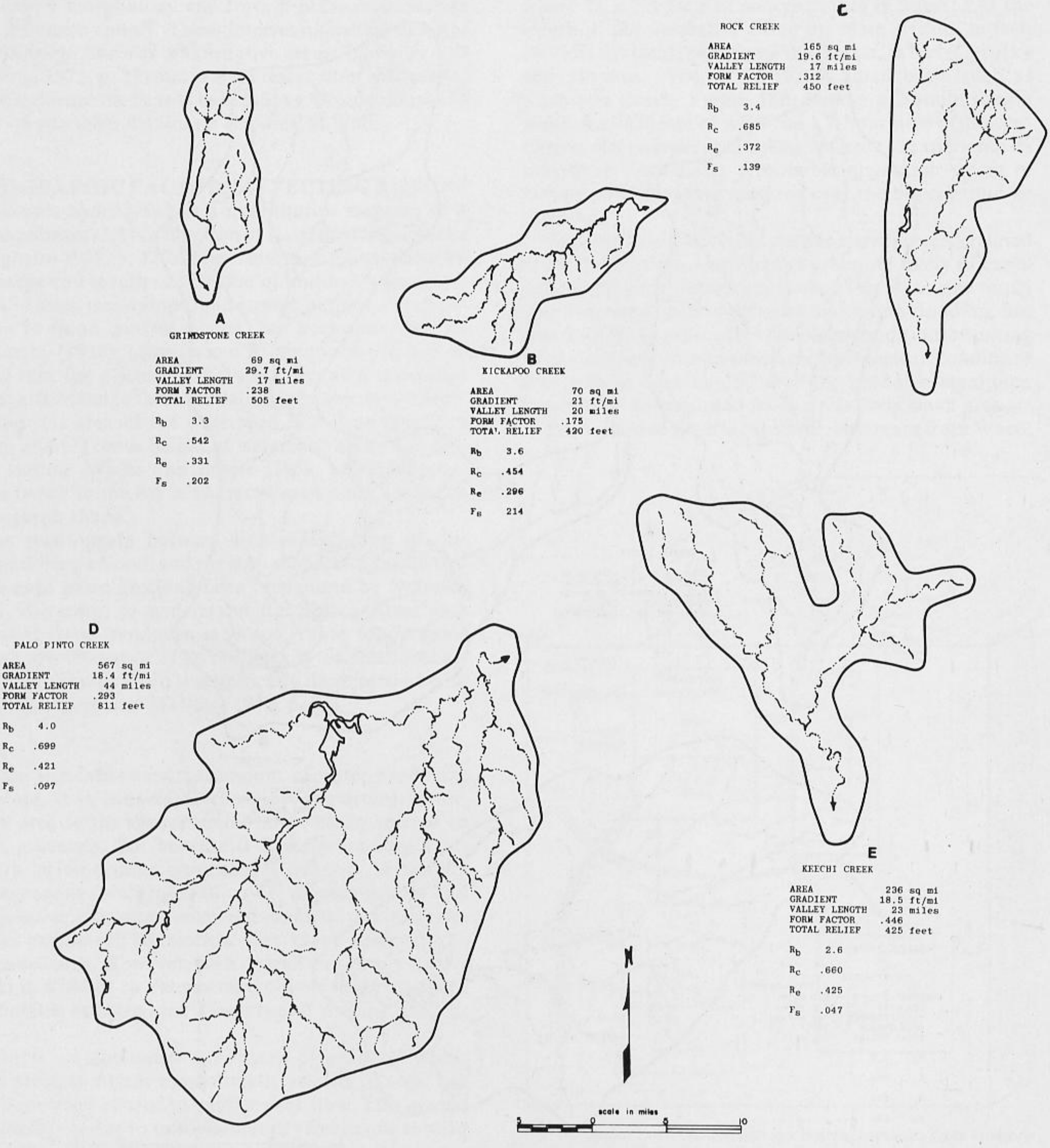


Fig. 18. Tributaries of the Brazos River. See Table 11 for key to indices.

length, since a drainage basin with a side outlet may be wider than it is long. The ratio, or form factor, is calculated by the formula

$$F = M/L^2 \tag{9}$$

where M is the drainage area in square miles, and L is the length. Valley length, rather than exact stream length, was used in Table 11. Use of valley length is logical since a probable maximum flood will overflow the banks, and after bankfull stage, part of the water flows over the flood plain, thus shortening the path floodwaters must follow. Thus, the effective length of a flooding stream is shorter than the meander length (Benson, 1962a, p. D25). Form factor has been used in connection with maximum flood-discharge formulas. For example, in long, narrow drainage basins, the form factor is indicative of the flood regimen of the stream (Horton, 1932, p. 351).

Compactness

This factor expresses the ratio of the perimeter of the drainage basin to that of a circle of equal area. It is derived by the following formula:

$$C = P/2M \tag{10}$$

where P is the perimeter of a basin, and M is its area.

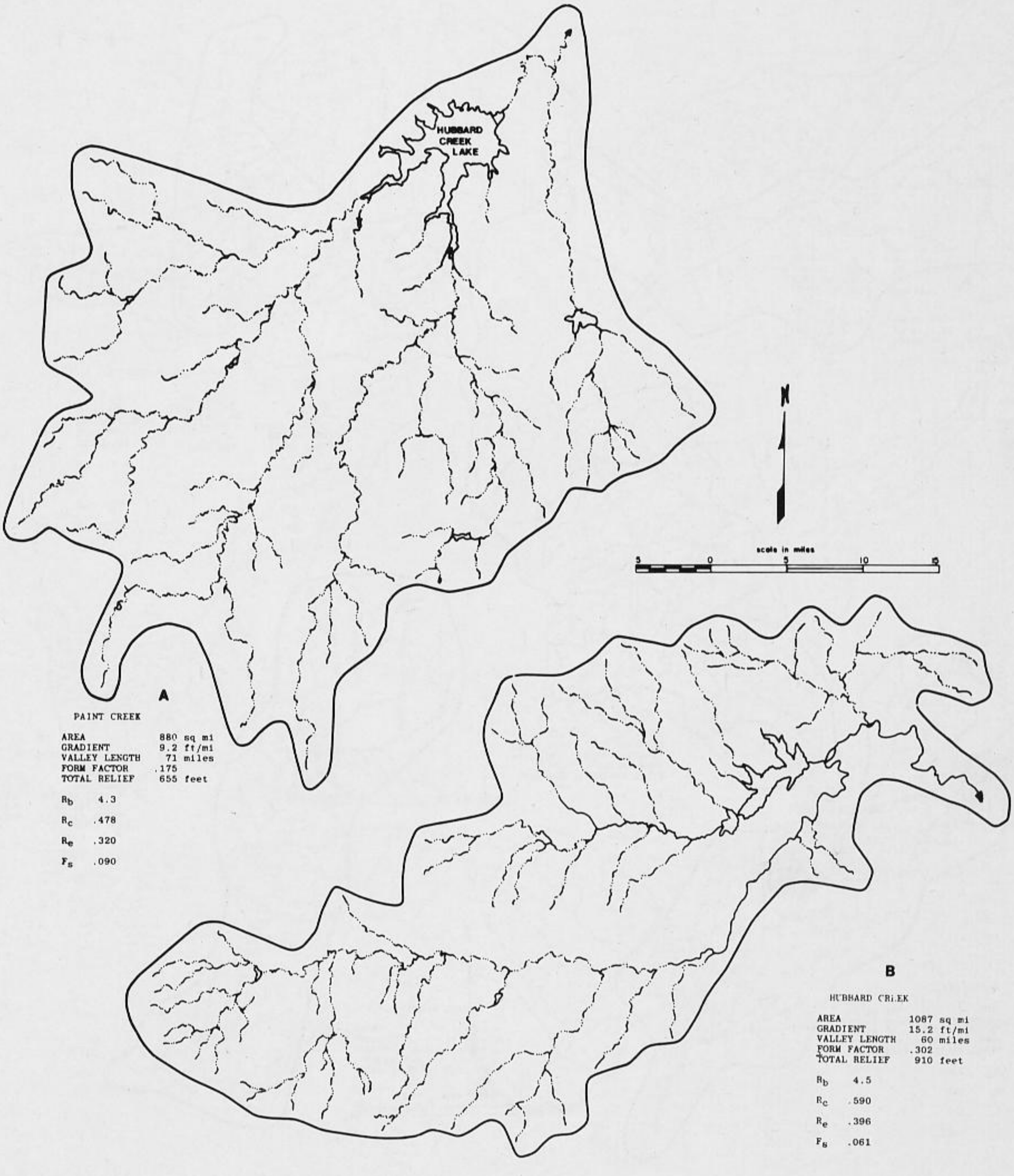


Fig. 19. Major subbasins of the Brazos River. See Table 11 for key to indices.

Elongation Ratio

This factor is defined as the ratio of the diameter of a circle of the same area as the basin to the maximum basin length. The ratio approaches one as the shape of the watershed approaches a circle. The formula

$$E = \frac{2\sqrt{A/\pi}}{L} \qquad (11)$$

where A is area and L is basin length is used in calculating basin elongation (Schumm, 1956, p. 612).

DRAINAGE NETWORK

Stream Order

The first step in basin analysis is designation of stream order (Strahler, 1957, p. 914). Strahler *(ibid.)* uses a system slightly modified from Horton (1945) and assumes the channel-network map being used includes all intermittent and permanent flow lines located in clearly defined valleys. Less importance is placed on precise maps by Benson (1962a, p. D28). His investigations of areas appearing on maps of more than one scale showed that the order number of streams determined from a 1:250,000 scale map was the same as if determined from a 1:125,000 scale map and one less than the order number if

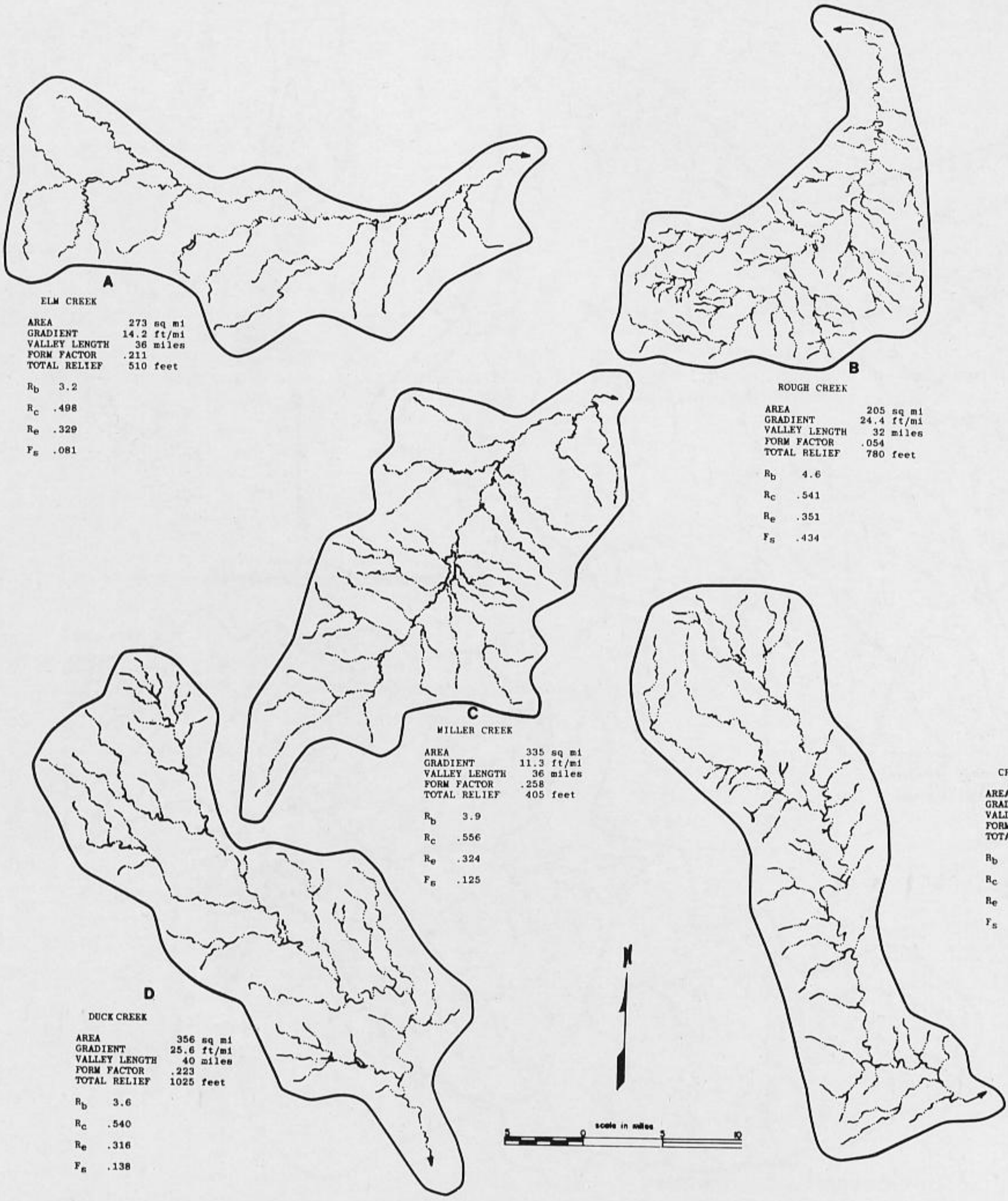


Fig. 20. Minor watersheds of the Brazos River basin. See Table 11 for key to indices.

taken from a 1:24,000 scale map. A 1:250,000 scale map was used in this study, and although the order numbers are not correct, they tend to be consistent and can be used as in index of the true order number.

The usefulness of stream order derives from the fact that order number is directly proportional to relative watershed dimensions, channel size, and stream discharge at a specific place on the stream. Drainage basins of different sizes can be compared at corresponding points in their geometry (Strahler, 1957, p. 914).

Strahler's method of designating stream order is used in this paper. Using this procedure the smallest fingertip tributaries are designated first order. Two first-order streams join to make a second-order segment; where two second-order streams join, a third-order segment is formed, and so forth.

In this system (Wisler and Brater, 1959, p. 48) the order number is a direct indication of the size and extent of the drainage net. This may be true in a homogeneous area, but by comparing Hubbard Creek, Figure 19, to Sweet-

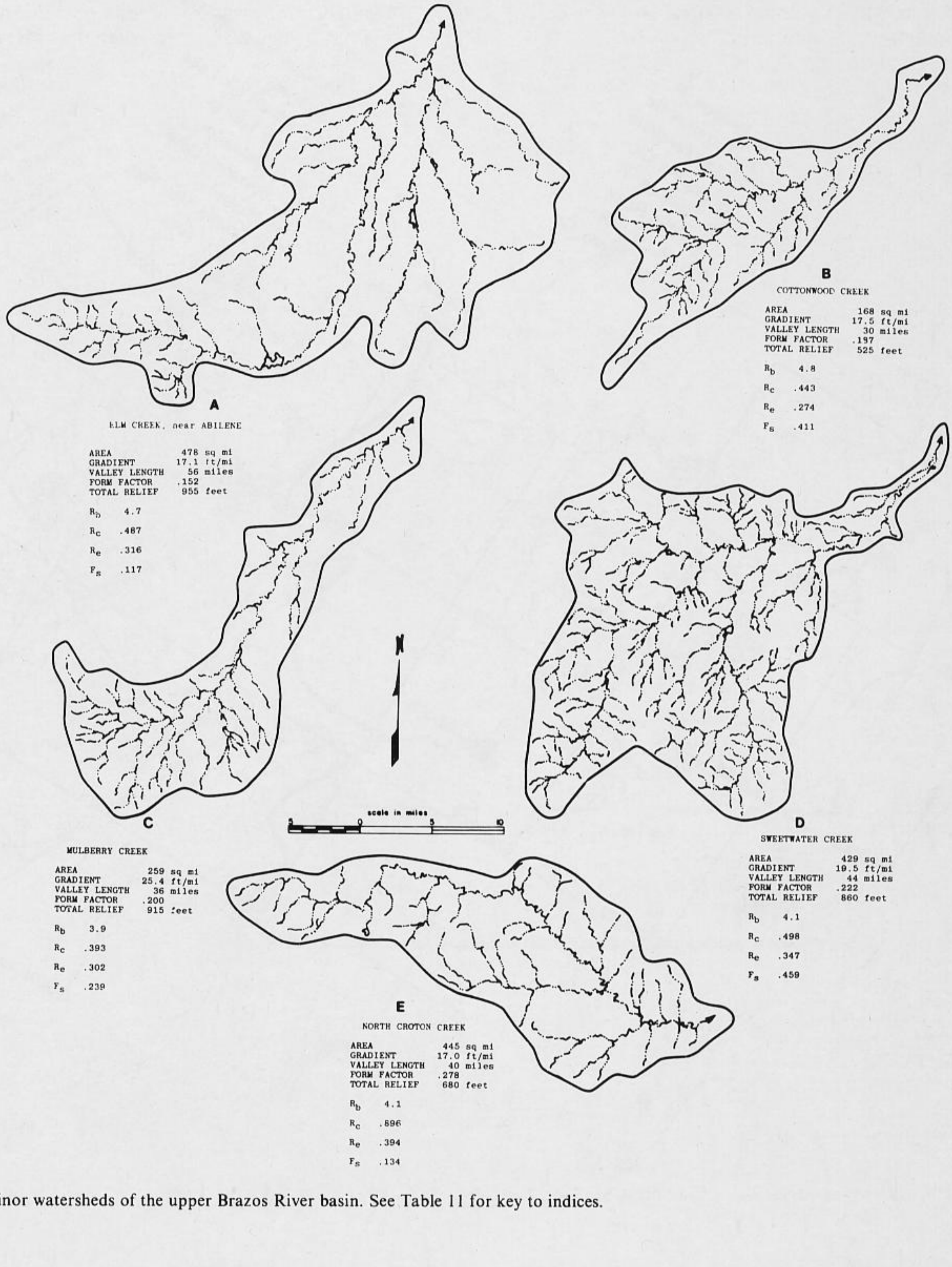


Fig. 21. Minor watersheds of the upper Brazos River basin. See Table 11 for key to indices.

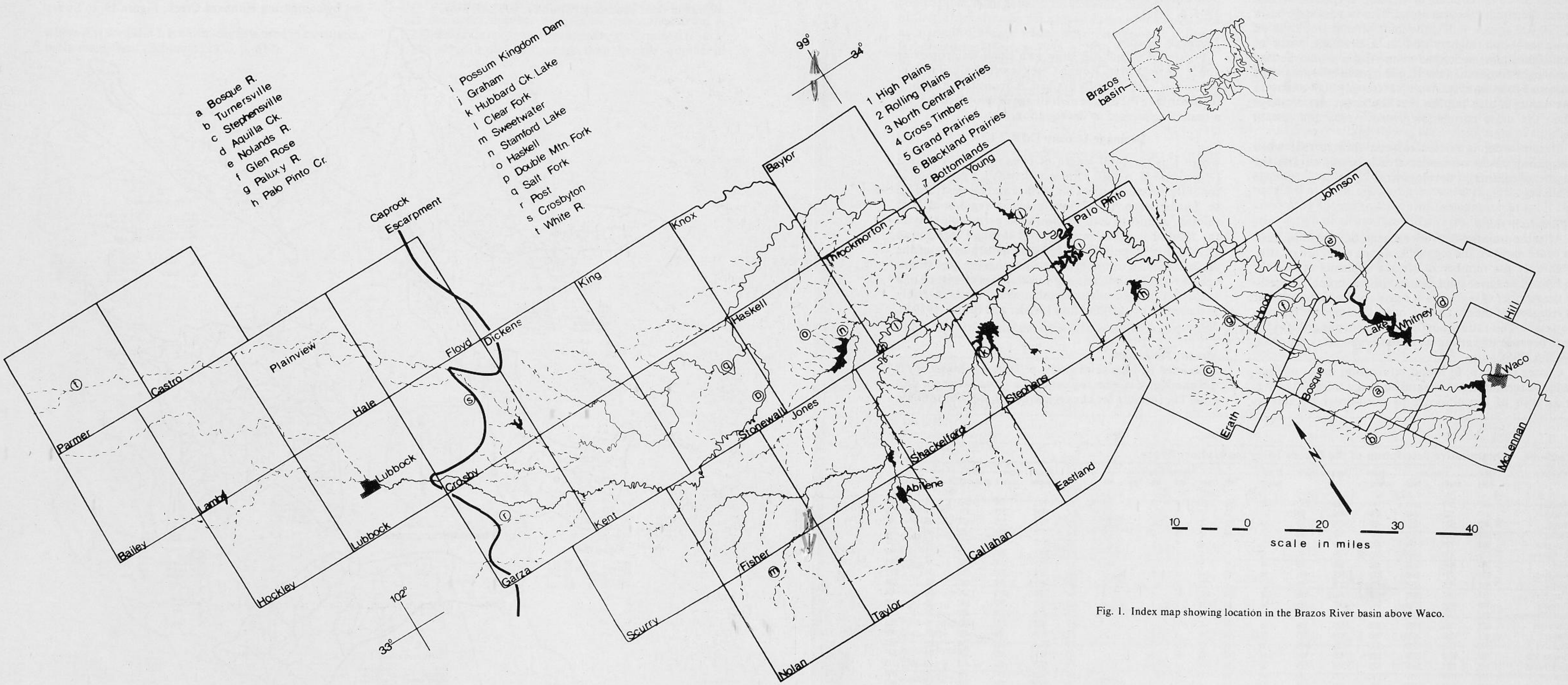


Fig. 1. Index map showing location in the Brazos River basin above Waco.

water Creek, Figure 21, it is not true for the Brazos basin, since both streams are the same order but vary greatly in area.

Horton (1945) related size of drainage area to stream order somewhat differently. He observed that the order of the main stream developed in a drainage basin of a given area increases to larger values in proportion to the logarithm of the area. For example, if an area of 10,000 square miles is required to develop a specific stream order, then under the same conditions in a drainage basin of 100,000 square miles, the main stream would be an order one unit higher, and in a drainage basin of 1,000,000 square miles the main stream would be two units higher order than the 10,000-square-mile area. This shows why stream systems with extremely high orders do not occur. It also implies that the larger the drainage basin the more correlation between area and stream order.

Stream order is related to peak flow in that when comparing basins of similar area it best illustrates the degree of drainage development, therefore, drainage efficiency.

Bifurcation Ratio

After the drainage-network elements have been assigned an order number, the segments of each order are totaled. Obviously the number of stream segments of a given order will be fewer than the next higher order. The ratio of the number of segments of a given order to the number of segments of the next higher order is termed the bifurcation ratio. This ratio is not the same from one order to the next because of variations in basin geometry (Horton, 1945, p. 286).

Coates (1958, p. 8) found bifurcation ratios of first-order to second-order streams to range from 4.0 to 5.1, and ratios of second-order to third-order streams to range from 2.8 to 4.9. Theoretically, 2.0 is the minimum possible value. Bifurcation ratio values far outside these ranges usually suggest some geological control is distorting the drainage pattern. The effects of such distortion upon maximum flood discharge are reflected in the resulting unit hydrograph. For example, an elongate basin having a high bifurcation ratio would yield a low but extended peak flow, whereas a round basin with a low bifurcation ratio would produce a sharp peak (Makey, 1964, p. 4-45).

Drainage Density

Figures 18E and 20B show two small watersheds of about the same area. Rough Creek is well drained whereas Keechi Creek is poorly drained. A quantitative method for describing the degree of drainage development within a basin is expressed as the equation:

$$\text{Drainage Density } Dd = \Sigma L/A \qquad (12)$$

where L is the total length of streams, and A is area (Horton, 1945, p. 283). Drainage density is a good indicator of the permeability of the surface and ranges from 1.5 to 2.0 for steep, impervious areas in regions of high rainfall, almost to zero for basins so permeable that all the rainfall is taken into the soil through infiltration (Horton, 1932, p. 357). The High Plains portion of the study area is an example of a surface having zero drainage density. An indication of the drainage efficiency of a basin is given by drainage density, which varies inversely as the length of overland flow (Wisler and Brater, 1959, p. 53).

Stream Frequency

Defined by Morisawa (1959, p. 7) stream frequency is the number of stream segments of a given order per unit area. The formula for stream frequency, F_u, is as follows:

Table 11. Quantitative description of the Brazos River basin above Waco.

Watershed	River mile	Elevation mouth	Elevation head	Total relief	Area	Perimeter	Valley length	Stream Order 1st	2nd	3rd	4th	5th	6th	R_b	Stream Gradient	Form Factor F_f	Ratio of Circularity R_c	Basin Elongation R_e	Stream Frequency F_s
Bosque	407	370	1510	1140	1670	225	100	148	35	8	2	1		4.2	11.4	.167	.514	.26	.089
Aquilla	417	385	840	455	426	93	42	33	7	1				4.7	10.8	.241	.618	.31	.078
Nolan	472	520	1000	480	276	81	35	28	8	2	1			3.5	13.7	.225	.528	.30	.101
Paluxy	509	568	1200	632	399	93	42	38	12	3	1			3.2	15.0	.226	.579	.30	.095
Kickapoo	581	700	1120	420	70	44	20	11	3	1				3.6	21.0	.175	.454	.27	.157
Grindstone	592	800	1305	505	69	40	17	10	3	1				3.3	29.7	.238	.542	.331	.145
Rock	503	810	1260	450	165	23	17	17	5	1				3.4	26.5	.570	.685.	.48	.103
Palo Pinto	613	731	1540	811	567	101	44	40	10	4	1			4.0	18.4	.293	.699	.34	.071
Keechi	657	825	1250	425	236	67	23	8	3	1				2.6	18.5	.446	.660	.42	.034
Clear Fork	757	1003	2610	1607	5750	389	270	596	139	36	8	2	1	4.3	6.0	.079	.477	.18	.104
Hubbard	782	1090	2000	910	1087	152	60	50	11	4	1			4.5	15.2	.302	.590	.35	.046
Paint & California	851	1245	1900	655	880	152	71	60	14	4	1			4.2	9.2	.175	.478	.26	.068
California	872	1380	1900	520	520	119	55	33	8	2	1			4.1	9.5	.172	.461	.26	.063
Elm	921	1555	2510	955	478	111	56	43	9	3	1			4.7	17.1	.152	.487	.25	.090
Mulberry	929	1595	2510	915	259	91	36	47	12	2	1			3.9	25.4	.200	.393	.28	.181
Sweetwater	987	1760	2020	800	429	104	44	148	36	10	2	1		4.1	19.5	.222	.498	.30	.347
Cottonwood	945	1875	2400	525	168	69	30	53	11	4	1			4.8	17.5	.187	.443	.27	.315
Elm	781	1090	1600	510	273	83	36	16	5	1				3.2	14.2	.211	.498	.29	.059
Miller	844	1195	1600	405	335	87	36	31	8	2	1			3.9	11.25	.258	.556	.32	.093
North Croton	888	1420	2100	680	445	79	40	45	11	3	1			4.1	17.0	.278	.896	.33	.101
Salt Fork	898	1450	3341	1891	2945	312	166	202	67	16	4	1		3.0	11.4	.107	.380	.21	.069
Croton	945	1700	2700	1000	296	91	44	47	11	2	1			4.3	22.7	.153	.449	.25	.159
Duck	974	1875	2900	1025	356	91	40	36	10	2	1			3.6	25.6	.223	.540	.30	.101
White	1026	2050	3341	1291	984	178	78	39	11	2	1			3.5	16.6	.100	.390	.25	.040
Double Mtn. Fork	398	1450	3000	1550	1486	269	131	347	73	16	3	1		4.8	11.8	.087	.258	.19	.234
Rough	1155	1830	2610	780	205	69	32	69	15	4	1			4.6	24.4	.200	.541	.28	.337
N. Fork Double Mtn.	1046	2070	3132	1162	244	144	67	74	21	5	1			3.5	17.3	.054	.148	.15	.303

$$F_u = N_u / A_u \quad (13)$$

Then the number of first-order stream segments per square mile of drainage area (F) is

$$F_1 = N_1 / A \quad (14)$$

where N_1 is the total number of first-order segments.

Stream frequency generally varies with basin size; therefore, large and small drainage basins are not directly comparable. A large basin may contain the same number of first-order streams per unit of first-order stream area as a small drainage basin, but in addition it contains larger streams (Horton, 1945, p. 285). This effect may not be noticed, however, since stream frequency usually increases with the slope increase associated with smaller basins. So, Horton's original formula for stream frequency

$$Fs = N / A \quad (15)$$

(which is simply the ratio between total number of stream segments in a basin to the basin area) may be more meaningful than the formula as modified by Morisawa (1959, p. 7).

Slope

The slope of the land surface within a drainage basin has an important but rather complex relation to surface-runoff. It is a major factor influencing the time of overland flow or concentration of rainfall in stream channels and is therefore of direct importance in the study of flood magnitude. In a study by Benson (1962b) slope was shown to be next in importance to drainage area size in explaining variations in peak discharge.

Slope is differentiated as either general slope or true slope. General slope as defined by Horton (1932, p. 352) is "the average slope of a surface, generated by a line one end of which is fixed at a given point on the stream above which the slope is to be determined, while the other end sweeps along the watershed-line."

Several methods of determining general slope have been developed, the object of which has been to furnish bases for determining the time of flood concentration. The various methods are not here explained however, since general slope is not well adapted for the purpose of determining time of concentration.

As far as overland flow is concerned, time of concentration involves true slope. The true slope between two contour lines equals the contour interval divided by the mean distance between the contour lines. Mean distance equals that area occurring between the contour lines divided by the mean length of the contour lines. If the total length of all contours in an area is known, the true slope can be determined by the formula

$$sg = \frac{D \Sigma l}{M} \quad (16)$$

where D is the contour interval, Σl is the sum of the

Table 12. Independent variables affecting runoff in the Brazos River basin.

	A	S	St	E	L	H	D	I	N	R	Ra
Double Mountain Fork at Lubbock	250	5.80	1.12	3420	98.0	426	17	3.96	40	.027	.09
Double Mountain Fork at Aspermont	1510	7.45	1.05	2180	175	977	20	4.52	40	.13	1.61
White River at Plainview	300	8.39	1.17	3850	126	794	17.5	3.87	42	.051	.22
Salt Fork of Brazos near Aspermont	2060	9.52	1.03	2270	164	1170	20.5	4.51	41	.12	1.06
Brazos River at Seymour	5250	5.24	1.03	1880	281	1100	21	4.64	43	.19	1.15
Clear Fork of Brazos at Nugent	2220	2.33	1.10	1810	110	191	22	4.92	40	.17	.84
Clear Fork of Brazos at Fort Griffin	3974	4.53	1.14	1570	198	673	22.5	4.96	42	.18	.90
Clear Fork of Brazos near Crystal Falls	5658	4.18	1.13	1490	244	763	23.5	5.03	42	.18	1.05
Brazos River at Palo Pinto	13520	3.76	1.07	1560	451	1270	23	4.92	43	.20	1.21
Paluxy River at Glen Rose	399	11.5	1.00	872	47.7	411	32.5	5.64	41	.22	2.06
Nolan River at Blum	276	11.8	1.00	734	31.8	281	34	5.78	43	.31	2.65
Aquilla Creek near Aquilla	309	9.88	1.00	610	32.3	239	35.5	5.92	41	.46	4.67
North Bosque River near Clifton	971	9.76	1.01	991	84.3	617	33	5.70	39	.38	2.78
Brazos River at Waco	19260	2.77	1.23	1230	706	1470	26	5.14	43	.38	1.85

See p. 38 for explanation of variables. *After* Benson, 1962a, p. 26.

contour lengths, and M is the drainage basin area.

Where channel flow is involved, the slope of the streams rather than the ground surface slope must be considered. Benson (1959) developed an index of the slope of the main stream channel which appears more effective than other related variables such as land slope or drainage density in representing the effects of slope in the basin. This main channel slope index is the slope between two points along the main channel at distances of 10 and 85 percent of the total main channel length. The main channel, proceeding upstream, is determined above each junction as that stream draining the largest area. Main channel slopes for several tributaries to the Brazos River are shown in Table 12, along with some other independent variables that effect runoff.

Data related to stream channel slope are given on Figure 17 through Figure 21 as stream gradient, and in Table 12 as channel slope and basin rise.

An explanation of the variable terms used in Table 12 follows:

A is the contributing drainage area, in square miles; S, the main channel slope between the 85 and 10 percent points along the stream, in feet per mile; St, the percentage of area in lakes and ponds, increased by 1 percent; E, the altitude index, an average altitude between the 85 and 10 percent points, in feet above mean sea level; L, basin length (total length of the main channel), in miles; H, basin rise (the elevation difference between 85 and 10 percent points), in feet; P, mean annual precipitation, in inches; I, 10-year, 24-hour rainfall intensity, in inches; N, mean annual number of thunderstorm days; R, ratio of runoff to precipitation during months when annual peak discharges occur; and Ra, mean annual runoff, in inches.

Soil and Geology

The effects of soil and geology are significant in the Brazos River basin. In many streams, headwater storm-discharges are high in the upper reaches of the stream but may disappear entirely as the flood wave moves downstream. Highly permeable and porous soils account for this phenomenon, which is compounded by long dry periods which cause low ground-water tables and low soil moisture. In limestone areas and faulted zones much of the storm runoff may pour into fissures and underground channels prior to reaching a tributary (Benson, 1962a, p. D28). Geologic features are difficult to evaluate numerically; consequently very little information is available on the geology-runoff relationship for the entire Brazos basin.

The hydrologic character of a soil or group of soils is an essential factor in the hydrologic analysis of watershed processes. If considered independently of watershed slope and cover, soils may be classified according to hydrologic properties. Four major groups are recognized for the primary classification of soils.

Group A is composed of soils having high infiltration rates when thoroughly wetted, therefore low runoff potential. They are mainly sands and gravels that are deep and well to excessively drained. These soils have a high rate of water transmission.

Group B consists of soils having moderate infiltration rates when thoroughly wetted. They are moderately deep to deep, moderately well to well drained and have moderately fine to moderately coarse texture. Group B soils have a moderate rate of water transmission.

Group C soils have slow infiltration rates when thoroughly wetted and have a slow rate of water transmission. Slow infiltration usually results from a soil layer that impeded the downward movement of water or from moderately fine to fine-textured soils.

Group D soils have high runoff potential. They have very slow infiltration rates when thoroughly wetted and also have a very slow rate of water transmission. Conditions or properties that cause slow infiltration may be clay soils having high shrink-swell potential, high permanent water tables, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious materials (U.S.D.A., 1971, p. 7-2). Dorroh (1946, p. 22) stated that the complexity of soil types, with the exception of the High Plains, makes it impossible to delineate any sizeable areas as having high or low infiltration rates. Benson (1962b, p. 33) developed a hydrologic soil index for the Southwest. In that study he stated that infiltration was not a significant variable in relation to peak discharge. Benson's statement would be true only in instances of high antecedent moisture conditions or in areas having soils with low infiltration capacity, that is, Group D soils. Under maximum probable flooding conditions, all soils will have low infiltration capacity because of antecedent moisture.

DESCRIPTION OF THE LOCAL AREA

UNCONTROLLED AREA

Floods on the Brazos River at Waco, regardless of origin, are conveyed by that reach of the Brazos River below Whitney and Waco reservoirs, which were designed to control runoff resulting from a 100-year recurrence-interval flood. Thus, at both reservoirs, flood release for the 100-year or lesser event is fully controlled. However, between these reservoirs and Waco are 672 square miles of uncontrolled drainage basin (HUD, 1977, p. 5). Thus, for the Brazos River at Waco the magnitude of flooding is determined by releases from upstream reservoirs, plus peak discharge from uncontrolled area.

Since failure of either dam would result in hazards to life or disastrous property damages downstream, adequate provisions have been made to insure against failure of the dam during the most severe flood or sequence of floods considered reasonably possible in the project basins (Snyder, 1964, p. 248). This policy is adhered to by the U.S. Army Corps of Engineers in establishing requirements for all spillway design for major dams. Hence the spillways of both Whitney and Waco reservoirs were designed for the probable maximum flood.

Since these reservoirs are located in drainage basins where volumes of runoff are normally large in comparison with the proposed storage capacity of the reservoirs, it was initially assumed that the reservoirs would be filled at the beginning of the probable maximum flood. For example, storm rainfall values, for use in establishing the beginning reservoir levels and in routing the probable maximum flood through the proposed Waco reservoir, were derived from the 1899 Hearne storm (Table 1, Fig. 7c) which occurred 3 days prior to the beginning of the synthesized probable maximum storm (U.S. Army Corps of Engineers, 1957, p. 3-6).

This policy of preceding the probable maximum storm with a major storm at a minimum time interval consistent with the meteorological conditions that caused the flood (Beard, 1975, p. 4-10), also establishes antecedent moisture conditions in the uncontrolled areas that promote nearly 100 percent runoff. Assuming total control of the Bosque River and the Brazos River above Whitney, the 672 square miles of uncontrolled basin between Whitney and Waco could produce flooding at Waco far greater than the flood of record. Using the simple Myers Formula the uncontrolled area could be responsible for a 260,000 cfs discharge at Waco. The estimated probable maximum peak flow for 672 square miles according to Commons' method, Figure 10, is approximately 850,000 cfs. The peak discharge for the flood of record at Waco was 246,000 cfs.

To accommodate these flows, spillway capacity for the maximum design water surface for Whitney reservoir is 684,000 cfs. Spillway capacity for the maximum design water surface for Waco the reservoir is 563,000 cfs. Both figures represent peak reservoir outflows during passage of the probable maximum flood (U.S. Army Corps of Engineers, 1974, p. 37). The probable maximum discharge for the intermediate 672 square mile uncontrolled area is in addition to these values and therefore must be determined and added to these values to compute the possible maximum flood.

Thus the following section describes a hypothetical flood based upon flow from runoff from the uncontrolled area between these two reservoirs and the City of Waco. To the value of this runoff the flows from both Whitney and Waco reservoirs are added to calculate the flood that will then be routed through Waco.

HYPOTHETICAL FLOOD

Flood experience in the uncontrolled area is insufficient to form a basis for flood control planning, nor has there been a flood on the Brazos River at Waco during recorded history that has approached the probable max-

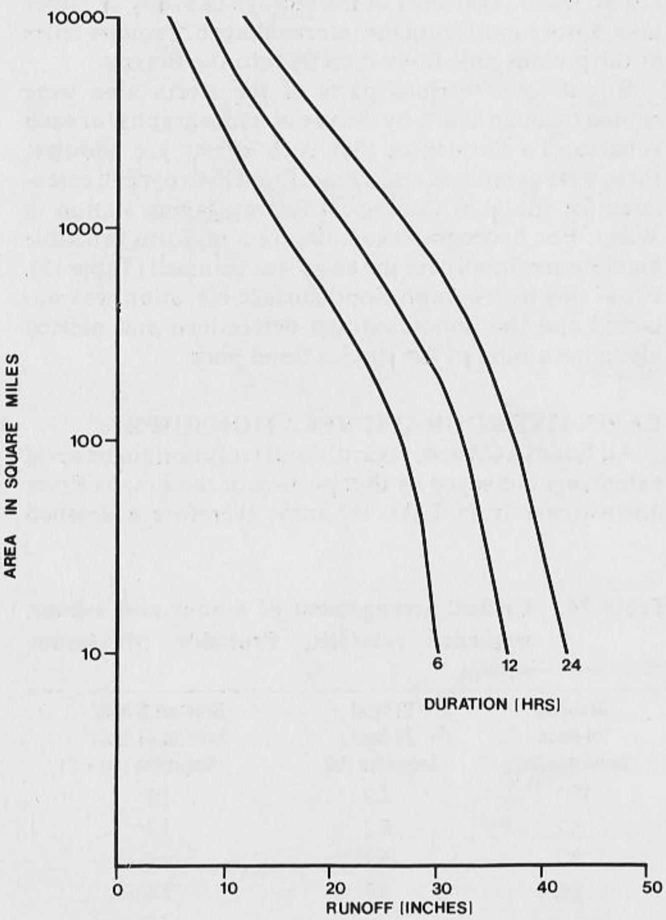


Fig. 22. Depth-area-duration curve for basins of 10 to 10,000 square miles, for 6- to 24-hour duration probable maximum storm.

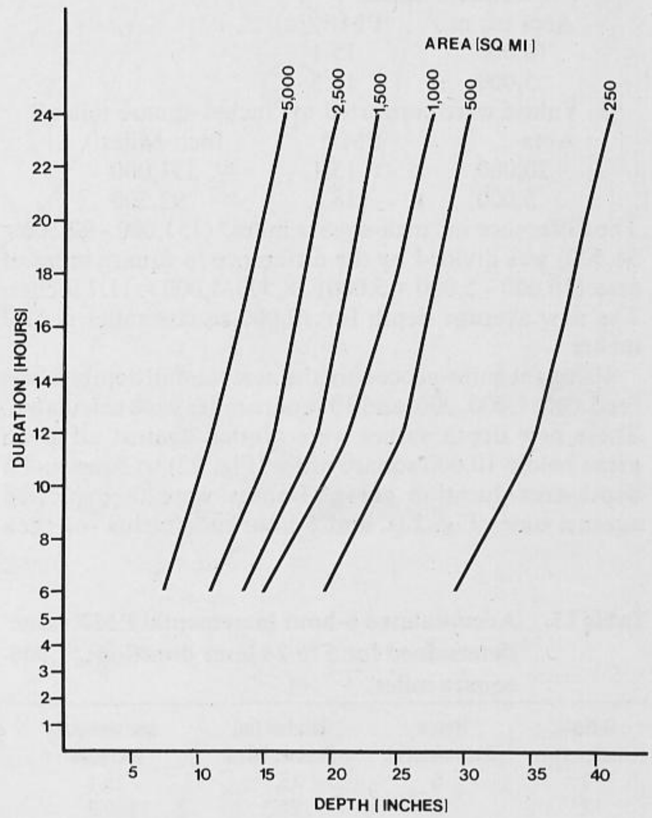


Fig. 23. Six-hour increments of rainfall for durations of 6 to 24 hours plotted against rainfall depth for probable maximum storms.

imum flood. Therefore, a hypothetical maximum flood, derived from hydrographs of artificial flood flow under maximized precipitation conditions, must be synthesized to simulate conditions appropriate to the objectives of this study.

A hypothetical flood for the uncontrolled area may be derived from (1) a study of ground conditions that would produce the greatest runoff rate, or (2) calculations can be based on runoff volume and peak flow frequencies and volume (Beard, 1975, p. 1.01). A hypothetical flood representing the most extreme conditions probable is applied to the uncontrolled area just as it was for the controlled areas used in spillway design.

While the process of determining a probable maximum flood is complicated, it may be briefly described in general terms. A 1,000 square mile, 24-hour duration storm centered between Waco and Lake Whitney has been selected to illustrate the method of calculations.

From the charts of probable maximum precipitation, Figure 11, rainfall amounts for each storm duration and storm area were determined. The probable maximum precipitation for a 24-hour duration storm covering 10,000 square miles is 15.1 inches. Since rainfall intensifies toward the center of the 10,000 square mile area, the rainfall amount in the inner 5,000 square miles was increased while the rainfall for the outer area was decreased, thereby maintaining the same total rainfall volume. This procedure was accomplished by the following computations (Cochran, 1975, p. C-7).

1. PMP was determined for 10,000 square miles and 5,000 square miles.

Area (sq mi)	PMP (in)
10,000	15.1
5,000	18.5

2. Values were converted to "inches-square miles,"

Area		PMP		Inch-Miles
10,000	x	15.1	=	151,000
5,000	x	18.5	=	92,500

The difference in "inch-square miles" (151,000 - 92,500 = 58,500) was divided by the difference in square miles of area (10,000 - 5,000 = 5,000) 58,500/5,000 = 11.7 inches. The new average depth for 10,000 square miles is 11.7 inches.

Using the same procedure the new rainfall depth values for 5,000, 1,000, 200, and 10 square miles were calculated. These new depth values were plotted against all given areas below 10,000 square miles (Fig. 22) to construct a depth-area-duration curve. Depths were then plotted against time (Fig. 23), and 6-hour increments for each area were obtained as shown on Table 13. Depth increases for each 6-hour period were determined and also listed on Table 13.

The incremental values for 1,000 square miles were then arranged in the sequence that would produce the greatest critical runoff. The 6-hour increments for the 24-hour storm were arranged in the order 4, 2, 1, 3—where 1 represents the greatest depth and 4 the least.

The 6-hour period of greatest rainfall intensity in the 24-hour sequence was then subdivided into one-hour intervals (Table 14). During the first one-hour interval, 4 percent of the total 6-hour increment of 15.1 inches is assumed to have fallen. During the following one-hour intervals 8 percent, 19 percent, 50 percent, 11 percent, and 8 percent of the total 6-hour increment are assumed to have fallen (Curtis, 1977, oral communication). All other 6-hour increments of the PMP series were assumed to be uniform (Cochran, 1975, p. C-71). Following this, an overlay, using a standard PMP isohyetal pattern (Beard, 1975, p. 3.05) was constructed, and the basin outline was superimposed over the isohyetal map to determine the basin area under each significant rainfall increment.

As shown in Figure 24 the isohyetal pattern is oriented over the basin so as to produce the maximum runoff. A storm of this particular pattern situated between Lake Whitney and Lake Waco will cause flooding on the Brazos at Waco regardless of the storage capacity of either lake, since runoff from the intermediate 672 square miles at the present time flows directly into the Brazos.

Runoff over various parts of the storm area were routed through Waco by the use of hydrographs for each subarea. To the degree that such effects are additive, these were combined and a mass flood hydrograph calculated for the U.S. Geological Survey gaging station in Waco. For hydrograph calculation a uniform probable maximum rainfall over the basin was assumed (Table 15). From this hydrograph flood surface elevation was obtained and the flood contours determined and plotted along both sides of the Brazos flood plain.

BASIN HYDROGRAPH RELATIONSHIPS

All floods at Waco, regardless of storm origin or areal extent, are conveyed by that portion of the Brazos River downstream from Lake Whitney; therefore a detailed

Table 13. Accumulated 6-hour incremental PMP value determined for 6 to 24 hour durations, 1,000 square miles.

6-Hour Increment	Hours Accumulated	Rainfall (in) Accumulated	Incremental Increase
1	6	15.1	15.1
2	12	21.3	6.2
3	18	25.0	3.7
4	24	27.9	2.9

Table 14. Critical arrangement of 6-hour and 1-hour sequence rainfalls, Probable Maximum Storm.

Graphed 24-Hour Sequence (in)	Critical 24-Hour Sequence (in)	Greatest 6-Hour Rainfall - 1 Hour Sequence (in)
15.1	2.9	1.2
6.2	6.2	1.2
3.7	15.1	2.9
2.9	3.7	7.6
		1.6
		.6

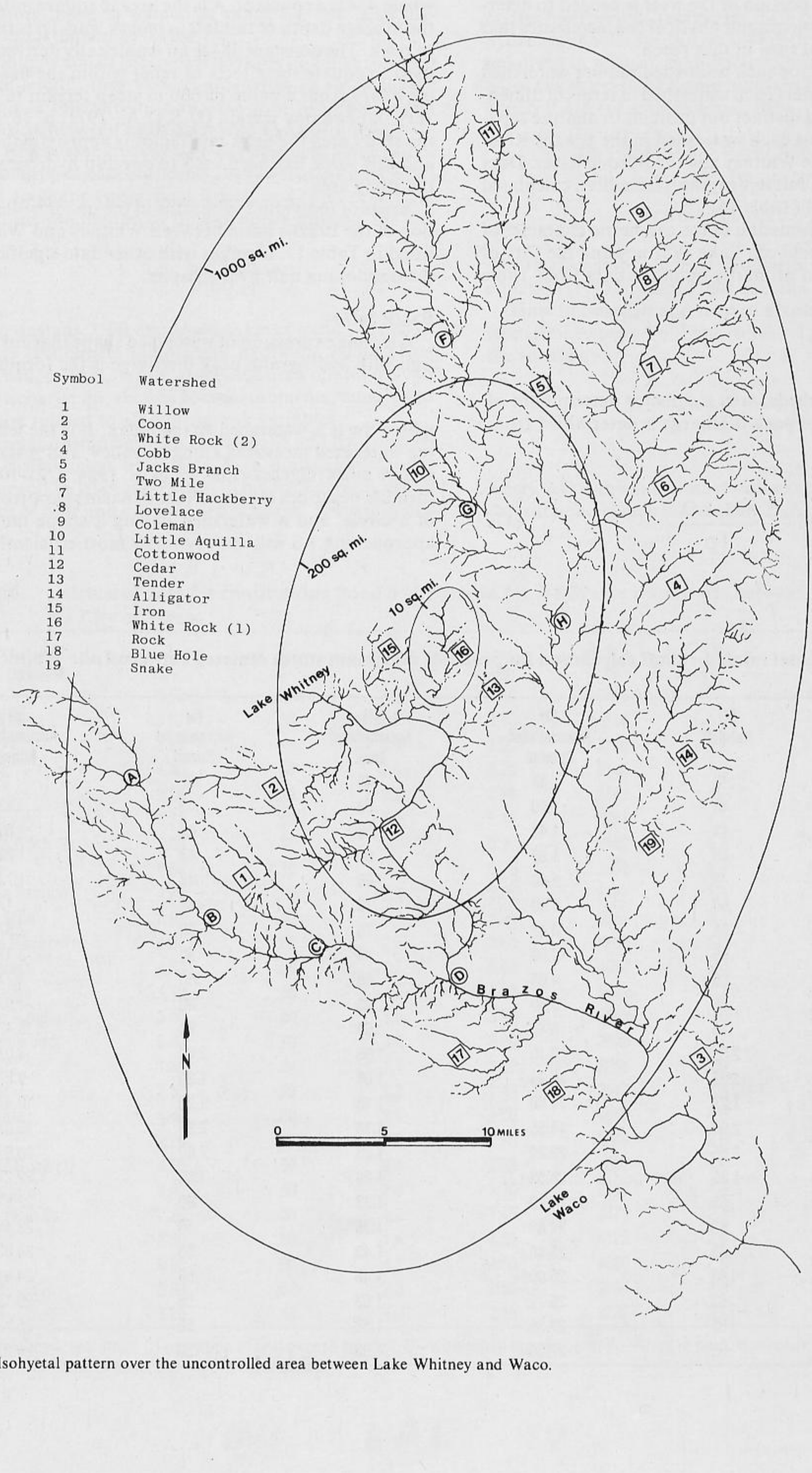


Fig. 24. Isohyetal pattern over the uncontrolled area between Lake Whitney and Waco.

description of this portion of the river is needed to determine specific hydrologic and physical characteristics that will influence flood flow in that reach.

Peak discharges for each watershed require watershed analysis that considers each watershed in terms of dimensions, separate and distinct but difficult to analyze separately. Table 16 lists each watershed in the Brazos River basin between Lake Whitney and the Bosque River. Data for constructing a unit hydrograph have been calculated for each watershed (Table 16).

The following discussion of the geometric character of the Brazos River between Lake Whitney and the City of Waco will be based primarily upon the data from Table 16.

Area

For small watersheds, area is a major determinant of peak discharge. The peak discharge is determined from the formula:

$$qp = \frac{484\ A\ Q}{Tp} \qquad (17)$$

where 484 is a constant, A is the area in square miles, Q is the average depth of rainfall in inches, and Tp is the time to peak. The constant 484 is an empirically derived value used to equate the effects of relief within the basin and may vary from a value of 600 in steep terrain to 300 in very flat swampy terrain (U.S.D.A., 1971, p. 16.7). For the study area the peak rate factor is approximately 484 and this value has been used to develop hydrographs in the study area.

Areas of individual subbasins in the uncontrolled portion of the Brazos basin between Whitney and Waco are listed in Table 17, together with other data significant to the developing unit hydrographs.

Basin Shape

A simple expression of watershed shape that correlates well with hydrograph peak discharge is the formula:

$$Sw = L^2/A \qquad (18)$$

where Sw is a watershed shape index, L is the length of the watershed measured along its valley, and A is area in square miles (Ogrosky and Mockus, 1964, p. 21-10). This formula describes the departure of basin shape from that of a circle, and a watershed having a shape index Sw approaching 1.3 will convey water most efficiently. The

Table 15. Incremental rainfall-runoff calculation for probable maximum storm centered between Lake Whitney and Waco.

(1) Hour	(2) Rainfall	(3) Accumulated Rainfall	(4) Accumulated Loss	(5) Incremental Runoff	(6) Accumulated Runoff
1	.48	.48	.48	0	0
2	.48	.96	.53	.43	.43
3	.48	1.44	.58	.43	.86
4	.48	1.92	.63	.43	1.29
5	.48	2.40	.68	.43	1.72
6	.50	2.90	.73	.45	2.17
7	.55	3.45	.78	.50	2.67
8	.55	4.00	.83	.50	3.17
9	.65	4.65	.88	.60	3.77
10	.85	5.50	.93	.80	4.57
11	.95	6.45	.98	.90	5.47
12	2.65	9.10	1.03	2.60	8.07
13	1.25	10.35	1.08	1.20	9.27
14	1.25	11.60	1.13	1.20	10.47
15	2.95	14.55	1.18	2.90	13.37
16	7.65	22.20	1.23	7.60	20.97
17	1.35	23.55	1.28	1.30	22.27
18	.65	24.20	1.33	.60	22.87
19	.63	24.83	1.38	.58	23.45
20	.63	25.46	1.43	.58	24.03
21	.63	26.09	1.48	.58	24.61
22	.63	26.72	1.53	.58	25.19
23	.63	27.35	1.58	.58	25.77
24	.55	27.90	1.63	.50	26.27

correlation between watershed shape Sw and peak discharge qp is shown by Table 18.

Although each of the five watersheds in Table 18 are 10 miles in length, they vary in area from 12 to 28 square miles. It is this variation in area that prohibits direct correlation between peak discharge and basin relief.

The first step in hydrograph development is the calculating of time of concentration Tc. Two basin dimensions related to shape (watershed length and total relief) are used in the calculation of time of concentration Tc:

$$Tc = \frac{L^{1.15}}{7700\ H^{0.38}}$$

The constant 7700 expresses average values of Manning's N (roughness factor) and hydraulic radius (Kirpich, 1940, p. 362). While watershed area relates only to peak discharge qp, the shape measurements, length and relief, are related to all hydrograph variables.

The relationship between basin shape and hydrograph shape is illustrated by Figure 25, a dimensionless unit hydrograph in triangular form. This hydrograph shows one unit of time and one unit of discharge. The rising side of the hydrograph represents 37.5 percent of the total hydrograph volume, thus allowing the time to base Tb to be solved in relation to the time to peak Tp using geometry of triangles. If the time it takes the hydrograph to peak equals 0.375 the total volume, then

$$Tb = 1.00/0.375 = 2.67 \text{ units of time} \quad (19)$$

$$\text{and } Tr = Tb - Tp \text{ or } 1.67\ Tp; \quad (20)$$

$$\text{therefore, } Tb = Tr + Tp. \quad (21)$$

The relationships are used to determine a peak discharge equation (17) and also to plot unit and flood hydrographs.

Time of base Tb and time of recession Tr are derived from time to peak Tp. Time to peak Tp is calculated using the formula:

$$Tp = \frac{\Delta D}{2} + L \quad (22)$$

where ΔD is the duration of unit excess rainfall, and L is the watershed lag in hours (U.S.D.A., 1971, p. 16.7). The

Table 16. Calculated data for constructing flood hydrographs for the Brazos watersheds between Lake Whitney and the City of Waco.

Stream	1 Tc	2 D	3 L	4 Tp	5 qp	6 Tr	7 Tb	8 Sw
Point A	6.59	.90	4.0	4.40	2156	7.4	11.7	8.9
A—B	3.57	.50	2.2	2.70	4589	4.5	7.2	2.8
B—C	2.81	.40	1.7	1.90	3770	3.2	5.1	3.3
C—D	4.40	.60	2.6	3.20	2541	5.3	8.5	3.4
Willow	3.80	.50	2.3	2.80	2687	4.7	7.5	6.0
Coon	3.72	.50	2.2	2.45	3951	4.1	6.6	4.8
White Rock (2)	5.80	.80	3.5	3.90	2482	6.5	10.4	7.8
Cobb	8.60	1.10	5.2	5.75	3451	9.6	15.4	9.8
Jacks Branch	4.80	.65	2.9	3.25	1787	5.4	8.7	8.3
Two Mile	2.82	.40	1.7	1.90	3057	3.2	5.1	4.1
Little Hackberry	4.50	.60	2.7	3.00	4195	5.0	8.0	4.7
Lovelace	4.50	.60	2.7	3.00	1452	5.0	8.0	7.1
Coleman	4.10	.55	2.5	2.80	3111	4.7	7.5	5.6
Little Aquilla	5.90	.80	3.5	3.90	3103	6.5	10.4	6.8
Cottonwood	5.80	.80	3.0	3.40	2705	5.7	9.1	7.6
Cedar	1.80	.24	1.1	1.22	2856	2.0	3.2	3.5
Tener	2.10	.28	1.3	1.44	2017	2.4	3.8	4.2
Alligator	4.40	.60	2.6	2.90	4673	4.6	7.5	3.6
Iron	2.70	.36	1.6	1.78	1849	3.0	4.8	5.3
White Rock (1)	4.00	.50	2.4	2.65	1607	4.4	7.0	9.2
Rock B	4.40	.60	2.6	2.90	2203	4.8	7.7	7.6
Blue Hole Br.	2.20	.30	1.3	1.45	3471	2.4	3.8	2.4
Snake	2.30	.30	1.4	1.55	4122	2.6	4.1	1.9
F	6.90	.90	4.1	4.55	4680	7.6	12.1	5.1
F—G	3.90	.52	2.3	2.56	3554	4.3	6.9	4.5
G—H	3.20	.43	1.9	2.13	3727	3.6	5.7	2.2

Tc—time of concentration, D—duration of unit excess rainfall, L—watershed lag in hours, Tp—time to peak, qp—peak discharge, Tr—time of recession, Tb—time of base, Sw—watershed shape.

Table 17. Significant data for constructing flood hydrographs for watersheds in the uncontrolled area between Lake Whitney and the City of Waco.

Stream Order	Area (sq mi)	Length (mi)	Relief (ft)	Grade (ft/mi)	Ist	2nd	3rd	4th	5th	Rb
Point A	19.6	13.2	188	14.2	24	5	2	1		4.8
A—B	25.6	8.4	240	28.6	31	8	2	1		3.9
B—C	14.8	7.0	260	37.1	22	6	1			3.6
C—D	16.8	7.6	285	37.5	30	10	3	1		3.0
Willow	13.6	9.0	255	28.3	20	3	1			6.6
Coon	21.0	10.0	365	36.5	27	7	1			3.9
White Rock (2)	20.0	12.5	223	17.8	15	1				15.0
Cobb	41.0	20.0	332	16.6	41	10	2	1		4.1
Jacks Branch	12.0	10.0	185	18.3	15	3	1			5.0
Two Mile	12.0	7.0	258	36.9	20	5	2	1		4.0
Little Hackberry	26.0	11.0	290	26.4	44	12	4	2	1	3.6
Lovelace	9.0	8.0	266	33.3	17	3	1			5.6
Coleman	18.0	10.0	281	28.1	26	7	2	1		3.7
Little Aquilla	25.0	13.0	241	18.5	40	7	2	1		5.7
Cottonwood	19.0	12.0	196	16.3	37	6	2			6.2
Cedar	7.2	5.0	285	57.0	21	5	1			4.2
Tender	6.0	5.0	192	38.4	8	2	1			4.0
Alligator	28.0	10.0	247	24.7	36	8	2	1		4.5
Iron	68.0	6.0	175	29.2	9	2	1			4.5
White Rock (1)	8.8	9.0	220	24.4	15	2	1			7.5
Rock	13.2	10.0	235	23.5	9	3	1			3.0
Blue Hole	10.4	5.0	182	36.4	7	2	1			3.5
Snake	13.2	5.0	167	33.4	12	2	1			6.0
Point F	44.0	15.0	245	16.3	68	16	3	1		4.3
F—G	18.8	8.0	166	20.8	21	5	1			4.2
G—H	16.4	6.0	120	20.0	21	5	1			4.2

average relationship of lag L to time of concentration Tc is:

$$L = 0.6\ Tc. \qquad (23)$$

The dimensionless unit hydrograph in Figure 25 has a time to peak Tp at one unit of time and point of inflection at about 1.7 units of time. Using the relationships shown on Figure 25, the relationship of ΔD to Tc can be computed using the following formulas:

$$Tc + \Delta D = 1.7\ Tp \qquad (24)$$

$$Tp = 0.6\ Tc + \Delta D/2. \qquad (25)$$

These two equations can be solved by substituting 0.6 Tc + ΔD/2 for Tp in equation (24):

$$Tc + \Delta D = 1.7\ (0.6\ Tc + \Delta D/2) \qquad (26)$$
$$0.15\ \Delta D = 0.2\ Tc$$
$$\Delta D = 0.133\ Tc.$$

The influence of basin shape on hydrographs is illustrated by comparing two watersheds having the same area but different shapes (Fig. 26). Snake Creek has a quick rise and high peak while Rock Creek has a long base hydrograph and a lower peak flow. The watershed shape factors Sw for Snake Creek is 1.9 and for Rock Creek is 7.6; however, total runoff from both basins is identical.

Network and Pattern

The Brazos basin between Lake Whitney and the City of Waco has a well-developed drainage network (Fig. 24). Within this network drainage patterns are uniform with the exception of areas near the main stem of the Brazos River that are drained by widely spaced first- and second-order streams. A comparison of representative streams on either side of the Brazos River suggests uniformity throughout. For example, Childress Creek has a bifurcation ratio of 4.1 for first-order streams and 4.4 for second-order streams. Aquilla Creek has a bifurcation ratio of 4.5 for first-order streams and 4.4 for second-order

Table 18. Peak discharge—watershed shape relationship.

Stream	Length (mi)	Relief (ft)	Sw	qp (cfs)
Alligator Creek	10	242	3.6	4673
Coon Creek	10	365	4.8	3951
Coleman Creek	10	281	5.6	3111
Rock Creek	10	235	7.6	2203
Jacks Branch	10	183	8.3	1787

Sw—watershed shape; qp—peak discharge.

streams. These ratios are extremely close despite the fact that these streams drain widely varying geology.

FLOOD STORAGE

Artificial and natural storage may effectively reduce the peak flows downstream from a water-retaining structure. Therefore storage is an important consideration in determining probable maximum flooding at Waco. Water supply reservoirs upstream of Lake Whitney have little effect on flood flows under PMF condition. Reservoir storage data for the Brazos River basin above Waco are shown in Table 19. In this reach there are 19 reservoirs that have capacities greater than 4,000 acre-feet. The primary purpose for these reservoirs is water conservation; however, Possum Kingdom lake is also used for hydroelectric power generation (U.S. Study Commission, 1962, p. 113).

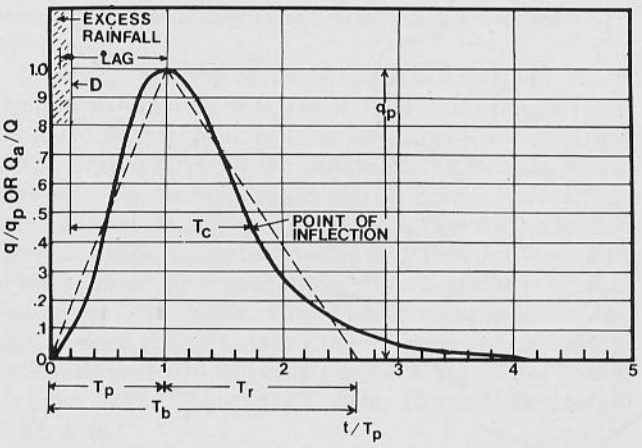


Fig. 25. Unit hydrograph in triangular form.

Whitney lake is the largest lake in the study area. The multipurpose lake, located on the Brazos River, 38 miles upstream from the City of Waco has a storage capacity of 2,100,400 acre-feet, and therefore has the greatest influence on flood control at Waco.

Lake Waco is also a multipurpose lake. Located on the Bosque River, it lies within the city limits of Waco. Because of its storage capacity and location, it is of prime importance to any flood study of the City of Waco. Constructed in 1965 it has a conservation storage capacity of 104,100 acre-feet (U.S. Study Commission-Texas, 1962, p. 105). Specific hydrologic data on Whitney and Waco reservoirs are shown in Table 20.

A design memorandum was published by the U.S. Corps of Engineers (1974) for future construction of a flood-retarding structure at river mile 23.3 on Aquilla Creek about one mile east of Aquilla, Texas. Construction on that project began in early 1978. Aquilla Dam is designed to control a 50-year flood runoff from the 252-square mile-area above the dam site. Capacity of the reservoir will be 146,000 acre-feet at the top of the flood-control pool.

The completion and subsequent operation of Aquilla Dam will have little or no impact on probable maximum flooding of the Brazos River at Waco for two reasons:

(1) The structure is designed to control only a 50-year flood; therefore, the 100-year flood antecedent to the probable maximum flood negates any influence the structure could have had on flooding.

(2) Only 252 square miles of the 410 square miles within the Aquilla Creek basin drain through the dam site.

Table 19. Lakes and reservoir storage on the Brazos River above Waco.

NAME	LOCATION	STREAM	DRAINAGE SQUARE MILES	TOTAL
Buffalo Springs Lake	near Lubbock	Double Mt. Fork	286	4,200
White River Lake	near Crosbyton	White River	172	71,600
Miller Creek Reservoir	near Munday	Miller Creek	228	25,520
Sweetwater Lake	near Sweetwater	Bitter & Cottonwood Creek	104	11,900
Lake Abilene	near Abilene	Elm Creek	110	7,900
Kirby Lake	Abilene	Cedar Creek	44	7,620
Ft. Phantom Hill Res.	near Nugent	Elm Creek	478	74,310
Lake Stamford	near Haskell	Paint Creek	360	53,930
Hubbard Creek Res.	Breckenridge	Hubbard Creek	1,107	515,930
Lake Daniel	Breckenridge	Gonzales Creek	115	9,515
Lake Graham	Graham	Salt & Flint Creeks	205	53,680
Possum Kingdom Lake	Graham	Brazos	22,550	724,700
Lake Palo Pinto	Mineral Wells	Palo Pinto	471	44,100
Lake Mineral Wells	Mineral Wells	Rock Creek	63	6,760
Lake Granbury	Granbury	Brazos	24,691	153,500
Lake Pat Cleburne	Cleburne	Nolan	100	66,700
Lake Whitney	Whitney	Brazos	26,606	2,100,400
Lake Waco	Waco	Bosque	1,670	828,300

Texas Water Development Board, 1973.

CHANNEL STORAGE CAPACITY

Channel capacity is a measure of natural storage within the river channel and relates to the geometric characteristics of the watershed. It is a factor in most flood routing procedures and is the single most important constraint in reservoir regulation.

Flood travel time between Whitney Dam and the mouth of the Brazos is from 5 to 6 days. If Whitney and Waco reservoirs are to be operated for maximum flood-control benefits at Waco, and along the Brazos River valley below Waco, it is necessary to withhold all flows at certain times. When releases are made they must be regulated at a rate below channel capacity at Waco to prevent flooding in Waco and downstream from Waco (U.S. Army Corps of Engineers, 1946, p. 32).

Channel capacity of the Brazos River at East Columbia (Table 21), 370 river miles downstream from Waco, is about 60,000 cfs. Between Whitney reservoir and East Columbia there are over 12,000 square miles of uncontrolled area in the Brazos watershed. Due to the size and flood-producing potential of the uncontrolled area and the long travel time for flood peaks along the Brazos

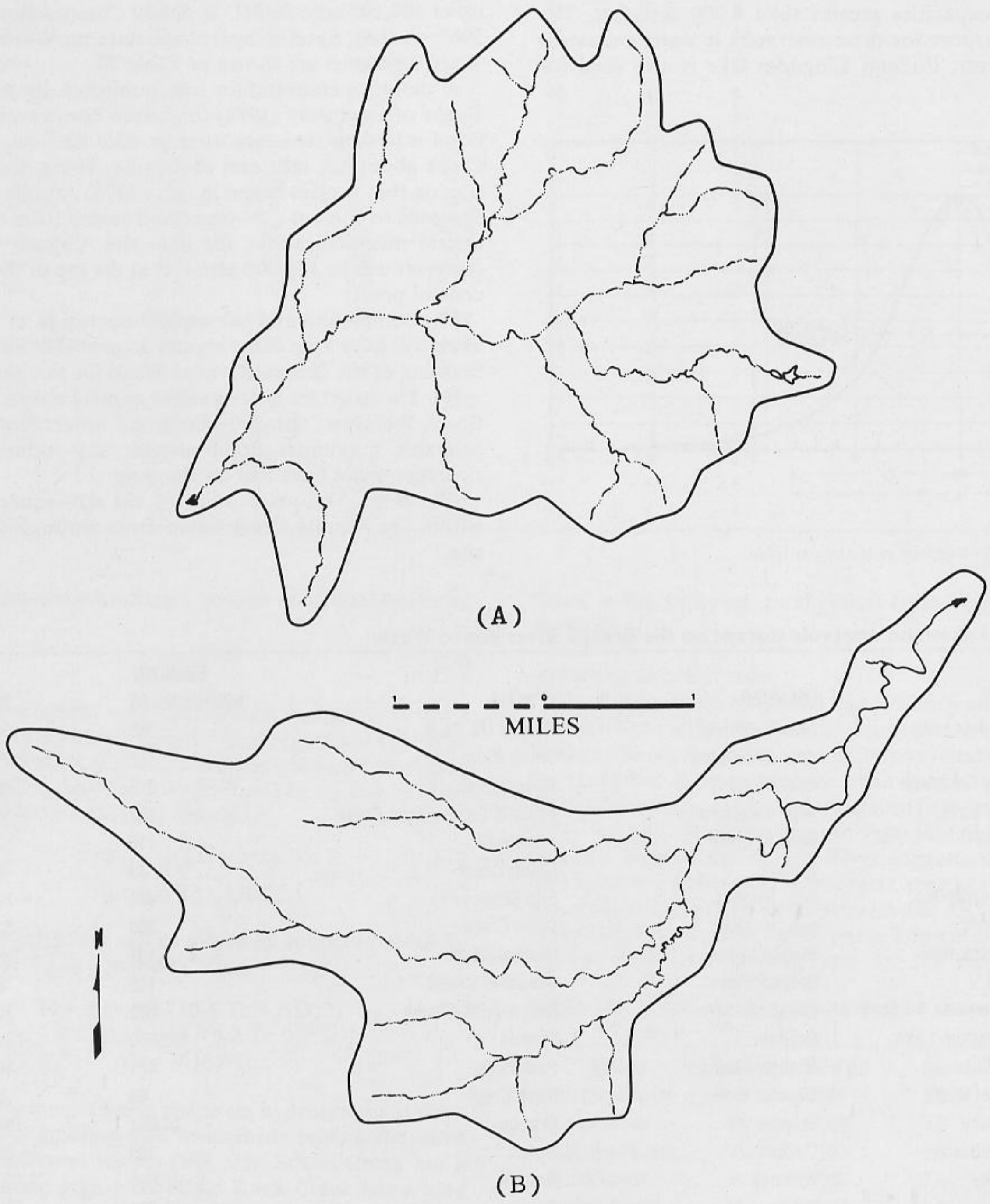


Fig. 26. Snake Creek (A) and Rock Creek (B), tributaries having the same area but greatly varying peak flood discharges.

Table 20. Hydrologic and reservoir data on Lake Waco and Lake Whitney.

	Waco	Whitney
Drainage area	1,670 square miles	17,656 square miles
One inch of runoff	89,067 acre-feet	941,653 acre-feet
Minimum channel capacity downstream on Brazos	65,000 cfs	60,000 cfs
Spillway design flood	622,900 cfs	700,000 cfs
Maximum design water surface		
Reservoir capacity	828,300 acre-feet	2,100,400 acre-feet
Spillway capacity	563,300 cfs	684,000 cfs
Top of flood control storage		
Reservoir capacity	726,400 acre-feet	1,199,500 acre-feet
Spillway capacity	458,000 cfs	632,000 cfs

U.S. Army Corps of Engineers, 1974.

River to reach East Columbia, it is necessary to regulate releases to limit peak flows to 60,000 cfs on the Brazos River below Whitney (U.S. Army Corps of Engineers, 1957, p. 5).

Channel capacity of the Bosque River from Waco Dam to its junction with the Brazos River ranges from 30,000 to 50,000 cfs, depending on coincident discharges in the Brazos River at the mouth of the Bosque River. However, operation of reservoirs on Brazos River tributaries downstream from Waco adds to flow on the Brazos River and thus reduces allowable releases from Waco and Whitney reservoirs in instances when flooding is general throughout the basin. Under such circumstances the apportioned releases among the reservoirs of the system limit releases to 10,000 cfs from Lake Waco and 35,000 cfs from Lake Whitney (U.S. Army Corps of Engineers, 1957, p. 6).

The rate at which the flood control pool elevations of Waco and Whitney reservoirs may be decreased following a 100-year flood is a critical factor because a second storm could occur causing peak flood flow into a full reservoir. Thus inflow volume for several days following a 100-year flood might well exceed the apportioned releases from Waco and Whitney reservoirs, and under these conditions uncontrolled flow will occur at both Whitney and Waco dam sites during the passage of a probable maximum flood.

OBSTRUCTIONS AND RESISTANCE TO FLOOD FLOW IN THE URBAN AREA

Watersheds within the Waco urban area in which natural stream channels have been supplemented or replaced by some form of artificial drainage system contribute to an increase in runoff volume due to sealing previous areas and contribute to a faster rise time or time of concentration because of increased conveyance efficiency (Holler, 1970, p. 1). Urban development affects drainage characteristics in two ways: (1) by reducing infiltration caused by impervious covering of streets, parking areas, roofs, etc., and (2) by providing more efficient hydraulic channels through which storm runoff can flow. While the increase in total volume is important, the most significant effect of urban development is the sharp increase in peak storm drainage rate (Hare, 1970, p. 2).

Another factor relating to flood stage in Waco urban streams is the stage of the Brazos River. Under probable maximum flooding conditions on the Brazos River the high discharge rate problem associated with urban streams is compounded when great volumes of floodwaters enter channel storage as a result of backwater effects of Brazos River flooding. Therefore, the probable maximum flood on the Brazos River is not restricted only to that evaluation to which the river might rise but will also generate flooding in the "uplands" of the city as well as along urban watercourses.

Table 21. Channel capacities of the Lower Brazos River and tributaries.

Stream	Location	Discharge (cfs)
Brazos	Whitney Dam to Aquilla Creek	25,000
Aquilla	Brazos River	3,000
Brazos	Aquilla Creek to Bosque River	27,000
Bosque	Waco Dam to mouth	30,000-50,000
Brazos	Waco	65,000
Brazos	Valley Junction	110,000
Brazos	Richmond	87,000
Brazos	East Columbia	60,000

Just as urbanization has had a significant impact on the hydraulics of minor Brazos River tributaries within Waco, man-induced developments on the Brazos River flood plain have significant effects on probable maximum flooding in Waco. The effects of disturbing a natural stream system are best understood in consideration of the simple peak discharge formula:

$$Q = VA \quad (27)$$

where Q is peak discharge in cfs, V is velocity in fps, and A is cross-sectional area in square feet. A change in one variable of the equation will always cause change in at least one of the other variables.

The 246,000 cfs flood of record for the Brazos at Waco occurred in 1936 and produced a flood stage of 40.9 feet. That stage and peak discharge (Q) reflect the conditions of the floodway in 1936. If since 1936 the Brazos River floodway has been altered in such a manner that decreases cross-sectional area (A) or its ability to convey water (V), a recurring flood of the same peak discharge (Q) may have a stage far greater than the previous 40.9 feet.

A maximum peak discharge at Waco can be determined by routing flood hydrographs along the Brazos River to Waco. Given this peak discharge it is therefore important to identify floodway areas within Waco having either reduced or increased flooded cross-sectional area. Cross sections of the Brazos River at Waco have been measured. Typical cross sections are shown in Figure 27.

Flood flow velocities vary along the cross section of the Brazos River, but where steep slopes and unobstructed channels occur, channel velocities range to twenty-nine feet per second. This is about twenty miles per hour. These high velocities pose serious threats to life and property. A velocity greater than three feet per second in water over three feet deep is considered hazardous (HUD, 1977, p. 4).

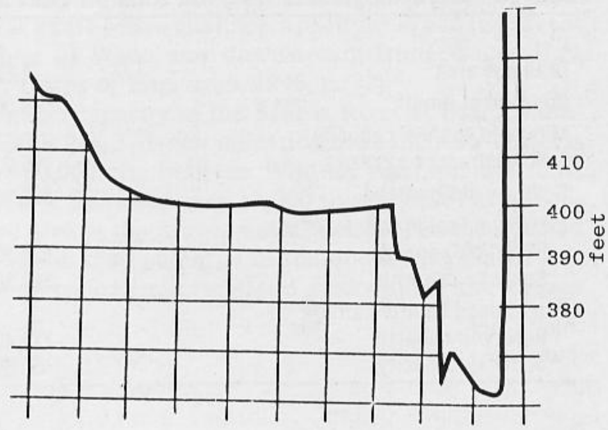
A widely used uniform-flow formula for open-channel flow computations is the Manning equation:

$$V = \frac{1.49}{N} R^{2/3} \quad S^{1/2} \qquad (28)$$

where V is mean velocity in fps, R is the hydraulic radius in ft, S is the slope of energy line, and N is the coefficient of roughness, specifically known as Manning's N (Chow, 1959, p. 99). The mean velocity through that specific river section can be derived using Manning's Formula (29), adjusting the Manning's coefficient N to conditions of flow resistance. Hydraulic radius R is the ratio of water area to the wetted perimeter, or

$$R = A/P \qquad (30)$$

where A is cross-sectional area, and wetted perimeter P is the channel wetted surface along the cross section (Chow, 1959, p. 22). Therefore an obstruction (such as a building) in the floodway of the Brazos River will (1) increase the cross-sectional area wetted perimeter P, (2) decrease the hydraulic radius R, (3) decrease mean velocity V, (4) increase flood stage, and (5) increase the area flooded within the City of Waco.



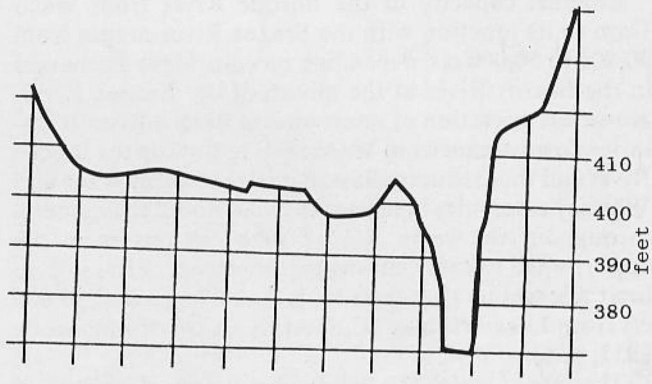


Fig. 27. Typical cross sections of the Brazos River in the City of Waco.

FACTORS AFFECTING FLOOD FLOW

The roughness coefficient in Manning's formula is highly variable and depends on a number of factors. The coefficient varies both linearly and across the floodway of the Brazos River, as changes occur in those factors to affect flood flow. For example, surface roughness, which is represented by the size and shape of material forming the wetted perimeter, varies across the Brazos floodway from fine silt at elevation to small well-rounded cobbles in the channel. Where the material is fine sand and silt, the roughness value is low, and the retarding effect is less than where the material is coarse. Surface roughness becomes less important as water surface elevations increase.

Vegetation is regarded as a kind of surface roughness since it reduces the capacity of the floodway and retards flow. The effect depends on vegetation height, density, distribution, and type (Chow, 1959, p. 102). Normally, small bushy growth such as in Figure 28 gives high roughness values, but under probable maximum conditions, such growth will be submerged and flattened, thus offering less resistance. As the Brazos River overflows onto the flood plain, high-stage floodwaters will encounter increasing amounts of vegetation, as shown in Figures 29 and 30, which will cause roughness values to increase as stage increases.

Seasonal growth of aquatic plants, grass, weeds, willow, and other riparian woodlands on the Brazos floodway contributes to increased roughness values during the growing season (Chow, 1959, p. 106). This factor is significant since experienced flooding in Waco has occurred during the spring and early fall seasons when vegetation is most dense. The bed and banks of the Brazos River channel in Waco are equally smooth and regular and the bottom slope is uniform; therefore, for the probable maximum flood the roughness value will remain constant. However, because of the type, height and distribution of vegetation on the flood plain, roughness values for overbank flow increase as stage increases.

The areas subject to flooding in Waco also retard flood flows. Within the flood plain are neighborhoods characterized by networks of small, fenced lots (Figs. 31, 32); athletic fields and parks with cyclone fencing (Fig. 33); securely fenced public utilities (Fig. 34); block-long buildings (Fig. 35); and dense riparian woodlands (Fig. 36). Such developments cause debris accumulations which in turn retard water movement, thus contributing to higher flood stages.

Obstruction in the Brazos floodway, such as bridges and piers, will increase the roughness value. In the case of probable maximum flooding the bridges become obstructions since they are submerged. Twelve bridges cross the Brazos River within the City of Waco. The combined effect these structures will have is illustrated on Figure 37. Notice the backwater effect that results from momentary velocity decrease caused by the La Salle Street twin bridge and the Interstate 35 bridge. Table 22 summarizes flood effects of all bridges crossing the Brazos River in Waco.

Subbasin Flood Hydrographs

Data for constructing unit hydrographs for each subwatershed within the Brazos basin between Lake Whitney and Waco are listed in Table 16. Utilizing this information from Table 16 and the method discussed below, composite flood hydrographs were developed for each subarea contributing runoff to the Brazos River.

The method of hydrograph development (U.S.D.A., 1971, Ch. 16) is demonstrated by calculating significant

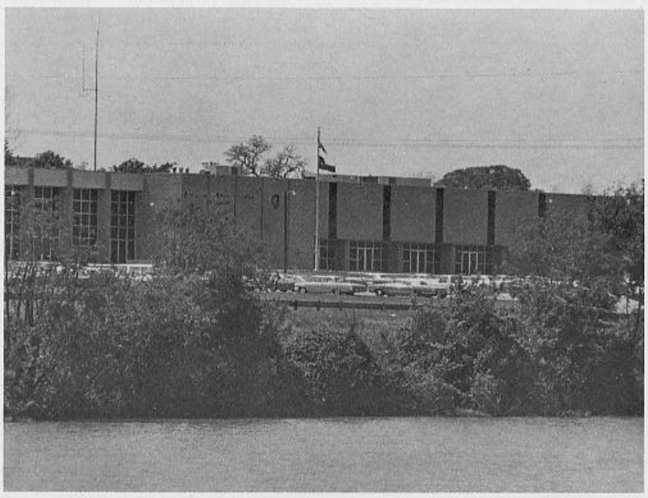


Fig. 28. Bushy growth along the Brazos which has a retarding effect on flood flow.

Fig. 29. Trees may not retard flood flow until the stage is high enough to cause water to flow through low-hanging branches. Under such circumstances roughness factors increase with stage.

Fig. 30. Dense vegetation growth may result in near zero velocities, especially when debris accumulates. In areas having this type vegetation the roughness factor will vary little with increased stages.

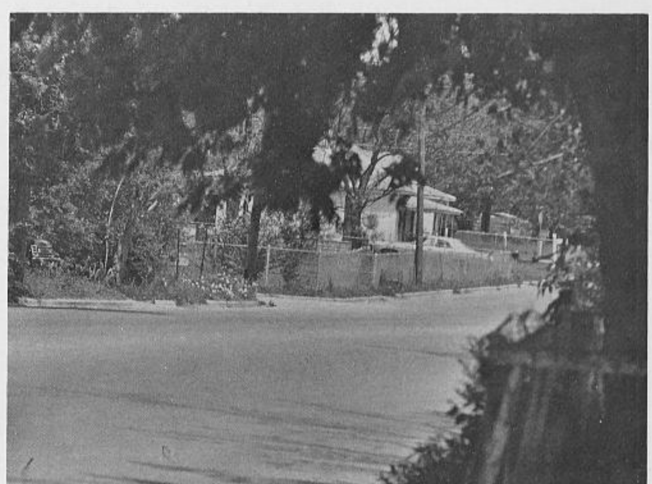


Fig. 31. Many areas within the Brazos flood plain are typified by small fenced lots. These fences accumulate debris and retard flood water flow.

Fig. 32. Typical fenced lots on the flood plain, east of the Brazos River.

Fig. 33. A common use of flood plain land is for public parks. Cyclone fences around these parks not only accumulate debris and retard flood flow, but are capable of withstanding more force and will not likely be flattened by flood waters.

Fig. 34. Cyclone-fenced public utilities are familiar sights on the Brazos flood plain in Waco.

Table 22. Bridges across the Brazos River in Waco.

River Mile	Bridge Name	Elevation from Stream Bed to Bridge Floor (ft)		Standard Project Flood Crest (ft)
402.92	La Salle Ave. (northbound)	351.0	401.87	400.8
402.93	La Salle Ave. (southbound)	351.0	401.87	400.8
403.93	IH 35 (north)	354.0	402.54	407.0
403.95	IH 35 (south)	354.0	402.54	407.0
404.19	MKT Railroad	358.7	398.7	407.2
404.25	St. Louis Southwestern Railroad	360.5	401.0	407.4
404.39	Franklin Ave.	357.0	401.2	407.9
404.49	Suspension Bridge	357.4	401.5	408.6
404.51	Texas Electric	356.9	400.0	408.7
404.56	Washington Ave.	357.5	403.0	408.8
404.96	Waco Drive	359.0	405.91	410.3
405.98	Herring Ave.	358.7	404.8	412.3

Fig. 35. Large buildings block flood flow in the flood plain. This causes increased velocities and higher stages.

Fig. 36. Riparian woodlands typical of the Brazos River flood plain.

variables for Snake Creek and Rock Creek (Fig. 26). In addition to explaining the procedure, the hydrographs also illustrate the influence of basin shape on hydrograph shape. A uniform probable maximum runoff of 26 inches was assumed for all hydrographs developed, using the previously computed incremental runoffs shown in Table 15. Table 17 shows significant descriptive data related on Snake Creek and Rock Creek basins.

COMPUTATION OF COMPOSITE PROBABLE MAXIMUM FLOOD HYDROGRAPHS

Step 1. Compute hydrograph variables:

Snake Creek:

$$Tc = \frac{(5 \times 5280)^{1.15}}{7700 \times 167^{.38}} = 2.26 \text{ hours}$$

$$\Delta D = 0.133\ Tc = 0.3 \text{ hours}$$

$$L = 0.6\ Tc = 1.4 \text{ hours}$$

$$Tp = L + \frac{\Delta D}{2} = 1.55 \text{ hours}$$

$$qp = \frac{484 \times 13.2 \times 1}{Tp} = 4122 \text{ cfs for 1-inch runoff}$$

$$Tr = 1.67\ Tp = 2.6 \text{ hours}$$

$$Tb = Tp + Tr = 4.15 \text{ hours}$$

Rock Creek:

$$Tc = \frac{(10 \times 5280)^{1.15}}{7700 \times 235^{.38}} = 4.4 \text{ hours}$$

$$\Delta D = 0.133\ Tc = 0.60 \text{ hours}$$

$$L = 0.6\ Tc = 2.6 \text{ hours}$$

$$Tp = L + \frac{\Delta D}{2} = 2.9 \text{ hours}$$

$$qp = \frac{484 \times 13.2 \times 1}{Tp} = 2203 \text{ cfs for 1-inch runoff}$$

$$Tr = 1.67\ Tp = 4.8 \text{ hours}$$

$$Tb = Tp + Tr = 7.7 \text{ hours}$$

Step 2. Compute the peak discharge for the first incremental hydrograph by multiplying the first increment of runoff shown in Table 15, column 5, by the peak discharge for one inch of runoff (4122 cfs). For purposes of illustration a value of ΔD of one hour is assumed. The peak flow of the first incremental hydrograph is 4122 cfs x .43 inch = 1775 cfs. Since the storm did not produce runoff the first hour, the zero point of the first incremental hydrograph is plotted at one hour after the beginning of the storm. The peak discharge of 1775 cfs is plotted at

Table 23. Hourly incremental runoff, peak discharge, time to peak and time of base for Snake Creek and Rock Creek.

		Snake Creek			Rock Creek		
Hour	Runoff	qp	Tp	Tb	qp	Tp	Tb
1	0						
2	.43	1775	3.55	6.15	950	4.9	9.7
3	.43	1775	4.55	7.15	950	5.9	10.7
4	.43	1775	5.55	8.15	950	6.9	11.7
5	.43	1775	6.55	9.15	950	7.9	12.7
6	.45	1875	7.55	10.15	990	8.9	13.7
7	.50	2060	8.55	11.15	1100	9.9	14.7
8	.50	2060	9.55	12.15	1100	10.9	15.7
9	.60	2475	10.55	13.15	1320	11.9	16.7
10	.80	3300	11.55	14.15	1760	12.9	17.7
11	.90	3710	12.55	15.15	1980	13.9	18.7
12	1.65	10925	13.55	16.15	5840	14.9	19.7
13	1.20	4950	14.55	17.15	2640	15.9	20.7
14	1.20	4950	15.55	18.15	2640	16.9	21.7
15	2.90	11950	16.55	19.15	6390	17.9	22.7
16	7.60	31325	17.55	20.15	16745	18.9	23.7
17	1.60	6600	18.55	21.15	3525	19.9	24.7
18	.60	2475	19.55	22.15	1320	20.9	25.7
19	.58	2390	20.55	23.15	1275	21.9	26.7
20	.58	2390	21.55	24.15	1275	22.9	27.7
21	.58	2390	22.55	26.15	1275	23.9	28.7
22	.58	2390	23.55	27.15	1275	24.9	29.7
23	.58	2390	24.55	28.15	1275	25.9	30.7
24	.50	2060	25.55	29.15	1100	26.9	31.7

qp—peak discharge; Tp—time to peak; Tb—time of base.

1.55 hours and the end of the hydrograph base is 6.7 hours. The process is continued by developing and plotting incremental hydrographs for each increment of runoff shown in Table 15, column 5. Each incremental hydrograph is plotted one hour later in time. See Table 23 for incremental runoff and peak discharges for Snake Creek and Rock Creek.

Step 3. Sum the ordinates of each incremental hydrograph at enough locations to provide a smooth composite flood hydrograph. The composite peak discharge for Snake Creek is 44,225 cfs (Fig. 38). Figure 39 is the composite flood hydrograph for Rock Creek.

FLOOD ROUTING

The purpose of flood routing is to establish both stages and rates at a specific location on the Brazos River at Waco, during the passage of the probable maximum flood. Flood hydrographs for subbasins in the local area plus outflows from Lake Whitney and Lake Waco have been routed through Waco using the Successive Average-Lag Method computer program developed by the U.S. Weather Service, Silver Spring, Maryland. The program was made available for this study by the River Forecast Branch, U.S. Weather Service, Fort Worth, Texas.

The Successive Average-Lag method is a procedure of flood routing by time displacement of average inflow and is based on the following premises (U.S. Army Corps of Engineers, 1960, p. 14):

1. The shape of a flood hydrograph tends to vary uniformly along a stream because of the floodway having adapted itself to discharges of the watershed.
2. The shape of the hydrograph reflects the cumulative effects of all the storage factors of the valley above the point of measurement.
3. The altered shape of the hydrograph at point B reflects the changes due to storage conditions between points A and B. Therefore, the process may be repeated as many times as needed in order to determine the hydrograph shape at a specific point downstream, as a direct result of routing through channel storage.

Using this method hydrograph A is defined by discharges $I_0, I_1, I_2 \ldots I_n$ at times $t_0, t_1, t_2, \ldots t_n$. Time interval t is short enough so that discharge varies linearly in the interval. Hydrograph B is the same hydrograph translated downstream to a point where travel time is $\Delta t/2$. The discharge at t_1 is $(I_0 + I_1)/2$; at t_2 it is $(I_1 + I_2)/2$; at t_3 it is $(I_2 + I_3)/2 \ldots (I_{n-1} + I_n)/2$. By connecting these discharge points hydrograph C is constructed. This is the first-step hydrograph of the Successive Average-Lag Method. In each successive step the midpoint discharges of the preceding hydrographs are connected, resulting in a progressively flattened wave as it moves downstream. Selection of small time units Δt results in hydrographs more closely retaining their original shape.

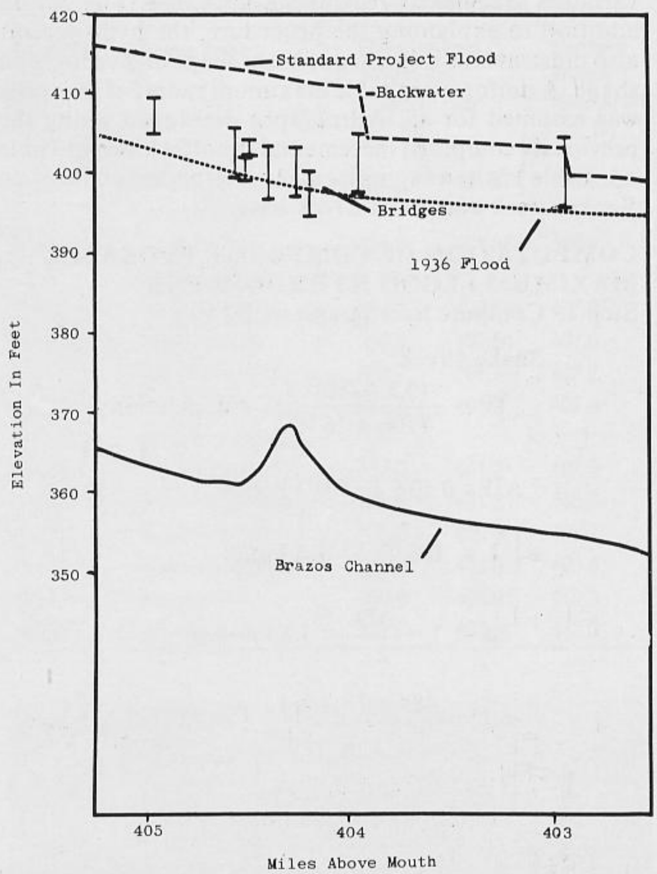


Fig. 37. Backwater caused by bridges across the Brazos River being inundated by flood waters.

A composite probable maximum flood hydrograph, developed from routed subbasin flood hydrographs, was constructed for the Brazos River at Waco. It is described in the section which follows.

THE PROBABLE MAXIMUM FLOOD AT WACO

FLOOD MODELS

The selected rainfall depths, duration, and critical time sequence for probable maximum flooding of the Brazos River at Waco are listed in Table 15. Using the U.S. Weather Service's river forecast computer program, four separate runoff models were considered in determining the probable maximum peak discharge and stage of the Brazos River at the U.S. Geological Survey gage in Waco. Identical probable maximum storms were assumed for all models. The models will be briefly discussed:

Model 1. The total combined storage capacity of Lake Whitney and Lake Waco is 3,305,100 acre-feet (Table

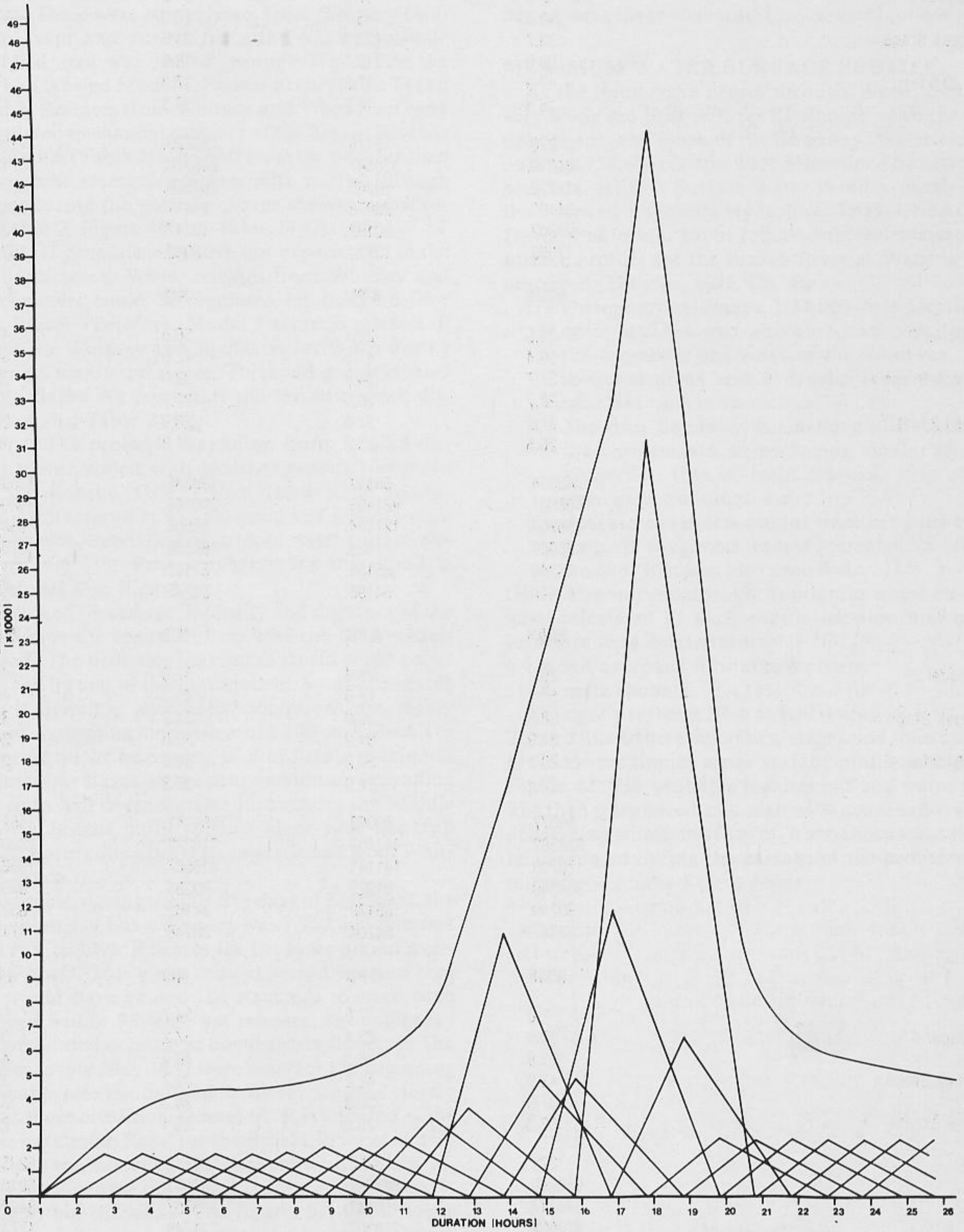


Fig. 38. Composite flood hydrograph for Snake Creek.

Table 24. Stage and discharge (cfs) at 6-hour increments for the probable maximum flood on the Brazos River at Waco.

	NOON	6 PM	MID	6 AM
Model 1	2.8	17.0	31.8	42.6
	48.8	45.7	40.9	37.8
Peak Stage =	33.7	28.8	24.6	22.0
	20.6	19.7	18.9	18.4
49.6 feet	17.9	17.6	17.3	17.0
	16.8	16.5	16.3	16.1
	276.	18178.	95729.	291592.
	464019.	376647.	245370.	157135.
	111776.	76205.	51565.	38293.
	31102.	26978.	24411.	22645.
	21302.	20192.	19217.	18330.
	17503.	16724.	15985.	15283.
	NOON	6 PM	MID	6 AM
Model 2	22.5	26.4	36.5	44.2
	50.4	47.3	42.5	39.4
Peak Stage =	37.7	34.6	32.0	29.9
	28.7	28.1	27.7	27.4
51.2 feet	27.2	27.0	26.9	26.7
	26.6	25.2	21.3	19.0
	40654.	60841.	139535.	335969.
	508681.	421453.	290246.	202047.
	156706.	121144.	96508.	83239.
	76049.	71925.	69358.	67593.
	66249.	65138.	64162.	63274.
	62447.	54198.	34745.	24685.
	NOON	6 PM	MID	6 AM
Model 3	26.1	29.4	37.8	44.9
	51.1	48.0	43.3	40.1
Peak Stage =	38.5	36.6	34.2	32.8
	31.9	31.2	30.8	30.6
51.9 feet	30.3	30.2	30.0	29.9
	29.8	26.9	22.3	19.7
	59077.	80052.	159141.	355772.
	528582.	441403.	310222.	222035.
	176700.	141141.	116507.	103238.
	964049.	91925.	89358.	87593.
	86249.	85138.	84162.	83274.
	82447.	64204.	39748.	27187.
	NOON	6 PM	MID	6 AM
	2.8	17.0	34.7	54.5
Model 4	66.6	62.4	57.2	53.8
	51.8	48.5	46.0	44.7
Peak Stage =	43.9	42.2	39.7	38.5
	37.9	36.8	34.3	33.0
68.6 feet	32.2	28.8	25.1	22.8
	276.	18252.	122112.	623517.
	958660.	842742.	697191.	601819.
	548217.	456642.	385757.	349363.
	328026.	279307.	211749.	177488.
	159898.	142640.	117865.	105078.
	98301.	76453.	53707.	42164.

20). These reservoirs were designed to "control" a 100-year flood—that is to regulate releases during passage of the 100-year flood so as to prevent overbank flow on the Brazos River downstream from the structures. Model 1 centered a probable maximum storm between Whitney and Waco. There were zero releases from Whitney Dam or Waco Dam and runoff from the 672-square-mile uncontrolled area was routed through Waco. See the hydrograph labeled Model 1, Figure 40 and Table 24 (1).

Model 2. Releases from Whitney and Waco reservoirs were regulated to channel capacity of the Brazos River at East Columbia (Table 21). Runoff from the uncontrolled area plus these reservoir releases were routed through Waco, producing the peak discharge shown by hydrograph Model 2, Figure 40 and Table 24 (2).

Model 3. If general rains were not experienced in the Brazos basin below Waco, releases from Whitney and Waco reservoirs could be regulated for bankfull flow through Waco. Therefore, Model 3 assumes releases of 35,000 cfs for Whitney and 30,000 cfs for Waco during the probable maximum storm. The hydrograph labeled Model 3, Figure 40, represents the resulting peak discharge. See also Table 24 (3).

Model 4. The probable maximum storm rainfall distribution was extended, with decreasing rainfall depth, to include the Bosque, Paluxy and Nolan River basins. Flow into full reservoirs was assumed and releases were made to prevent exceeding maximum water surface elevations (Table 20). Peak discharge for this flood is labeled Model 4 on Figure 40.

The assumed placement, intensity and duration of the selected storm are logical for each of the four models considered. The probable maximum storm could occur as described by any of the four models, but for probable maximum flooding, antecedent conditions are highly significant. Assuming the passage of a 100-year flood 3 to 5 days prior to the beginning of a probable maximum storm, reservoir stages will be near maximum. Prevailing general rains will cause streams throughout the Middle and Lower Brazos basin to flow at or near bankfull stages, thus preventing flood storage releases from Whitney and Waco.

For example, during the last five days of May 1957, the average volume of Lake Whitney was 1,952,800 acre-feet (Yost, 1963, p. 149). Releases for the same period averaged 53,920 cfs. This was a critical period because zero release would have caused the structure to have been overtopped within 9 hours, yet releases, although very high, were limited because of downstream flooding. The conditions in late May 1957 were ideal for the beginning of a probable maximum flood at Waco. Model 4 closely simulates those conditions; therefore, it is adopted as the probable maximum flood for the Brazos River at Waco.

Results of the model analyses are shown as Tables 25, 26, and 27 to illustrate the probable maximum flood as it develops within the basin. The figures list flood stages and corresponding peak discharges in 6-hour increments for selected stations. Table 28 shows water surface elevations and reservoir storage in acre-feet for Lake Whitney and Lake Waco during passage of the probable maximum flood.

Flood stages calculated by the river forecast program that are greater than the flood of record are linear extrapolations of historical flood events and are thus unrealistic representations of water surface profile points. For this reason the following method was selected for determining the probable maximum water surface profile.

MAXIMUM WATER SURFACE PROFILE

As the flood wave passes through Waco, stages will vary along the Brazos River depending upon the condition, shape, and slope of the floodway. Water elevation during a 958,660 cfs flow were determined by a computer program, HEC 2, Surface Water Profiles, developed by the Corps of Engineers Hydrologic Engineering Center, Davis, California. Input required for calculating water surface profiles for the Brazos River at Waco is briefly described (Thomas, 1975, Ch. 6).

(1) On topographic maps, 1:24,000 scale, locations for cross sections were chosen which best described the geometric character of the floodway. Cross-sectional areas and hydraulic radii were determined at each cross section.

(2) The river floodway was divided into reaches and the reaches into strips having similar hydraulic properties, that is, main channel, strip of trees, open area, buildings, etc.

(3) Specific roughness values were assigned to each strip. If roughness values increased as stage increased, that was also specified.

Given this information the maximum water elevations were calculated at each profile location and average velocities were determined:

(1) left overbank flow at two points,

(2) main channel,

(3) right overbank flow at two points.

Table 29 lists these velocities, stages and locations. The probable maximum water surface profile is plotted on Figure 41. The probable maximum flood water surface was then transferred to a map of Waco, Figure 42, thus delineating within the City of Waco those areas that will be inundated during the passage of the probable maximum flood on the Brazos River.

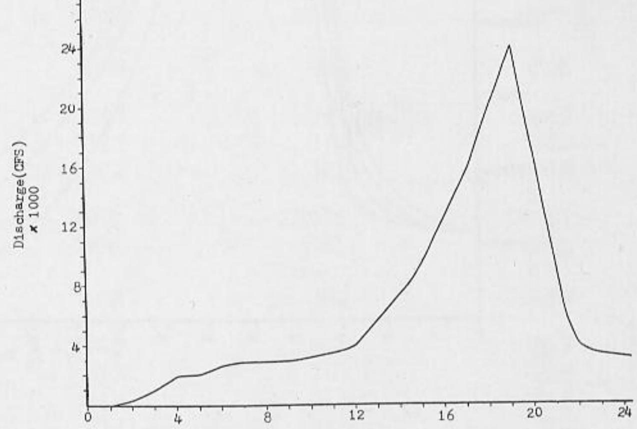


Fig. 39. Composite flood hydrograph for Rock Creek.

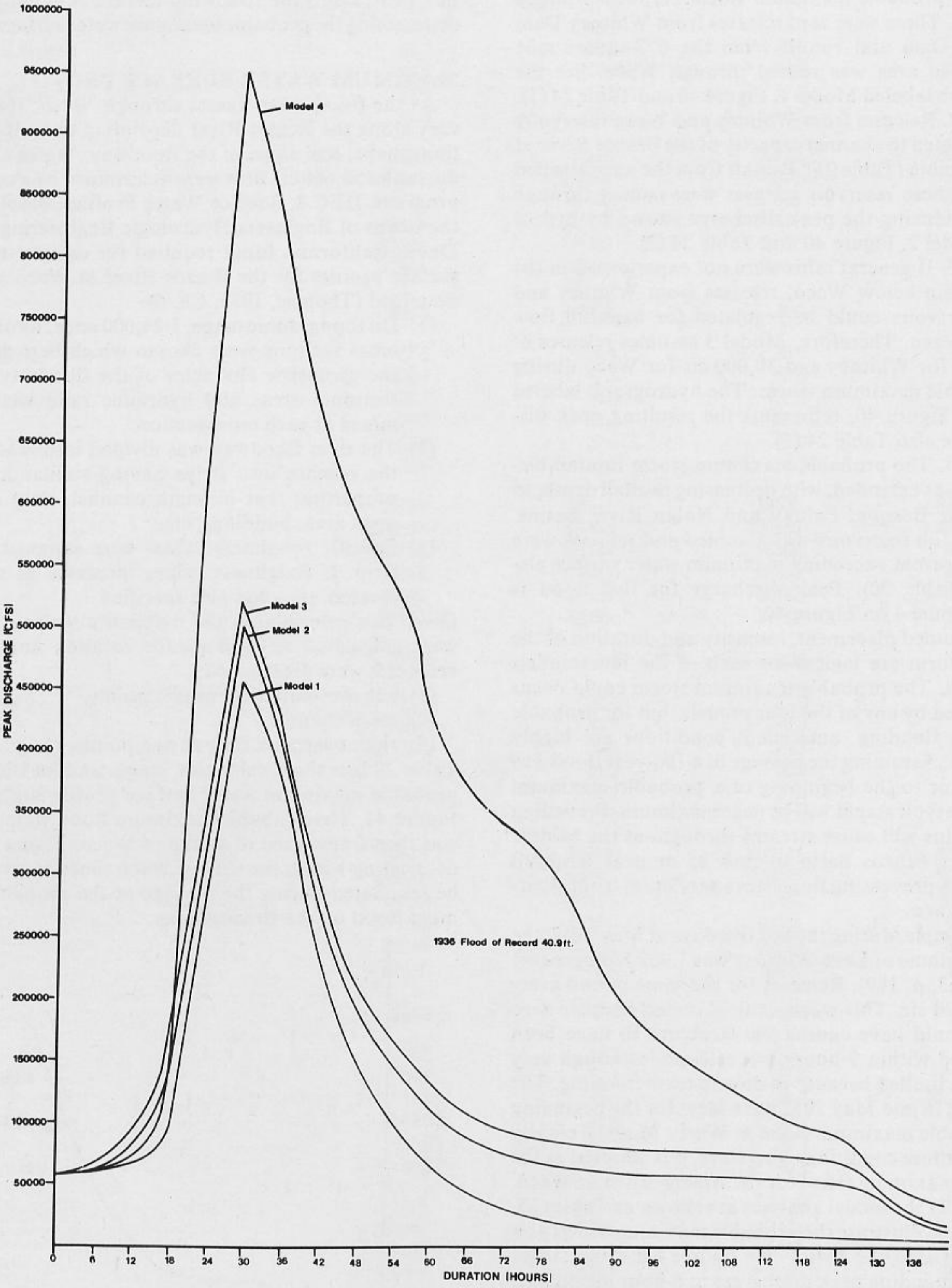


Fig. 40. Composite flood hydrographs for 4 models of probable maximum floods.

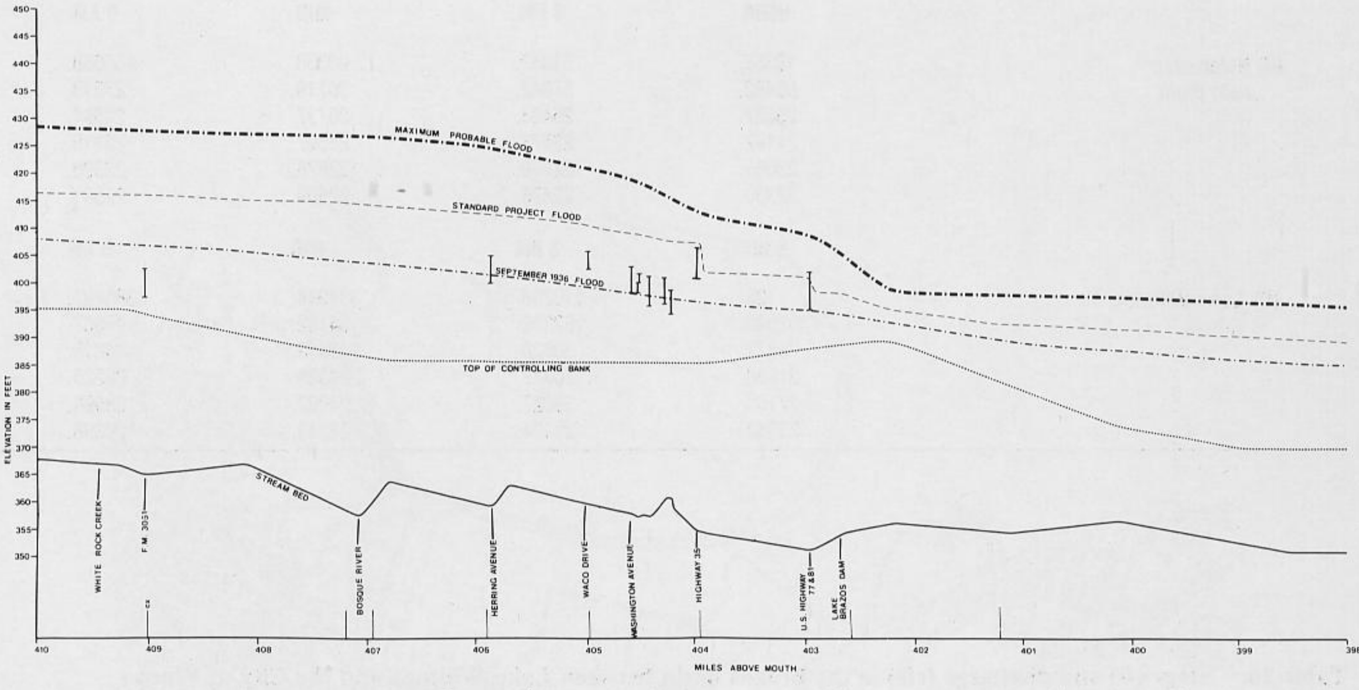


Fig. 41. Probable maximum flood surface water profile.

Table 25. Flow into Lake Whitney during passage of probable maximum flood at Waco.

	NOON	6 PM	MID	6 AM
(A) Brazos River at Glen Rose	4.7	13.5	26.6	32.5
	27.3	19.7	17.9	17.6
	17.3	17.0	16.7	16.4
	16.1	15.9	15.6	15.4
	15.1	14.8	14.6	14.3
	14.1	13.9	13.7	13.4
	86.	12098.	54604.	81107.
	57359.	29369.	23999.	23044.
	22127.	21246.	20401.	19589.
	18810.	18062.	17344.	16654.
	15993.	15357.	14747.	14162.
	13599.	13059.	12541.	12043.
	NOON	**6 PM**	**MID**	**6 AM**
(B) Paluxy River at Glen Rose	0.1	34.3	74.7	44.7
	23.4	13.2	11.0	10.7
	10.5	10.2	10.0	9.8
	10.	90010.	270910.	136410.
	40960.	9950.	5982.	5743.
	NOON	**6 PM**	**MID**	**6 AM**
(C) Nolan River near Blum	20.0	28.2	66.9	102.7
	68.8	43.3	31.1	25.6
	24.5	24.4	24.2	23.9
	23.6	23.4	23.3	23.1
	22.9	22.8	22.7	22.5
	22.5	22.6	22.6	22.6

	NOON	6 PM	MID	6 AM
(C) Nolan River near Blum	18357.	31857.	96358.	156008.
	99482.	57042.	36719.	27519.
	25627.	25498.	25137.	24591.
	24142.	23873.	23597.	23315.
	23065.	22849.	22625.	22396.
	22330.	22425.	22509.	22581.
	NOON	6 PM	MID	6 AM
(D) Lake Whitney inflow	126.	110238.	387944.	385297.
	302649.	192299.	134162.	99667.
	75371.	58620.	45913.	34815.
	31886.	30617.	29398.	28228.
	27105.	26027.	24992.	23998.
	23042.	22124.	21243.	20398.

Table 26. Stage (ft) and discharge (cfs) in the Brazos basin between Lake Whitney and the City of Waco.

	NOON	6 PM	MID	6 AM
Brazos River below Lake Whitney	1.7	38.9	98.2	97.6
	54.3	54.3	54.3	54.3
	26.2	26.2	26.2	26.2
	19.4	19.4	19.4	19.4
	17.8	17.8	17.8	17.8
	9.8	9.9	10.1	10.2
	100.	110200.	387900.	385300.
	182200.	182200.	182200.	182200.
	53700.	53700.	53700.	53700.
	30100.	30100.	30100.	30100.
	25500.	25500.	25500.	25500.
	5550.	5901.	6225.	6526.
	NOON	6 PM	MID	6 AM
Aquilla Creek near Aquilla	0.0	30.0	35.4	40.0
	39.1	36.6	33.5	30.1
	27.8	27.4	27.2	27.0
	0.	25200.	122220.	214120.
	196460.	146080.	84540.	25980.
	11296.	9795.	9305.	8840.
	NOON	6 PM	MID	6 AM
Bosque River below Lake Waco with Brazos River backwater	2.0	38.0	70.4	86.0
	72.3	72.3	72.3	72.3
	68.6	68.6	68.6	68.6
	43.8	43.8	43.8	43.8
	35.4	35.4	35.4	35.4
	14.2	14.2	14.2	14.2
	202.	58901.	244801.	333801.
	255401.	255401.	255401.	255401.
	234301.	234301.	234301.	234301.
	92301.	92301.	92301.	92301.
	49401.	49401.	49401.	49401.
	10001.	10001.	10001.	10001.

Fig. 42. Probable maximum flood delineated within the City of Waco.

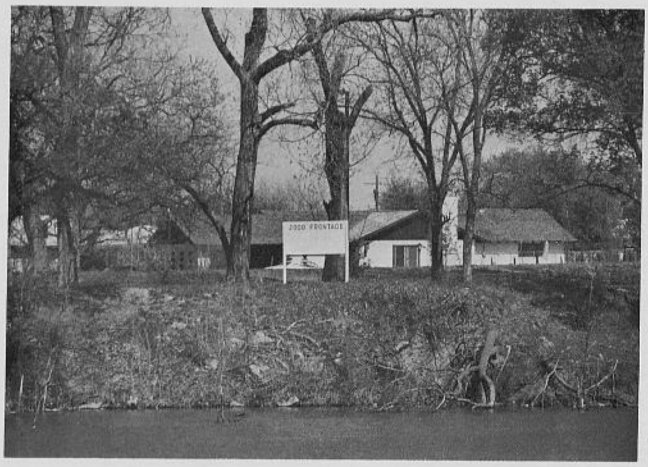


Fig. 43. Disregarding potential danger, Waco citizens build as near to the river as possible.

Fig. 44. Some developers will build on any site unless prohibited by government regulations.

Table 27. Bosque River basin inflow to Lake Waco during probable maximum flood on Brazos River in the City of Waco.

	NOON	6 PM	MID	6 AM
(A) North Bosque near Clifton	0.1	16.1	34.7	36.3
	38.1	37.0	35.7	35.0
	34.2	26.0	22.5	22.1
	10.	12010.	71010.	265010.
	482010.	357010.	195010.	105010.
	56010.	27330.	21750.	21098.
	NOON	6 PM	MID	6 AM
(B) North Bosque at Valley Mills	0.2	30.6	40.2	41.7
	43.1	44.9	44.9	43.6
	41.9	40.5	38.9	37.4
	35.9	34.9	34.4	34.0
	33.7	33.2	32.8	32.5
	32.1	31.8	31.5	31.2
	15.	23069.	106939.	178511.
	244494.	333759.	332322.	267682.
	188444.	119232.	77863.	56174.
	44811.	38627.	35047.	32783.
	31193.	29952.	28901.	27956.
	27078.	26244.	25446.	24676.
	NOON	6 PM	MID	6 AM
(C) Middle Bosque near McGregor	0.3	34.7	71.1	33.7
	14.1	11.1	10.8	10.6
	10.4	10.2	10.0	9.8
	5.	64005.	156005.	61405.
	13709.	8601.	8257.	7927.
	NOON	6 PM	MID	6 AM
(D) Bosque River inflow to Lake Waco	25.	58938.	244787.	333819.
	218850.	221221.	275135.	306647.
	294005.	253594.	253594.	175289.
	130232.	97868.	97868.	63975.
	55816.	50555.	50555.	44375.
	42332.	40618.	40618.	37717.

Table 28. Water surface elevations (above sea level) and storage during passage of the probable maximum flood on the Brazos River at Waco.

	Lapse Time—Flood Stage			
	NOON	6 PM	MID	6 AM
Lake Whitney	571.1	571.1	571.1	571.1
	571.7	572.3	572.1	571.5
	571.2	571.4	571.4	571.2
	571.1	571.2	571.2	571.1
	571.1	571.2	571.2	571.1
	571.2	571.4	571.5	571.7
	Storage Required in Acre-Feet			
	2027992.	2028008.	2028028.	2028038.
	2058150.	2090786.	2081301.	2048658.
	2033443.	2040090.	2039375.	2032705.
	2028430.	2029006.	2028959.	2028316.
	2028250.	2028781.	2028786.	2028283.
	2032280.	2040709.	2048519.	2055741.
	Lapse Time—Flood Stage			
	NOON	6 PM	MID	6 AM
Lake Waco	500.0	500.0	500.0	500.0
	499.0	497.1	496.7	498.6
	501.6	503.8	503.7	501.6
	501.0	502.2	501.9	500.8
	500.2	500.4	500.3	500.1
	500.9	502.6	504.2	505.7
	Storage Required in Acre-Feet			
	559835.	559826.	559832.	559833.
	550700.	533018.	529407.	547152.
	574889.	594639.	594453.	574690.
	569420.	580295.	577863.	566957.
	561480.	563372.	563055.	561194.
	568020.	583757.	598688.	612892.

Table 29. Water elevation and flow velocities for the probable maximum flood on the Brazos River at Waco, Texas.

River Mile	Water Elevation	VELOCITIES Left overbank flow		Main Channel	Right overbank flow	
399.81	398.038	2.73	2.24	8.28	2.71	0.98
400.55	399.045	2.18	2.41	7.87	2.53	1.71
401.28	399.801	2.21	2.43	9.38	2.59	2.14
402.20	398.667	2.69	4.14	24.63	7.66	5.13
402.56	403.104	3.04	4.96	17.71	4.73	3.70
402.59	404.266	3.56	5.43	14.76	6.18	3.75
402.62	403.692	3.75	5.01	15.75	4.29	3.31
402.98	409.876	2.20	4.96	12.15	4.77	2.91
403.93	412.555	7.44	8.03	20.08	7.18	5.47
404.38	419.234	4.02	5.97	16.74	3.19	2.12
404.56	419.336	4.46	4.65	18.34	3.64	2.67
404.94	420.300	3.50	4.02	16.96	1.78	1.47
404.99	421.183	3.29	4.21	15.27	2.51	2.07
405.86	423.927	2.43	3.84	14.62	3.04	0.46
405.89	424.589	3.01	4.63	13.00	1.21	0.60

River Mile	Water Elevation	VELOCITIES Left overbank flow		Main Channel	Right overbank flow	
406.19	424.909	3.55	4.23	14.35	3.93	1.82
406.96	425.576	3.97	3.90	13.73	2.42	1.02
407.18	427.002	2.74	2.75	9.69	2.61	2.22
409.00	428.067	0.10	1.13	9.29	3.25	2.82
410.10	428.524	0.69	1.15	10.84	3.62	3.13
411.60	429.281	2.02	3.53	11.87	4.28	3.30
412.50	430.130	3.11	3.83	11.9	2.97	1.28
413.60	430.889	2.74	3.01	9.86	3.28	1.79
414.90	431.596	2.45	4.06	10.07	3.15	2.41
415.80	432.419	1.05	3.88	9.64	3.14	2.37
416.90	433.092	2.49	3.02	7.71	1.44	2.32
417.90	433.632	2.26	1.98	6.53	1.34	1.90
418.80	433.984	2.78	2.43	8.90	1.73	1.61
419.80	434.942	3.20	2.24	10.16	3.08	2.25
420.80	441.05	2.50	4.19	29.27	8.12	5.47
421.50	449.099	3.80	3.91	18.96	5.95	4.40

Velocity measured in feet/sec. and elevation in feet above sea level.

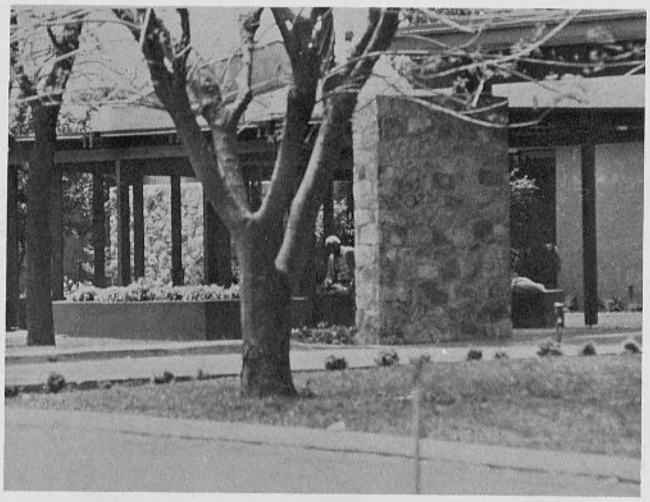


Fig. 45. As land within Waco becomes more scarce, flood plain development will increase. A convalescent home on the flood plain is an example of ill-advised flood plain use.

CONCLUSIONS

This report does not contain plans for the solution of flood problems, nor does it suggest a land use policy for the City of Waco, but rather it is intended to cause the planner to be aware of impending danger. Hopefully it will form bases for further studies directed toward solving current floodway use problems and preventing future problems. Conclusive comments that I feel are appropriate will follow.

(1) The Upper Brazos basin will influence probable maximum flooding in Waco only to the extent of contributing to necessary antecedent conditions.

(2) Waco is situated in a physiographic region that experiences climatological conditions capable of producing the exact critical combination of climatic events that are necessary to trigger a probable maximum storm.

(3) Compared to other areas within the same physiographic region, Waco has not yet experienced a great flood.

(4) A flood on the Brazos River in the City of Waco, far greater than the 1936 flood of record, could result from rainfall within the 672 square miles of "uncontrolled" basin between Waco and Lake Whitney.

(5) Flood storage capability of Lake Whitney and Lake Waco will be depleted by antecedent weather condi-

tions and will therefore offer minimal retardation of the probable maximum flood flow at Waco. Construction of Aquilla Creek dam in the uncontrolled area will not lessen the impact of probable maximum flooding in Waco.

(6) The threat of flooding in Waco is overshadowed by the Waco citizens' desire to live near the water (Fig. 43) and by their confidence in the federal government's ability to control flooding by constructing flood-control dams. To the flood-plain dweller these upstream flood-control structures apparently represent security, while in fact they are setting the stage for a great disaster.

(7) The floodway will continue to be developed (Fig. 44). An increasing demand for building sites in Waco makes the flood plain a valuable asset to a city that is promoting growth. This in itself is not a problem; however, a convalescent home in the flood plain (Fig. 45) indicates maldevelopment.

(8) A flood far greater than the flood of record will occur on the Brazos River in the City of Waco.

REFERENCES

Beard, Leo R. (1962) Statistical methods in hydrology: Civil works investigation project CW-151, U.S. Army Corps of Engineers, Sacramento, p. 9-14.

——————, *ed.* (1970) Proceedings of a seminar on urban hydrology: The Hydrologic Engineering Center, Davis, 225 p.

—————— (1975) Hypothetical floods, Hydrologic Engineering Methods for Water Resources Development, v. 5: U.S. Army Corps of Engineers, Davis, 65 p.

Benson, Manuel A. (1959) Channel-slope factors in flood-frequency analysis: American Society of Civil Engineers, Separate Number 1994, 9 p.

—————— (1962a) Factors affecting the occurrence of floods in the Southwest: U.S. Geological Survey Water-Supply Paper 1580-D, 71 p.

—————— (1962b) Factors influencing the occurrence of floods in a humid region of diverse terrain: U.S. Geological Survey Water-Supply Paper 1580-B, 64 p.

Bishop, Arthur L. (1976) Flood potential of the Bosque Basin: Unpub. senior thesis, Baylor University. [Published 1977, Baylor Geological Studies Bulletin 33.]

Bowden, K.L. and Wallis, J.R. (1964) Effect of stream ordering technique on Horton's laws of drainage composition: Geological Society of America Bulletin 75, p. 767-774.

Boyer, M.C. (1957) Characteristics of great storms: American Geophysical Union Transactions, v. 38, p. 233-238.

Breeding, Seth D. and Dalrymple, Tate (1944) Texas floods of 1938 and 1939: U.S. Geological Survey Water-Supply Paper 914, 116 p.

Breeding, Seth D. and Montgomery, J.H. (1952) Floods of September 1952 in the Colorado and Guadalupe River basins, central Texas: U.S. Geological Survey Water-Supply Paper 1260-A, 46 p.

Byers, Horace R. (1951) Thunderstorms *in* Compendium of Meteorology (Thomas F. Malone, *ed.*): American Meteorological Society, Boston, p. 681-692.

Carr, J.T. (1966) Hurricanes: Symposium on conditions of some aspects of storms and floods in water planning: Texas Water Development Board Report 33, Austin, p. 19-31.

—————— (1967) The climate and physiography of Texas: Texas Water Development Board Report 53, Austin, 125 p.

Chow, Ven Te (1959) Open channel hydraulics: McGraw-Hill, New York, p. 89-129.

—————— (1964) Handbook of applied hydrology: McGraw-Hill, New York, p. 14-1 - 14-49.

Coates, D.R. (1958) Quantitative geomorphology of small drainage basins of southern Indiana: Project NR 389-042, Tech. Report 10, Columbia Univ., Department of Geology, ONR Geography Branch N.Y.

Cochran, A.L. (1975) Spillway and freeboard requirements for dams: Draft Engineer Circular No. 1110-2-163, U.S. Gov't Printing Office, Washington, D.C., p. C-4a - C-14.

Commons, C.G. (1945a) Flood peaks in Texas: Unnumbered Report, Texas Board of Water Engineers, p. 1-4.

—————— (1945b) Flood frequencies: Unnumbered Report, Texas Board of Water Engineers, p. 1-6.

—————— (1945c) Flood routing by the Barrows method: Unnumbered Report, Texas Board of Water Engineers, p. 1-4.

—————— (1945d) Flood hydrographs: Unnumbered Report, Texas Board of Water Engineers, p. 1-4.

Cornthwaite, H.G. (1919) Panama rainfall: Monthly Weather Review, v. 47, p. 302.

Court, A. (1961) Area-depth rainfall formulas: Journal of Geophysical Research, v. 66, p. 1823-1831.

Curtis, Leon (1977) Oral Communication: Hydrological engineer, Southwest Division U.S. Army Corps of Engineers, Dallas, Texas.

Dalrymple, Tate (1960) Flood frequency analysis: U.S. Geological Survey Water-Supply Paper 1543a, 80 p.

Davis, Darryl W., *ed.* (1975) Hydrologic frequency analysis: Hydrologic Engineering Methods for Water Resources Development: U.S. Gov't Printing Office, Washington, D.C., 107 p.

Dorrah, J.A., Jr. (1946) Certain hydrologic and climatic characteristics of the Southwest: Publications in Engineering, New Mexico Univ. Press, Albuquerque, 64 p.

Fletcher, R.D. (1950) A relationship between maximum observed point and areal rainfall values: American Geophysical Union Transactions, v. 31, p. 344-348.

—————— (1951) Hydrometeorology in the United States *in* Compendium of Meteorology (Thomas F. Malone, *ed.*): American Meteorological Society, Boston, p. 1033-1047.

Gilman, Charles S. (1964) Rainfall *in* Handbook of Applied Hydrology (Ven Te Chow, *ed.*): McGraw-Hill, New York, p. 9-1 - 9-65.

Godfrey, Curtis L.; McKee, Gordon S.; and Oakes, Harvey (1973) General soils map of Texas: U.S. Gov't Printing Office, Washington, D.C., 2 p.

Gregory, K.J. and Walling, D.E. (1973) Drainage basin form and process: John Wiley & Sons, New York, 456 p.

Guy, H.P. (1964) An analysis of some storm-period variables affecting stream sediment transport: U.S. Geological Survey Professional Paper 462E, p. 7, 8.

Hampton, B.B. (1972) Hydrologic studies of small watersheds, Green Creek, Brazos River basin: Texas Water Development Board Report 159, Austin, 55 p.

Hare, George S. (1970) Effects of urban development on storm runoff rates *in* Proceedings of a seminar on urban hydrology (Leo R. Beard, *ed.*): Hydrologic Engineering Center, Davis, p. 1-16.

Hayes M.O. (1967) Hurricanes as geological agents: Texas Bureau of Economic Geology Report of Investigations No. 61, 54 p.

Holler, Albert G. (1970) Urban hydrological considerations in design of inlet drainage facilities for local floods *in* Proceedings of a seminar on urban hydrology (Leo R. Beard, *ed.*): Hydrologic Engineering Center, Davis, p. 1-12.

Horton, Robert E. (1914) Derivation of runoff from rainfall data: American Society of Civil Engineers, v. 77, p. 369-375.

——— (1932) Drainage basin characteristics: American Geophysical Union Transactions, v. 13, p. 350-361.

———(1935) Surface runoff phenomena: Horton Hydrological Lab, Publication 101 (*cited in* Langbein & Iseri, 1960).

——— (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geological Society of America Bulletin, v. 56, pt. 1, p. 281-369.

HUD (1977) Federal insurance administration flood insurance study, Waco: U.S. Dept. of Housing and Development, p. 1-45.

HUNT, CHARLES B. (1967) Physiograph of the United States: Freeman & Company, San Francisco, 480 p.

Hydrologic Engineering Center (1973) Hydrograph analysis, v. 4: U.S. Army Corps of Engineers, Davis, 45 p.

JARVIS, CLARENCE S. (1936) Floods in the United States—magnitude and frequency: U.S. Geological Survey Water-Supply Paper 771, 497 p.

JENNINGS, A.H. (1950) World's greatest observed point rainfalls: Monthly Weather Review, v. 78, p. 4.

JOHNSTON, DON (1948) Elements of applied hydrology: The Ronald Press, New York, 275 p.

KIRKHAM, DON and CURTISS, CHARLES F. (1964) Soil physics *in* Handbook of Applied Hydrology (Ven Te Chow, *ed.*): McGraw-Hill, New York.

KIRPICH, Z.P. (1940) Time of concentration of small agriculture watersheds: Civil Engineer, v. 6, p. 362 (Cited in Chow, 1964).

LANGBEIN, WALTER B. (1940) Some channel storage and unit hydrograph studies: American Geophysical Union Transactions, v. 21, p. 620-627.

——— (1947) Topographic characteristics of drainage basins: U.S. Geological Survey Water-Supply Paper 968-C, p. 125-157.

——— and ISERI, KATHLEEN T. (1960) Manual of hydrology Part 1- General surface water techniques: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

LEOPOLD, LUNA B. and MADDOCK, THOMAS JR. (1953) The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 56 p.

———(1954) The flood control controversy: The Ronald Press, New York, 251 p.

——— and MILLER, J.P. (1956) Ephemeral streams hydraulic factors and their relationship to the drainage net: U.S. Geological Survey Professional Paper 282A, 37 p.

MAKEY, GEORGE B. (1964) Hydrogeology *in* Handbook of Applied Hydrology (Ven Te Chow, *ed.*): McGraw-Hill, New York, p. 4-1 - 4-76.

MCCARTHY, G.T. (1938) The unit hydrograph and flood routing: Unpub. manuscript presented at Conference of North Atlantic Division, U.S. Army Corps of Engineers (*Cited in* Langbein, 1947).

MILLS, W. B.; MCGILL, H.N. and FLUGRATH, M.W. (1965) Hydrologic studies of small watersheds—Deep Creek, Colorado River basin, Texas: Texas Water Development Board Report 3, Austin, 121 p.

——— (1969) Hydrologic studies of small watersheds, Cow Bayou, Brazos River basin: Texas Water Development Board, Austin, 66 p.

MORGAN, R. and HULLINGHORST, D.W. (1939) Unit hydrographs for gaged and ungaged watersheds: U.S. Engineer Office, Binghamton, N.Y. (*Cited in* Langbein, 1947).

MORISAWA, MARIE E. (1959) Relation of quantitative geomorphology to stream flow in representative watersheds of the Appalachian Plateau Province: Office of Naval Research, Geography Branch, Project NR 389-042: Technical Report 20, 94 p.

OGROSKY, HAROLD O. and MOCKUS, VICTOR (1964) Hydrology of agricultural lands *in* Handbook of Applied Hydrology (Ven Te Chow, *ed.*): McGraw-Hill, New York, p. 21-10.

ORTON, ROBERT B. (1964) The climate of Texas and the adjacent gulf waters: U.S. Gov't Printing Office, Washington, D.C., 194 p.

——— (1966) Easterly waves: Symposium on conditions of some aspects of storms and floods in water planning: Texas Water Development Board Report 33, Austin, p. 3-17.

PATTERSON, JAMES L. (1965) Magnitude and frequency of floods in the United States. Part 8. Western Gulf of Mexico basins: U.S. Geological Survey Water-Supply Paper 1682, 506 p.

PETTERSSEN, SUERRE (1969) Introduction to meteorology: McGraw-Hill, New York, 333 p.

RIEHL, HERBERT (1951) Aerology of tropical storms *in* Compendium of Meteorology (Thomas F. Malone, *ed.*): American Meteorology Society, Boston, p. 902-913.

SAUER, STANLEY (1965) Hydrologic studies of small watersheds, Mukewater Creek, Colorado River basin, Texas: Texas Water Development Board, Austin, 70 p.

SCHONER, ROBERT W. (1968) Climatological regime of rainfall asociated with hurricanes after land-fall: U.S. Weather Bureau Technical Memorandum ER-29, 24 p.

SCHREINER, LOUIS C. and RIEDEL, JOHN T. (1976) Probable maximum precipitation estimates, United States east of the 105th meridian: Hydrometeorological Report. No. 51. U.S. Gov't Printing Office, Washington, D.C., p. 1-109.

SCHUMM, S.A. (1956) Evolution of drainage systems and slopes in Badlands at Perth Amboy, New Jersey: Geological Society, of America Bulletin 67, p. 612.

SEARCY, JAMES K. (1960) Graphical correlation of gaging station records: U.S. Geological Survey Water-Supply Paper 1541-C, p. 67-100.

——— and HARDISON, CLAYTON H. (1960) Double mass curve: U.S. Geological Survey Water-Supply Paper 1541-B, p. 31-58.

SMITH, J.T. and WELBORN, C.T. (1967) Hydrologic studies of small watersheds, Pin Oak Creek, Trinity River basin, Texas: Texas Water Development Board, Austin, 69 p.

SNYDER, FRANKLIN F. (1938) Synthetic Unit-Graphs: American Geophysical Union Transactions, v. 19, p. 447-454.

——— (1964) A conception of runoff phenomena: American Geophysical Union Transactions, v. 20, p. 725.

STRAHLER, ARTHUR N. (1957) Quantitative analysis of watershed geomorphology: American Geophysical Union Transactions, v. 38, no. 6, p. 913-920.

THOMAS, W.A. (1975) Surface water profiles, v. 6: The Hydrologic Engineering Center, Davis, 125 p.

Texas Water Development Board (1973) Engineering data on dams and reservoirs in Texas, Report 126, Part II: Austin, p. 12.01. A-12.19 E.

U.S. Army Corps of Engineers (1946) Definite project report on Whitney Reservoir: U.S. Gov't Printing Office, Washington, D.C., p. 1-46.

———(1957) Design memorandum No. 1 on Waco Reservoir Bosque River, Texas: U.S. Gov't Printing Office, Washington, D.C.

———(1960) EM 1110-2-1408, Routing of floods through river channels: U.S. Gov't Printing Office, Washington, D.C., p. 1.15.

——— (1970) Flood plain information, Brazos and Bosque Rivers: U.S. Army Corps of Engineers, Fort Worth District, 39 p.

——— (1974) Design memorandum 1, Aquilla Creek: U.S. Army Corps of Engineers, Fort Worth District, 82 p.

U.S. Department of Agriculture (1966) Methods of flow frequency analysis, Bulletin 13: U.S. Gov't Printing Office, Washington, D.C., 78 p.

——— (1971) National engineering handbook, section 4, hydrology: Soil Conservation Service, Chapters 15, 16, and 17.

U.S. Study Commission-Texas (1962) The eight basins, Part III: U.S. Gov't Printing Office, Washington, D.C., p. 91-124.

VANCE, A.M. (1934) Excessive rains in Texas: State of Texas Reclamation Office Bulletin 25, Austin, 125 p.

WILLIAMS, GORDON R. and CRAWFORD, LAWRENCE C. (1940) Maximum discharge at stream-measurement stations: U.S. Geological Survey Water-Supply Paper 847, p. 136.

WISLER, C.O. and BRATER, E.F. (1959) Hydrology: John Wiley & Sons, Inc., New York, 408 p.

YOST, I.D. (1963) Floods of April-June 1957 in Texas and adjacent states: U.S. Geological Survey Water-Supply Paper 1652-B, 315 p.

INDEX

BAYLOR GEOLOGICAL PUBLICATIONS*

Baylor Geological Studies

1. Holloway, Harold D. (1961) The Lower Cretaceous Trinity aquifers, McLennan County, Texas: Baylor Geological Studies Bull. No. 1 (Fall). Out of print.
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