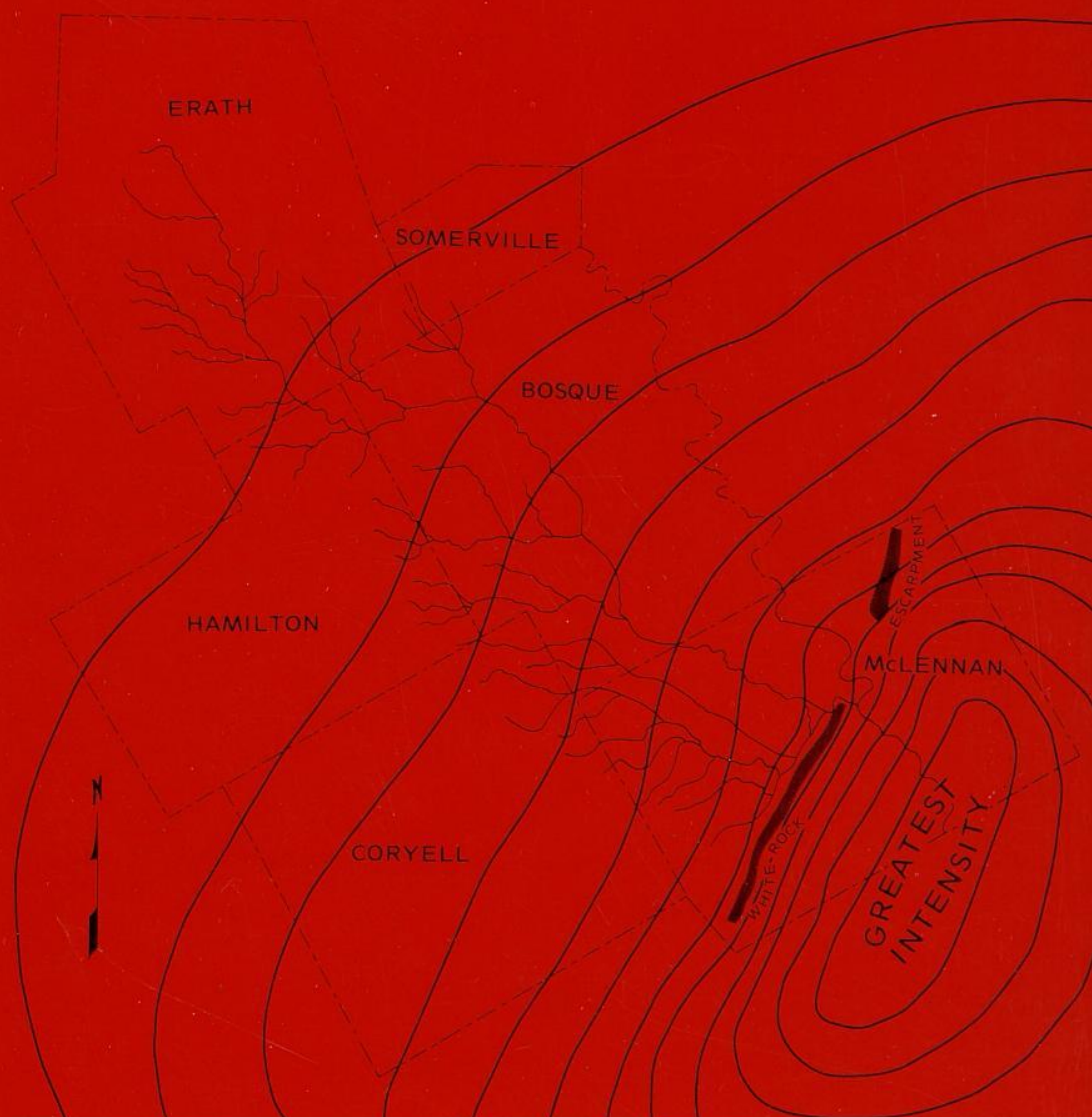
BAYLOR GEOLOGICAL STUDIES



FALL 1977

Bulletin No. 33

BAYLOR UNIVERSITY – WACO, TEXAS
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Flood Potential of the Bosque Basin

ARTHUR L. BISHOP

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

FRANK CARNEY, PH.D.
PROFESSOR OF GEOLOGY
BAYLOR UNIVERSITY
1929-1934

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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.

THE BAYLOR UNIVERSITY PRESS
WACO, TEXAS

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 33

Flood Potential of the Bosque Basin

Arthur L. Bishop

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Fall, 1977

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published semi-annually, Spring and Fall, by the Department of Geology at Baylor University. The Bulletin is specifically dedicated to the dissemination of geologic knowledge for the benefit of the people of Texas. The publication is designed to present the results of both pure and applied research which will ultimately be important in the economic and cultural growth of the State.

ISSN 0005-7266

Additional copies of this bulletin can be obtained from the Department of Geology, Baylor University, Waco, Texas 76703. $1.05 postpaid.

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Flood Potential of the Bosque Basin

Arthur L. Bishop

ABSTRACT

Maximum flood potential of the Bosque basin is concentrated in the Hog Creek, South Bosque and Middle Bosque basins, and the lower reaches of the North Bosque River where impermeable bedrock has maximum areal extent. The White Rock Escarpment forms part of the basin divide in this area. Since the Escarpment significantly affects the intensity and distribution of precipitation and its juxtaposition to the area of maximum runoff, flood planning should be developed in this area.

Three types of storms will produce maximum flooding from this area. The thunderstorm will be the most frequent, but will produce the smallest volume of flooding. The tropical cyclone will produce the maximum flooding, but is least frequent in occurrence. The tropical wave can be considered to produce the maximum flood with greatest chance of occurrence in the Bosque basin.

Regardless of storm type, the "100-year" flood discharge can be produced by as little as 2.02 inches of runoff from the entire basin. Since so little runoff is required to produce this statistical flood, new guidelines should be developed for flood forecasting and flood planning.

INTRODUCTION*

PURPOSE

Recent major flooding in central Texas has renewed interest in flood analysis and prediction. Of particular interest were rapid rises in Lake Waco. The rainfall which produced such inflow was of less intensity than others previously recorded in central Texas; yet, despite this, no study has been made of the effect larger rains would have in the Bosque basin.

Since numerous small communities are in close proximity to major streams within the Bosque drainage, a study of flood potential is desirable. In addition, if the flood storage capacity of Lake Waco were to be exceeded by waters derived from the Bosque system, there would be a direct flood threat to the major metropolitan area of Waco.

Therefore the purpose of this investigation is to determine those factors which contribute to maximum flooding and to predict the magnitude of flooding which would result from various combinations of circumstances. Emphasis is also given to the nature and probability of storms which might produce such flooding. While this is an introductory study, it is designed to serve as a guide to planners, communities, and citizens whose work and livelihood may be affected by flooding.

LOCATION

The Bosque River drains an area of 1655 square miles north and west of Waco, Texas (Fig. 1). The basin is bounded by the Leon River to the west and the Brazos River to the east.

The largest of the four tributaries of the Bosque system is the North Bosque River which heads in northern Erath County and discharges into Lake Waco (Fig. 2). This basin, 1290 square miles in area, includes parts of Erath, Sommervell, Hamilton, Bosque, Coryell, and McLennan Counties. A second major tributary, Hog Creek, heads in Hamilton County, extends through Coryell, Bosque, and McLennan Counties to discharge into Lake Waco. The Middle Bosque River originates in eastern Coryell County, drains portions of Bosque and McLennan Counties and discharges into the South Bosque River immediately upstream from Lake Waco. The South Bosque River drains

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*A thesis submitted in partial fulfillment of the B.S. degree in Geology, Baylor University, 1976.

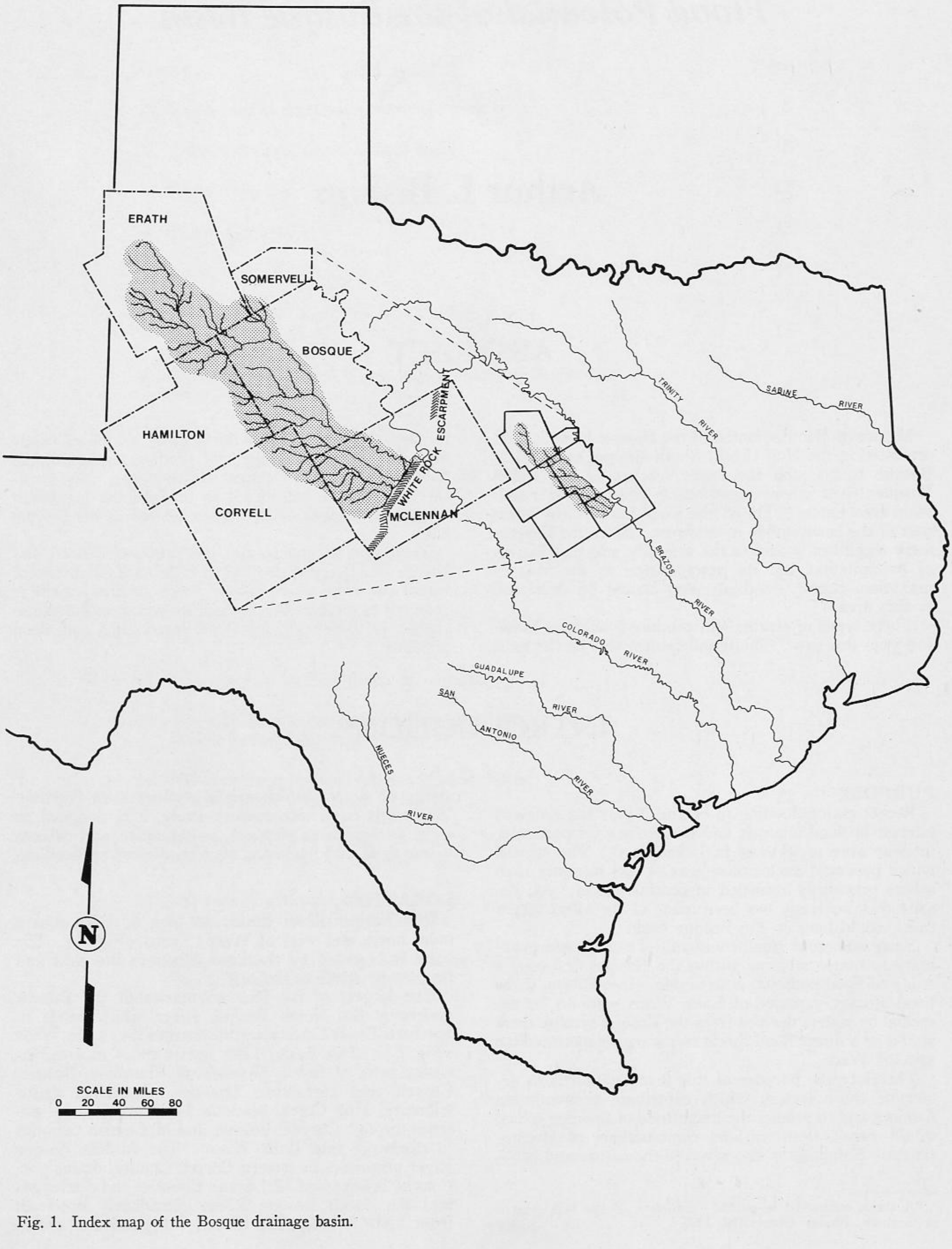


Fig. 1. Index map of the Bosque drainage basin.

only western McLennan County and its northwestward course makes a right angle with the courses of the other three rivers.

PROCEDURES

Initial study began with literature review of: (1) historical flooding of the Bosque system and the causes of flooding; (2) physical data on soils, geology, and hydrologic character of soils and rocks; and (3) analysis of flood prediction methods as they apply to the study area. A base map was prepared from county highway maps and checked for accuracy in the field and on aerial photographs. Soils, geologic formations, and land use were plotted from existing geologic and soil maps and later checked in the field. In addition, original investigation was used to confirm published information and to fill gaps in the literature.

Interpretations were based on application of accepted practices to the unique historical record and physical character of the Bosque drainage system in central Texas.

PREVIOUS WORKS

Previous works can be divided into several categories.

1. General works on hydrology which offer information of use on analysis of flooding and flood potential. Among these, the books most directly useful in the study include: Patterson (1963), the only analysis of potential flooding specifically applicable to the Bosque basin. General works on hydrology by Wisler and Brater (1959); Ven Te Chow, *ed.* (1964); and Mockus (1969); and the *Compendium of Meteorology* by Malone (1951) were used to design models of rainfall and flooding specifically for the Bosque basin.

2. Flood studies in central Texas include those by C. E. Ellsworth (1923) who analyzed the Little River flood of 1921 and the associated rainfall, including the orographic effect of the Balcones Escarpment. Tate Dalrymple, *et al.* (1937) analyzed flooding in central Texas during September, 1936, the first report on flooding in central Texas based on accurate measurements of rainfall amount and flood magnitude (this report also showed that the severe damage to Waco resulted from a high rapid rise in the Brazos River coupled with a maximum discharge from the Lake Waco flood control structure). The *Symposium on Consideration of Some Aspects of Storms and Floods in Water Planning* (1966) by the Texas Water Development Board contains papers on three common flood-producing storms which occur in Texas. It also includes a paper on the limitations to transposition on any of these storms from one basin to another within the state.

3. Physical character of the Bosque basin has been described in a number of papers. Most useful in this study was J. B. Brown's (1963) study of Flat Top Ranch. More recently reconnaissance mapping in the basin has been published by the Texas Bureau of Economic Geology in the Waco (1970), Abilene (1972), and Dallas (1972) sheets. Portions of the Bosque basin were mapped by Proctor (1969), Moore (1970), and T. E. Brown (1971). Information from Proctor's work served to guide the calculation of potential flooding in various sub-basins of the Bosque basin and served as an indirect check of predicted flooding based on hydrologic analysis.

ACKNOWLEDGMENTS

Appreciation is expressed to O. T. Hayward, Department of Geology, Baylor University, for guidance and support in this study. Jean M. Spencer, Department of Geology, Baylor University, assisted in collection and interpretation of meteorological data and edited the manuscript for publication. David Durler, Department of Geology, Baylor University, aided in the field work and assisted in interpretation of hydrological properties of soils. In addition, appreciation is extended to faculty, staff, and student body of the Department of Geology of Baylor University for suggestions and support in the progress of this study. The writer extends his deepest appreciation to his wife, Diane, for manuscript preparation of this thesis and her patience in the course of this investigation. Finally, the writer greatly appreciates the thoughtful prepublication review of this manuscript by Robert Orton, National Weather Service Office, El Paso, Texas.

PHYSICAL CHARACTERISTICS OF DRAINAGE SYSTEMS

Physical factors influencing flooding within the Bosque drainage system are geology, climate, topography, soils, land use, vegetation, and meteorological conditions. Among the first four variables (geology, climate, topography, and soils) variations are so slight that they may be assumed to be constant. Since agricultural practices are dependent on the relationships among these same four factors, land use is also essentially constant over relatively extended periods of time. Vegetation remains constant over periods of tens of years, because, in areas unmodified by farming, plant communities approach climax conditions. Thus, variability of flooding within the Bosque basin is due almost entirely to specific meteorological events occurring within the basin. However, despite the fact that a number of these variables may be considered constants, they still have significant influence on flooding and flood potential and are considered individually below.

GEOLOGY

Among common rock properties, the one significant to overland flow and flooding is permeability. Therefore, normal stratigraphic nomenclature is not significant to hydrologic interpretation, as formation names do not necessarily describe units with different hydrologic properties. For this reason the surface geology of the basin is described in terms of dominant lithology (limestone, shale, etc.) and permeability (permeable vs. impermeable). This allows rapid qualitative analysis which may indicate the potential for flood production in various outcrop areas.

In soil mapping, the Soil Conservation Service has adopted letter designators to describe runoff potential. This same letter designation can be adapted to geology. For example:

> A. (Low Runoff Potential) Soils having high infiltration rates even when thoroughly wetted and consisting of deep well to excessively drained sands and gravels. . . .
>
> B. Soils having moderate infiltration rates when thoroughly wetted and consisting of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately course textures. . . .
>
> C. Soils having slow infiltration rates when thoroughly wetted and consisting of soils with a layer that impedes downward movement of water or soils with moderately fine to fine textures. . . .
>
> D. (High Runoff Potential) Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan at or clay layer near the surface, and shallow soils over nearly impervious material. . . .
>
> (U.S. Soil Conservation Service, 1969, p. 7.2)

These same letter designators can be applied to exposed formations, the characters of which are not radically different from those of the soils developed on them. The following informal names were adopted from this study, and for each the equivalent letter designation is given. Also included is relative distribution in the basin.

SANDS AND GRAVEL-PERMEABLE (B)
Formations of this group consist of Holocene (Recent) alluvium and Pleistocene terraces. Alluvial deposits are found in the flood plains of the major streams within the Bosque basin. The extensive terrace deposits most commonly occur parallel to these same streams. Higher terraces are generally of smaller size and are more deeply dissected. They exist largely to the west of Lake Waco along the upland divides between North, Middle, and South Bosque Rivers and Hog Creek (Fig. 2).

SANDS-PERMEABLE (B)
The only formation within this category is the Paluxy Sandstone which crops out only in the North Bosque basin. It is exposed northwest of Meridian, Bosque County, particularly in the basins of Green and Duffau Creeks and the North and South forks of the North Bosque River. Paluxy Sandstone is a shallow aquifer in the Bosque basin.

LIMESTONE-PERMEABLE (B)
The Edwards Limestone has high permeability because of an extensive network of vugular porosity. It is a primary shallow aquifer in the Middle Bosque and Hog Creek basins. It crops out in all the counties within the study area but has greatest areal extent in Bosque, Coryell, Hamilton, and Somervell Counties.

LIMESTONE-IMPERMEABLE (D)
There are four formations of impermeable limestone which crop out within the study area. In descending stratigraphic order, they are: the Austin Chalk, Main Street Member of the Georgetown Formation, Comanche Peak Limestone, and Glen Rose Formation. The Austin Chalk crops out only along the southeastern drainage divide of the South Bosque River, immediately west of Waco (Fig. 2). The Main Street Member crops out between the North and South Bosque Rivers in west-central McLennan County. The Comanche Peak Limestone crops out immediately below the Edwards Limestone and is found throughout the study area; it is most widely distributed north of McLennan County. The Glen Rose Formation crops out in Bosque, Hamilton, Somervell, and Erath Counties. It is most widely exposed in Hamilton and Erath Counties.

LIMESTONE AND SHALE-IMPERMEABLE (D)
The only mixed limestone-shale units within the study area are in the Georgetown Formation, exclusive of the Main Street Member. The remaining members are admixtures of thin argilliceous limestone beds, calcareous shales or limestone and shale units. Upon weathering, clays of these units form an effective seal to downward percolation of water. These units crop out throughout the area of investigation, except in Erath County. However, the area of maximum exposure is in western McLennan, southeastern Bosque, and northwestern Coryell Counties along and between the channels of the South Bosque and Middle Bosque Rivers and Hog Creek. In the North Bosque basin this lithologic type is confined to small upland surfaces atop the Edwards-capped divides.

SHALE-IMPERMEABLE (D)
Shales within the study area are geographically separated into three groups. Eagle Ford and Pepper Shale are exposed in the west-facing slopes of the Austin Escarpment in central McLennan County. Del Rio Clay crops out west of the South Bosque River and Lake Waco where it forms a rolling upland in McLennan County. Walnut Clay crops out throughout the area of investigation. Its area of maximum exposure is in Bosque and Hamilton Counties. In Erath County it is found on upland divides and headwater areas of the North Bosque River. In Coryell County, Walnut Clay occurs only in the northeast corner in the valley of Neils Creek. In McLennan County, it is exposed only in an incised section of the North Bosque River where it enters the county.

CLIMATE

The average annual precipitation varies from 28 inches in the northwest extremity of the basin to 33 inches at Waco (Geraghty *et al.*, 1973, Pl 2). Excessive precipitation from single storms has occurred in and near the area of investigation. Storm tracks and storm magnitudes are discussed under sections entitled Meteorology and Historical Rains and Flooding.

Snowfall is minimal with an average amount of two to three inches (*idem*) and thus has little effect on flooding, except to increase antecedent moisture prior to heavy rainfalls. Frost penetration may have a significant effect on flooding. However, in the study area the length of time the ground is subject to freezing ranges from 135 days in the northwest section of the basin to 118 days in the southwest section. Maximum frost penetration does not exceed five inches and rarely do flood-producing storms coincide with periods of frost penetration.

TOPOGRAPHY

The area is readily divided into natural physiographic regions. The boundaries approximate those of the underlying geology. For this reason the topography is described in its relation to the underlying geology.

The White Rock Prairie is a subdivision of the Black Prairie of Texas. It is underlain by Austin Chalk and generally forms rolling topography of moderate relief. Within the Bosque basin, the White Rock Prairie forms the drainage divide and slope face of the White Rock (or Austin) Escarpment. Along this escarpment, topographic characteristics depart from those of the typical White Rock Prairie. Slopes generally range from six to ten degrees, though in local areas vertical faces exist depending upon the degree of dissection and maturity of small drain ways.

The Eagle Ford Prairie lies west of the White Rock Prairie and is also part of the Texas Black Prairie. The underlying bedrock of the Eagle Ford Prairie consists of the South Bosque and Lake Waco Formations (of the Eagle Ford Group) and the Pepper Shale. Typical topography in the Eagle Ford Prairie consists of gently rolling landscape of low relief. Within the area of investigation, the Eagle Ford Prairie is confined to a narrow strip lying north and west of the White Rock Prairie at the base of the White Rock Escarpment. In the study area the Eagle Ford Prairie has relief of as much as 100 feet or more; slopes are commonly less than ten degrees. Under conditions of extreme erosion slopes of 45 to 60 degrees may exist.

The Washita Prairie lies west of Lake Waco and the South Bosque River and is the easternmost part of the Grand Prairie of Texas. It is commonly subdivided into four smaller prairie areas whose boundaries are likewise those of the underlying formations upon which the prairies are developed. On the east the Washita Prairie is underlain by the Del Rio Clay. This area has low relief with slopes generally of five degrees or less. To the west, in the outcrop belt of the Main Street Member, is the rolling Georgetown Prairie of low to moderate relief again characterized by gentle slopes. However, where major streams are incised relief may be as much as 50 feet and slope angles range from 45 degrees to vertical faces along some main stem reaches.

Immediately west of the Main Street Prairie lies the prairie area underlain by the Paw Paw, Weno, and Denton Members of the Georgetown Formation. This too is typically rolling prairie with very gentle slopes and relief seldom exceeding 40 feet. Steep slopes and high relief are found only in deeply dissected areas immediately adjacent to major streams.

The westernmost sub-prairie of the Washita Prairie is that underlain by the Fort Worth, Duck Creek, and Kiamichi Members of the Georgetown Formation. This is typically rolling upland divided by limestones of the Fort Worth Member. A middle slightly convex slope break is underlain by the relatively more resistant Duck Creek Member and a lower concave slope is developed on the Kiamichi Clay. Relief seldom exceeds 50 feet and slope angles vary but seldom exceed 15 degrees. This topography typically extends to the edge of the Lampasas Cut Plain. Westward in the Lampasas Cut Plain small remnants of the Georgetown Prairie can be found on top of outliers capped by Edwards Limestone.

The Lampasas Cut Plain topography exists where streams have entrenched through the Edwards Limestone. The topography of the Lampasas Cut Plain has developed because of the relative resistances of the Edwards Limestone, the Comanche Peak Limestone, and the Walnut Clay. Steep slopes develop on the Edwards which forms a protective weather-resistant cap. Beneath the Edwards the Comanche Peak Limestone forms a concave slope between divides and valley floors. This relatively steep slope averages 30 degrees with extremes of 50 to 90 degrees. Valley floors developed on Walnut Clay are commonly gently undulating with low relief. Slope angles rarely exceed five degrees except where small "benches" are formed on fossiliferous limestone ledges. Overall relief in the Lampasas Cut Plain varies from 120 to 150 feet with slopes as high as 90 degrees. Where Edwards Limestone has been eroded away, the mesa topography of the Lampasas Cut Plain is no longer maintained and uplands are rapidly reduced by erosion. The greatest portion of the Bosque basin lies in the Lampasas Cut Plain.

West of the Lampasas Cut Plain is the Paluxy Cross Timbers, underlain by Paluxy Sandstone. Relief within the Cross Timbers is low and slope angles are gentle. Steepest slopes and highest relief are developed where a protective fossiliferous limestone of the Walnut Clay protects the Paluxy Sandstone. Even under these conditions slope angles are generally less than ten degrees. Elsewhere friable sands develop a rolling, slightly convex topography with indistinct divides.

Within the Bosque basin, the Glen Rose Prairie forms the valley walls and floor in the upper part of the North Bosque River basin where Walnut Prairies form the divides. The Glen Rose Prairie is characteristically a "benched" topography developed upon interlaminated resistant limestones and softer marly clay beds. Relief in the Glen Rose Prairie may be as much as 100 feet with steepest slope angles formed where the thicker limestones crop out.

SOILS

Reconnaissance mapping of soils is adequate to define the relationship of soil types to runoff. Hydrologic properties of the soils are nearly identical to those of the underlying bedrock. Friable sandy soils developed on Paluxy Sandstone have high infiltration capacities. Thick impermeable clay soils develop on clay and shale. Limestones with abundant clay form impermeable clay soils. Where soils are thin, infiltration travels laterally atop unweathered parent material to emerge as runoff.

The major exception is that the soil associations developed on Edwards Limestone, although thin, have high infiltration capacities because of the vugular porosity of the underlying bedrock.

So consistent are these relationships that the hydrologic properties of soils and rocks may be grouped together for the purpose of this study. The hydrologic group properties normally assigned to soils are here assigned to bedrock geology.

VEGETATION

In this study, vegetation is applied to woody plants. Weeds, forbs, and grasses are considered to be reflective of certain land uses, and are treated under that heading. Therefore, vegetated areas are those areas in which the dominant plant cover consists of woody vegetation. These areas are the product of abandoned fields, poor land management, or natural woodlands undisturbed by human activity. These latter are extremely rare.

Analyses of aerial photographs and field observations confirmed the following generalizations:

1. Land suitable for grazing or cultivation is commonly used for those purposes.
2. Other areas unsuitable for grazing or cultivation are normally heavily vegetated with woody plants.
3. Woodland areas normally occupy deeply dissected stream valleys and valley walls; areas of thin soils which preclude farming; and flood-plain areas too small for farm land use.

Species zonation of woody plants within the Bosque basin corresponds to the outcrop patterns of underlying bedrock. The extent and type of woody vegetation is therefore discussed as it relates to the underlying geology. Vegetation belts are designated by number.

Vegetation belt #1 includes flood-plain areas within the basin. Flood plains support a variety of deciduous trees. The most common are pecan, live oak, and elm. As the flood plain narrows the pecan gives way to the live oak and elm, and eventually the live oak dominates.

Vegetation belt #2 is the White Rock Escarpment. On the scarp edge and slope underlain by Austin Chalk, juniper and live oaks are dominant. Junipers thrive on the thinner soils, while live oaks are more common along floors and valley walls of tributaries draining the scarp. Because the scarp face is largely undeveloped it forms the second most extensive vegetation belt in the basin. In the vicinity of Waco, urban development along the scarp has tended to reduce somewhat the woody cover thereby increasing runoff potential from the scarp.

Extensive farming and ranching on the outcrop belts of Del Rio Clay and Georgetown Formations have served to limit woody vegetation cover. Only in narrow valleys of incised tributaries do woodlands exist. Mesquites are most common on the Del Rio Clay, and juniper, live oak, and skunk bush are relatively common on the Georgetown. Because of limited areal extent of this cover it has little hydrologic effect.

Vegetation belt #3 forms on the outcrop of the Edwards Limestone and Comanche Peak Limestone in the Lampasas Cut Plain. The thin soils of the Edwards Limestone support mountain scrub oak and junipers. Texas oak grows on the steep slopes of the Comanche Peak. This woodland is the largest in the basin. In the memory of living man this woodland belt has expanded widely, apparently encouraged by overgrazing.

The Walnut Prairie is extensively farmed and only adjacent to major stream courses are woodlands commonly found. These consist largely of hackberry, mesquite, live oak and elm. In the Paluxy Cross Timbers, woody vegetation has been stripped by farming and ranching practices. In the area where the Glen Rose Limestone crops out, woody vegetation occurs only along stream coarses and consists largely of juniper and Spanish oak.

LAND USE

Land use is the second most critical factor controlling the magnitude of flooding. It is perhaps more significant because it is the only major hydrologic factor which man controls. Even in areas of normally high infiltration capacity, poor land management may cause high runoff.

In the Bosque basin land use correlates closely with bed rock geology because geology controls soil development and soil development controls land use. In an analysis such as the present one, land use may be divided into three major categories: farm land, ranch (or grazing land), and urban areas. Of these three land uses, farm and ranch land are closely related to underlying geology. Urban land is not so subject to this control, and urban land uses are therefore discussed under the heading "Effects of Urban Development."

Farm land is defined as plowed land and is confined almost entirely to outcrop areas of shale formations. Among the shale formations of the study area, only the uppermost and lowermost Eagle Ford Group and the Pepper Shale remain unfarmed, chiefly because of steep slopes along scarp faces. Large areas underlain by the Georgetown Formation are under cultivation throughout the basin. The Paluxy Sandstone in Paluxy Cross Timbers Province is dominantly in farm land.

Land not in woodland or farm land is in grassland or pasture land. This area includes the lower slopes of the Comanche Peak Limestone, much of the outcrop belt of Paluxy Sandstone within the Lampasas Cut Plain, the Glen Rose Prairies, and substantial portions of the Walnut and Georgetown Prairies.

EFFECTS OF URBAN DEVELOPMENT

The effects of urbanization on flooding in the Bosque basin have not been defined, though studies have been completed in Austin, Texas. Similarities in basin hydrologic properties allow some transfer from the Austin investigations to the Bosque basin. When a rural area becomes urbanized, 50 percent of the basin comes under impervious cover. The effect of this is to increase the rate of rise and peak discharge by 100 to 300 percent over that existing before urbanization. Total yield also increases. The net change in hydrologic characteristics in a basin altered from rural to urban land use is an increase in magnitude and frequency of flash foods and an increase in flood stage and duration (Espey *et al.*, 1966, p. 88-89).

Flood frequency increases after urbanization. Flood calculations based on precipitation frequencies (that is, a 25-year storm produces a 25-year flood) are altered by urbanization because the 25-year storm in an urbanized area produces larger floods than were typical prior to urbanization. What might have been a 25-year flood under rural conditions, now has the magnitude of a 50-year, 100-year or even greater flood because of increased runoff (*idem*).

METEOROLOGY

Thunderstorms, tropical cyclones, and tropical waves are the three major types of flood-producing storms which may reasonably be expected within the Bosque basin. Each such storm is capable of producing extensive flooding within the basin.

Thunderstorms may occur any time of the year, but they are most frequent during the period of April through August. Thunderstorms are the most common type of flood-producing storm in the Bosque basin. However, because of short duration and initial high intensity, they commonly produce flash floods of moderate volume and short duration. They do not normally produce floods of such magnitude as to fill the flood storage capacity of Lake Waco and therefore do not represent major flood threats to the City of Waco.

Though tropical cyclones develop over open warm water and decrease in intensity as they move inland, they may deliver floods of greater magnitude than any other atmospheric disturbance. The largest flood and point rainfall amounts for the State of Texas were derived from a dying hurricane which tracked over 160 miles inland. The Bosque basin is not immune from tropical cyclone-derived flood waters because of its distance inland from the Texas Gulf Coast.

Tropical waves represent the greatest potential threat of dangerous flood-producing rains in central Texas. They produce tropical cyclone-like rainfall amounts and are more common than tropical cyclones. However, with the utilization of upper air charts and satellite photographs they can easily be tracked (Orton, 1966, p. 5). Tropical waves are essentially weak troughs of low pressure. Their movement is east to west, and the place of origin for waves affecting central Texas is the southern periphery of the Azores-Bermuda high (*idem,* p. 3).

Tropical waves are not accompanied by major temperature discontinuity or conspicuous surface fronts as are westerly troughs. They are preceded by clear weather, followed by rains in the central part of the trough and to the east of the trough. Troughs tend to move slower than the prevailing winds (*idem*).

Tropical waves strike Texas from June through September with highest incidence in August and September. Their effects are normally confined to the Coastal Plain because on moving inland they are altered by orographic and diurnal factors. Stronger waves, however, do affect inland areas and "waves that reach the Balcones Escarpment are profoundly influenced by this orographic barrier" (*idem*). The result is heavy rainfalls in areas immediately adjacent to the scarp.

THE BALCONES ESCARPMENT AS AN OROGRAPHIC BARRIER

The Balcones Escarpment is a nearly continuous topographic high extending from Dallas to Uvalde, Texas. Both theoretical and observational studies suggest that it exerts major influence on local weather and storm potential in central Texas. The effect is orographic, caused by the lifting of moist air and adiabatic expansion as a result of that lifting.

In theory, weather is a system which can be studied thermodynamically. When an air mass is forced to rise by surface topographic features it is adiabatically cooled. The rate of cooling, called the adiabatic lapse rate, is defined as follows:

$$\text{For dry air: } \gamma_d = -\left(\frac{dT}{dz}\right)_{dry} = \frac{g}{c_p}$$

where: γ_d = lapse rate of dry air, dT = change in temperature, dz = change in altitude or amount of displacement, g = acceleration of gravity, and c_p = specific heat of air at constant pressure.

$$\text{For moist air: } \gamma_s = -\left(\frac{dT}{dz}\right)_{sat} = \gamma_d + \left(\frac{L}{c_p}\right)\left(\frac{dr}{dz}\right)$$

where: γ_s = lapse rate of saturated air, L = latent heat of vaporization, and dr = change in mixing ratio (Pettersen, 1964, p. 3-7).

If the rate of temperature change in the ascending air mass is less than the rate of temperature change in the surrounding air envelope, then the rising air mass is accelerated by buoyancy. The acceleration is expressed as:

$$a = \frac{\gamma - \gamma_d \; g \; \Delta z}{T}$$

where: a = acceleration, γ = lapse rate of nondisplaced air envelope, and T = temperature after lifting and adiabatic cooling (Pettersen, 1964, p. 3-9).

This formula describes the acceleration imparted to a dry air mass through adiabatic lift. If the air mass is saturated, the lapse rate for saturated air is used. The acceleration is imparted by buoyancy. If the lapse rate for the moving mass is greater than the lapse rate in the surrounding envelope, then the moving air mass becomes cooler than its surroundings and the acceleration is negative or downward. This condition imparts stability. If the adiabatic lapse rate is less than the lapse rate for the surrounding air envelope, the displaced air becomes more buoyant and the acceleration is upward. Upward acceleration produces further cooling and condensation with release of latent heat of vaporization. This causes the rising air mass to become yet warmer and it continues to rise. Eventually convective overturning takes place. Meanwhile, from saturated air, condensed moisture falls to earth. The Balcones Escarpment is not a "rain barrier" in the sense of major north-south mountain ranges. However, through the "chimney effect" of the rising air mass it does offer definite potential for the generation of high precipitation rates.

EXAMPLE #1.

A moisture-laden front approaches the escarpment from the northwest. Unless it is considerably colder than the surrounding air it will be accelerated upward. With convection, heavy rainfall begins within the Bosque basin along the South Bosque River, lower

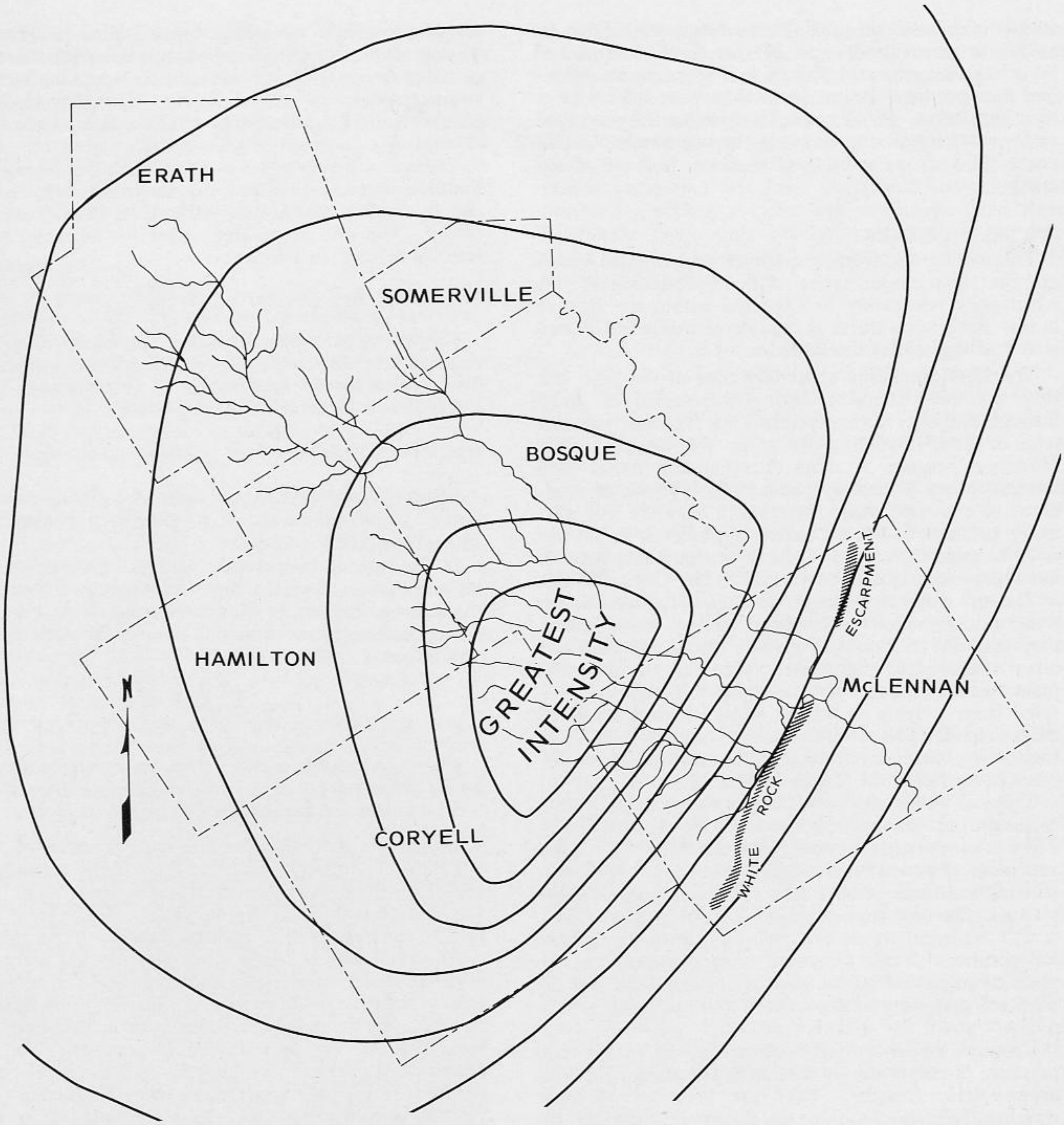


Fig. 3. Storm type No. 1. Isohyet contours are representative of geographic distribution with respect to intensities.

parts of the Middle Bosque River, and Hog Creek basin. Rainfall east of the scarp will be less intense. The isohyetal map would appear as in Figure 3.

EXAMPLE #2.

A tropical cyclone or tropical wave approaches the escarpment from the southeast. As it rises, adiabatic cooling causes condensation. The air mass, unstable even before it encounters the Balcones Escarpment, receives added acceleration due to buoyancy, thereby increasing instability. Intense rains may fall east of the escarpment and the disturbance may tend to stall in the immediate vicinity of the scarp, held in position by the "chimney effect" of the rising air. The isohyetal map might appear as in Figure 4. However, if the winds are from the southeast, the chimney may incline far to the northwest, causing heavy rains far up the Bosque basin.

EXAMPLE #3.

A dry cold front approaches the scarp from the northwest. It is both colder and drier than the sur-

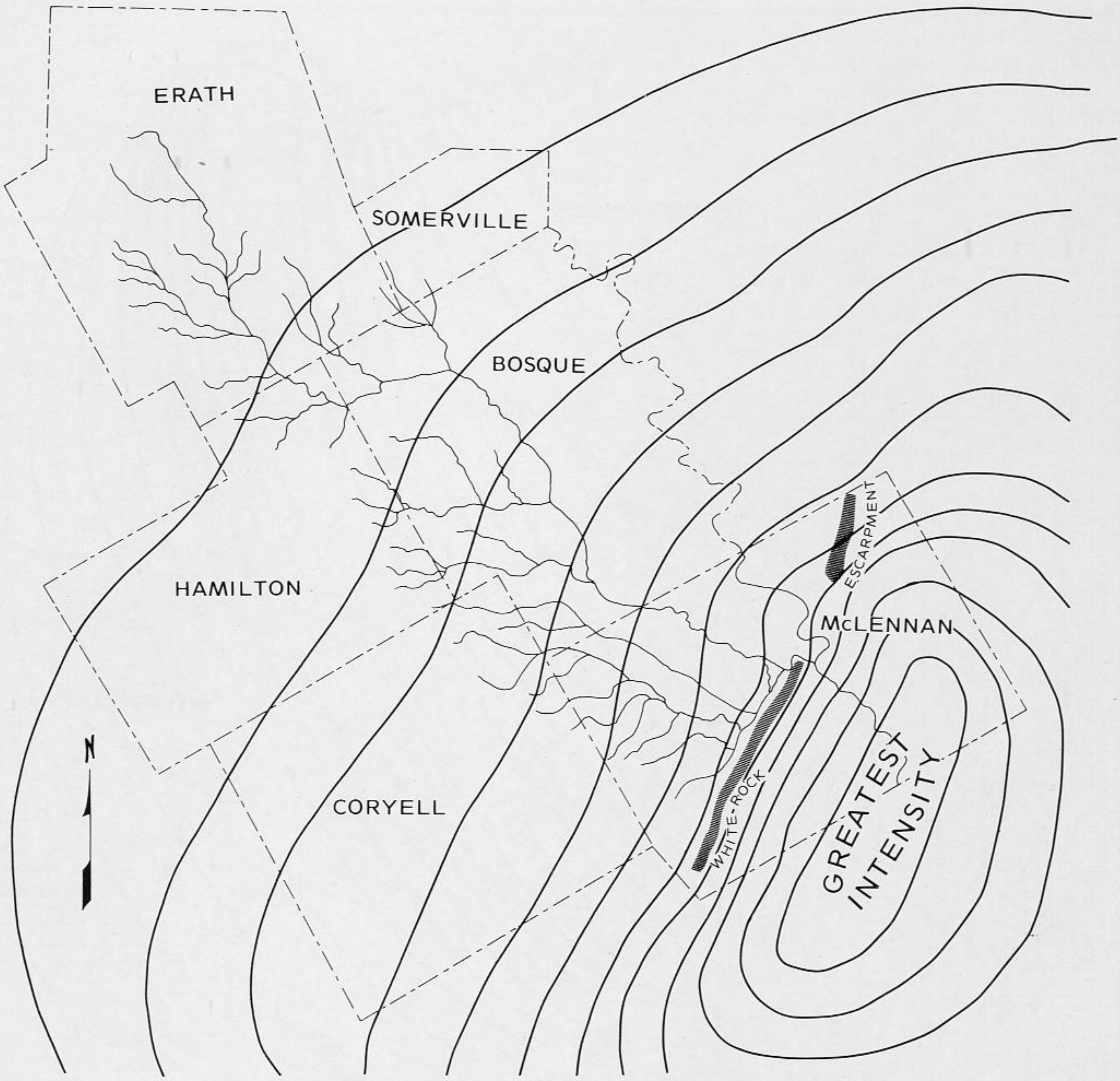


Fig. 4. Storm type No. 2. Isohyet contours are representative of geographic distribution with respect to intensities.

rounding air envelope and therefore the lapse rate is more than for the surrounding air. Hence, it receives a negative acceleration and appears with a steepened front. Warm moist air from the Gulf of Mexico approaching the scarp from the southeast undergoes adiabatic cooling caused by lifting. The effect of the cold air is to increase the apparent height of the escarpment, and rain originates from the rising moist Gulf air as it ascends over the cold front. However, the effect of the escarpment is to oversteepen the cold front producing more intense and localized rains. The rainfall should be most intense just west of the escarpment, and the isohyetal map might appear as in Figure 5.

Observed storms along the Balcones Escarpment in Texas have exhibited these various histories. The storm of September 9-10, 1952, originated from a tropical wave. Intense rains were localized along the Balcones Escarpment as shown in Example #2 (Orton, 1966, p. 15).

Disastrous floods on the Little River in 1921 originated from intense rainfall associated with the breakup of a hurricane and were localized just east of the Balcones Escarpment (Ellsworth, 1923, Pl. I). In this report on the storm Ellsworth stated "the effect of the escarpment on precipitation is not known, but it unquestionably increases it." This too is a situation similar to that pictured in Example #2 (Fig. 6). Heavy rainfall extended also northwestward along the valley of the

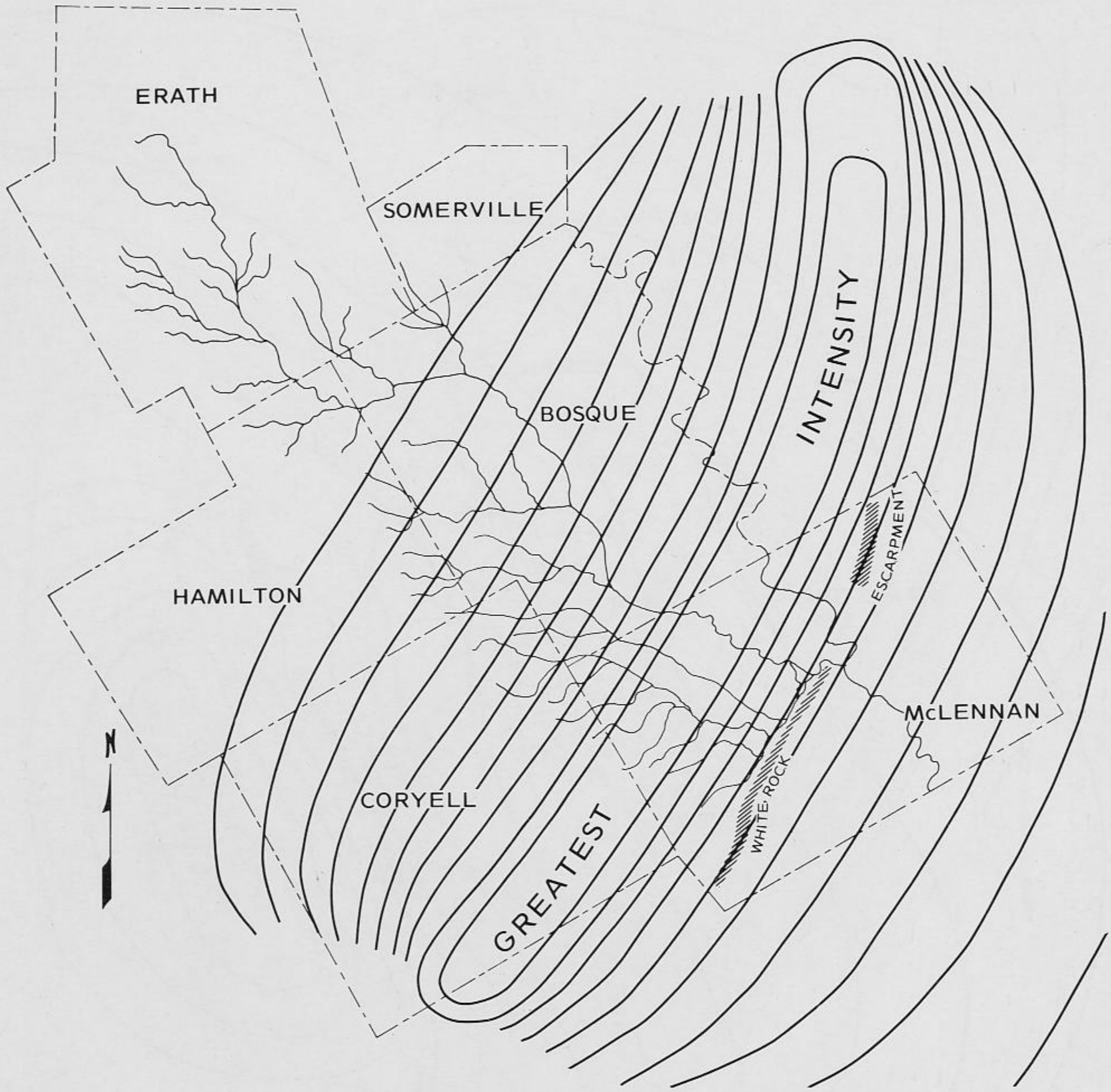


Fig. 5. Storm type No. 3. Isohyet contours are representative of geographic distribution with respect to intensities.

Colorado River where the valley transects the Balcones Escarpment. In the region of the major valley, the rainfall should not be localized against the escarpment and, as the isohyetal map shows, rainfall intensities were not localized in that area. This too suggests the significant orographic effect of the escarpment, because where the escarpment is absent rainfall intensities are less and are randomly distributed.

Records of individual storms during the floods on the Brazos and Bosque Rivers, near Waco, on September 25-28, 1936, show magnitude axes parallel to the escarpment (Figs. 8, 9, 10). This is particularly evident in the two days prior to the major storm on September 27, 1936. During that particular rain, the storm was a convective thunderstorm which approached from the northwest and the rainfall pattern was similar to that shown in Example #1 (Fig. 3).

These case histories are offered as confirmation of the theoretical prediction concerning the effect of the Balcones Escarpment on rainfall intensities and duration in the central Texas area. Further confirmation comes from other historical rains and floods in central Texas.

Fig. 6. Map of central Texas showing drainage basins and total rainfall September 7-11, 1921. *From* Ellsworth, 1923, U.S. Geological Survey Water-Supply Paper 488, Plate I.

HISTORICAL RAINS AND FLOODS, CENTRAL TEXAS

While all areas have experienced rainfalls and floods which are record setting for the specific region, central Texas has been the locus of rainfalls unequaled in magnitude or intensity in the coterminous United States. Floods on Little River, immediately south of Waco, have equaled in flow-rate magnitude the discharges of the Mississippi River at St. Louis, Missouri, during moderate flood. Furthermore, these peak rainfalls and floods have occurred on several occasions in a limited area apparently related to the Balcones Escarpment. In order to predict the flood potential of the Bosque system, it is essential to review these historic floods and to describe them in terms of origin; storm magnitude and intensity; areal extent; flooding magnitude and associated impact; and the probability of occurrence in the Bosque drainage system. Historic floods are listed by storm type, dates of occurrence, and stream system with the greatest degree of flooding.

HURRICANE-DERIVED THUNDERSTORMS: SEPTEMBER 8-10, 1921; LITTLE RIVER, CAMERON, TEXAS

The flood derived from this storm was the most destructive (in terms of lives and property losses) up to that date. Two hundred twenty-four people died and $10,000,000 in property damage occurred as a result of this storm. The primary cause of the storm was a dissipating hurricane which had its origin in the Gulf of Mexico. Storms and flooding centered in Williamson, Bell, and Milam Counties. The storm set several rainfall records at Taylor, Thrall, and Austin (Table 1, Fig. 6) and the rainfall at Thrall was the second greatest 24-hour rainfall ever recorded in the 48 coterminous United States (Ellsworth, 1923, p. 11).

The rain lasted 35 hours beginning at 3:30 a.m. on September 9, and ending at 2:30 p.m. on September 10, with a total of 23.98 inches measured at Taylor. During this period, there were two intervals of intense continuous rain. The first was from 6:45 p.m. to 9:42 p.m. on September 9 and the second was from 3:00 a.m. to 7:28 a.m. on September 10. During the intervening periods, the rainfall intensities slackened, but the rainfall was constantly classified as "moderately heavy" (*idem*). The rains were accompanied by thunder, lightning and tornadoes.

Flooding derived from this storm is summarized on Table 1, which gives the significant data for each basin. Maximum discharge computed for this flood occurred at Cameron on Little River. Peak discharge was 647,000 cfs from a drainage basin of 7,010 square miles, or 92.3 second-feet per square mile. However, of the 7,010 square miles of basin, 2,000+ square miles were essentially non-contributing, and the readjusted discharge was determined as 125 second-feet per square mile. Gage height at Cameron was 49.5 feet and the mean velocity was 5.19 feet per second.

As is shown in Table 2, smaller basins contributed even higher runoff figures. Peak discharge at Little River was 331,000 cfs. These floodwaters were derived largely from the Lampasas River, since the peak discharge on the Leon River was computed as 5,000 cfs (*idem,* p. 14). Discharges from Salado, San Gabriel, and Brushy Creeks augmented the flood to generate the peak wave at Cameron (Table 2). Flood waves from each of the tributaries apparently arrived at Little River in phase with the main trunk flood wave (Table 2, Fig. 6). This is indicated by arrival times of flood peaks on Little River at Belton: 10:30 a.m.; Salado Creek at Salado: 9 a.m.; San Gabriel at Georgetown: 11:00 a.m.; and Brushy Creek at Round Rock: "early morning" (*idem,* p. 19).

There are historic records of two floods of similar magnitude on these same streams in the period of record from 1860 to 1921 observed by early settlers of this region. Although, for these earlier floods there is no record of the storms which produced them, it appears that they were of the tropical cyclone or tropical wave origin and were localized by the orographic effect of the Balcones Escarpment. Only storms having a continually replenished moisture column could produce the magnitude and intensity of precipitation necessary to

TABLE 1. RAINFALL DATA FOR STORM OF SEPTEMBER 9-10, 1921

Site	Date	Duration (time)*	Amount (inches)	Authority
Thrall	Sept. 9-10, 1921	24 h	38.2	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	24 h	23.11	U.S. Wthr. Bur.
Austin	Sept. 9, 1921	24 h	19.03	U.S. Wthr. Bur.
San Antonio (near)	Sept. 9, 1921	24 h	17.0	U.S. Geol. Sur.
Thrall	Sept. 9-10, 1921	12 h	29.8	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	12 h	18.96	U.S. Wthr. Bur.
Thrall	Sept. 9-10, 1921	6 h	19.6	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	6 h	14.16	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	3 h	10.72	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	2 h	7.51	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	1 h	4.25	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	30 m	2.89	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	15 m	2.53	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	10 m	2.00	U.S. Wthr. Bur.
Taylor	Sept. 9, 1921	5 m	1.30	U.S. Wthr. Bur.

*h—hour; m—minute

After Spencer, Jean M. (1966) Urban geology of greater Waco. Part III: Water—Surface waters of Waco: Baylor Geological Studies Bull. 10. p. 11. *From* Ruggles, Frederick H., Jr. (1966) Floods on small streams in Texas: U.S. Geological Survey—Water Resources Division, Open Fill Report No. 89, p. 5.

TABLE 2. MAXIMUM DISCHARGE OF LITTLE RIVER AND ITS CHIEF TRIBUTARIES DURING FLOOD OF SEPTEMBER 9-10, 1921

Stream	Location	Drainage area sq mi	Maximum discharge Total cfs	Maximum discharge Per sq mile cfs	Mean velocity per sec	Width at peak stage feet
Little River	Near junction of Leon and Lampasas Rivers	5,300	331,000	62.5	7.32	3,050
Little River	Near Cameron	7,010	647,000	92.3	5.19	6,168
Salado Creek	Near Salado	148	143,000	966	8.62	1,491
San Gabriel River	Near Georgetown	431	160,000	371	7.29	2,000
Brushy Creek	Near Round Rock	74.7	34,500	462	10.92	460

From Ellsworth, C. E. (1923) The floods in central Texas in September, 1921: U.S. Geol. Survey Water-Supply Paper 488, p. 19-28.

produce floods of such magnitude. Localization of such storms and repetition of storms of similar magnitude in the same area appear to require a fixed topographic control, such as the Balcones Escarpment.

The mathematical probability of a Thrall-type storm occurring in the Bosque basin cannot be established. However, there appears to be little reason to believe that it could not occur there. Procedures exist for theoretical transposition of maximum storms into other basins (Myers, 1966, p. 49-51). Two conditions appear essential for the generation of maximum storms in a given area. The first is a modified polar front which stalls the tropical cyclone from further inland movement. Such occurrences are generally limited to a 150-mile-wide belt paralleling the cost from Corpus Christi, Texas, northward along the Gulf Coast (*idem,* p. 50). The Bosque basin appears to be too far inland to be subject to this type of tropical cyclone localization.

The second triggering mechanism is orographic and any significant topographic imminence which extends across the path of a tropical cyclone might effectively act as the triggering mechanism. On June 28, 1954, a peak discharge of 948,000 cfs was measured on the Pecos River at Comstock, Texas. The cause of this flood was rainfall derived from Hurricane Alice over the lower Pecos River basin. The storm was localized by orographic effects (*idem,* p. 47).

Thus it appears probable that all or part of the Bosque basin might be subject to flooding caused by a tropical cyclone-generated storm localized by the Bosque Escarpment. The resulting discharges could be in excess of anything previously known. For example, if discharge per square mile in the Bosque basin were equal to that of Little River at Cameron, the flood discharge into Lake Waco would be 153,000 cfs or 57,000 cfs greater than any known previous discharge at that point in the Bosque system. The lower half of the basin would likely receive even more torrential rains because of its proximity to the scarp and hence the discharge per square mile of basin area would approach that recorded for San Gabriel River, Brushy Creek, or even Salado Creek during the 1921 Thrall storm. Thus, an area of 825 square miles could produce a discharge of 304,000 cfs, 382,000 cfs, or 796,000 cfs from a storm at the intensity and duration of the Thrall storm. Though the Balcones Escarpment at Waco, Texas, is distant from the coast, it is not so distant as is the Pecos.

TROPICAL WAVE, SEPTEMBER 8-10, 1952, COLORADO RIVER, LAKE TRAVIS-MANSFIELD DAM

Flooding from this storm was confined to the basins of the Pedernales, San Saba, and Llano Rivers. Property losses of "several million dollars," 454 homes damaged, 17 homes destroyed, five persons killed and three injured record only the physical damage of the storm (Orton, 1966, p. 14-15). The floods occurred in rural areas, and Mansfield Dam held most of the floodwaters which prevented serious flooding on the Colorado River in Austin, Texas (*idem*). Had it not been for the flood-control pool of Mansfield Dam the destruction of life and property would probably have been in excess of that for the Thrall-Taylor storm.

The largest flood on the Colorado River at Austin occurred in 1869, when peak discharge was approximately 550,000 cfs at a stage of 43 feet. The most destructive flood occurred in June, 1935, with a peak discharge of 481,000 cfs at a stage of 41.2 feet. During that flood property damage totaled $13,000,000. Had the September 9-10, 1952, floodwaters not been held in check by Lake Travis, at peak flood height the discharge at Austin would have been 750,000 cfs at a stage of 47 feet.

The cause of this storm was a tropical wave which

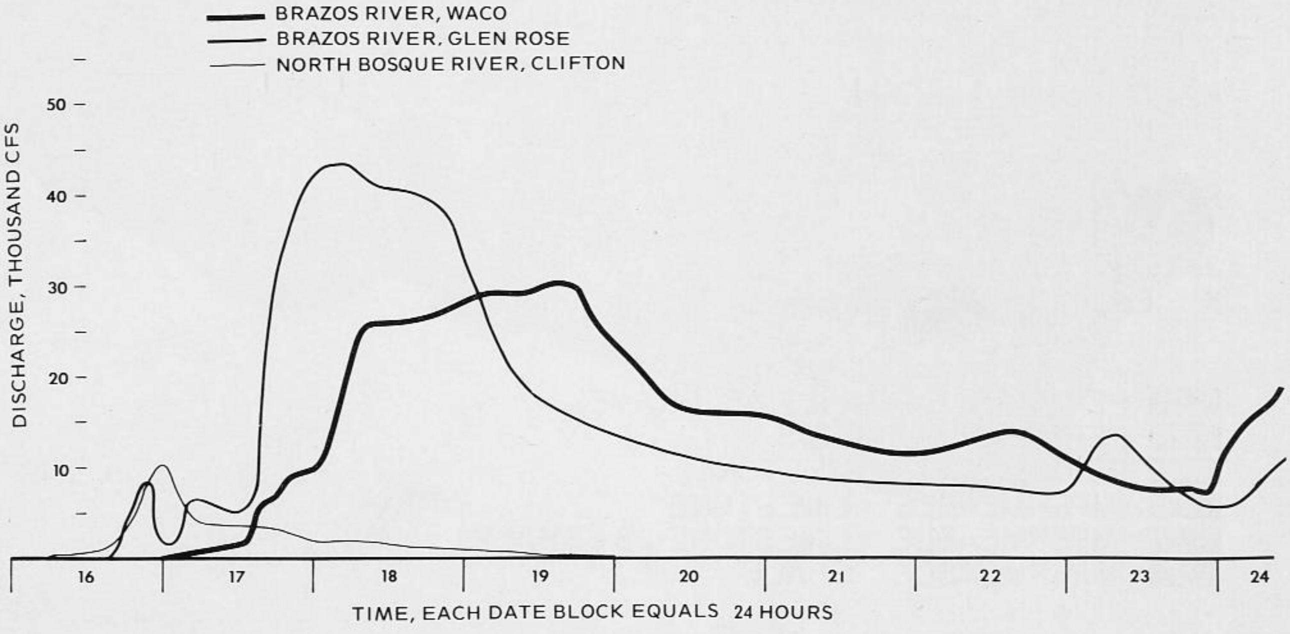


Fig. 7. Hydrographs, central Texas gaging stations, September 16-24, 1936.

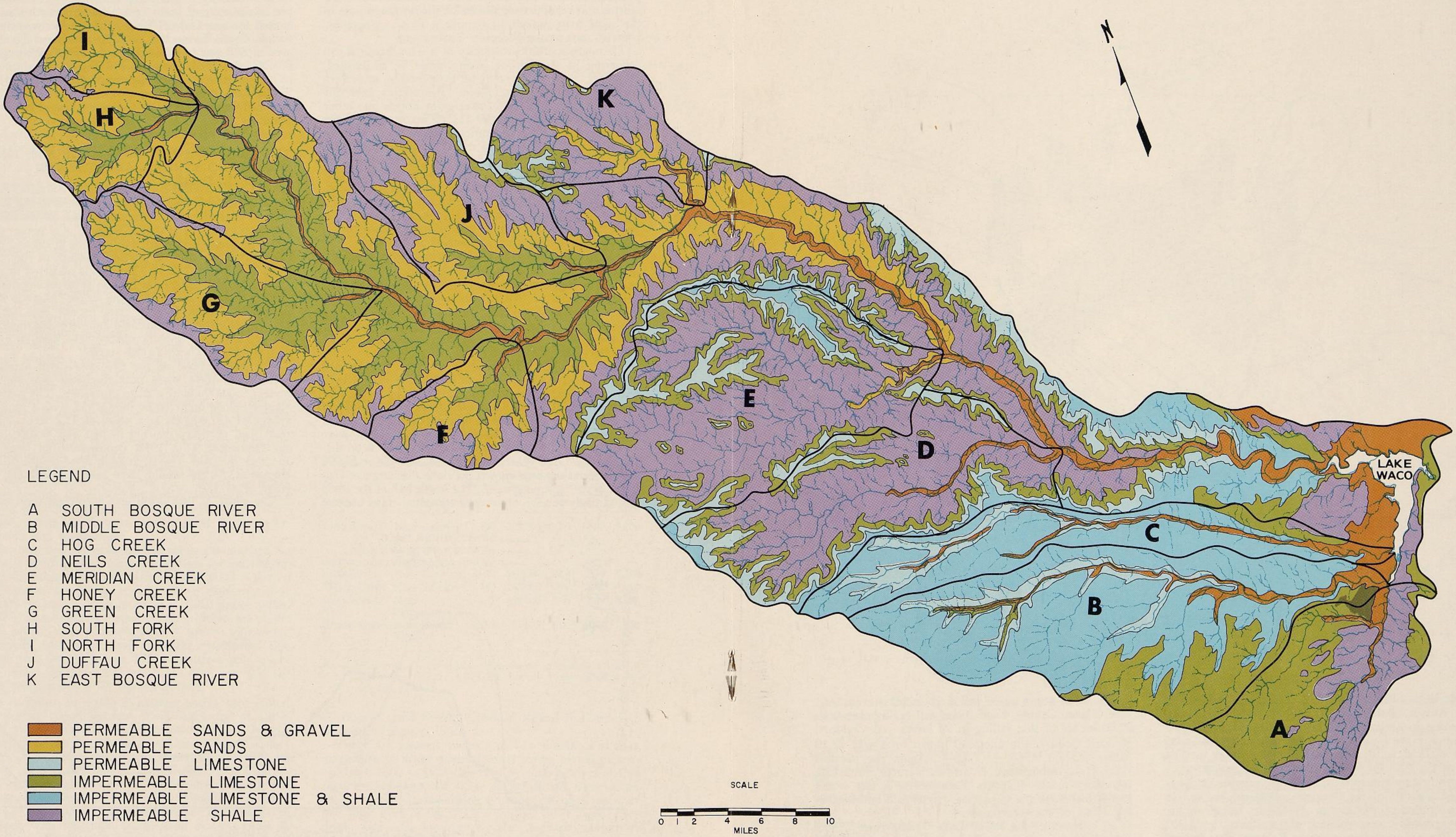


Fig. 2. Litho-hydrologic units, Bosque basin.

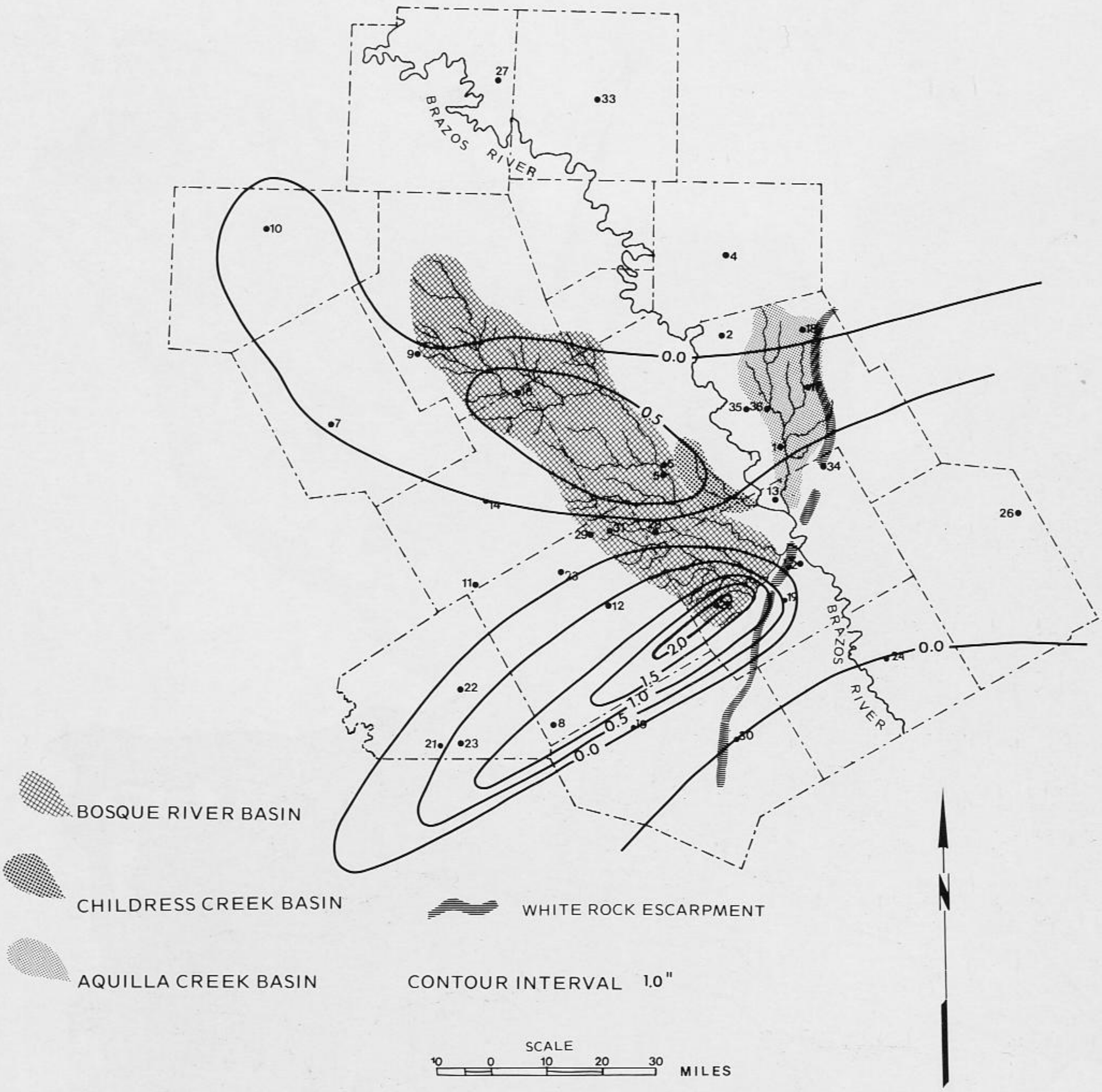


Fig. 8. 24-hour isohyetal map, September 25, 1936.

migrated inland from the Gulf of Mexico and arrived near Austin on the 9th of September. Heavy rains preceding its arrival began on the 8th with initial precipitation in the Guadalupe, Colorado, and Cibolo basins (Orton, 1966, p. 12). Rains continued through the 9th, and on the 10th the heaviest precipitation originated.

Upper air soundings at San Antonio provided a documented analysis of the physical processes involved in the generation of this storm. When the trough of the wave arrived it was convectively unstable to 15,000 feet. Upward movement over the Balcones Escarpment caused saturation of the air column. There followed widespread rain of 10 to 12 inches with recorded total depths of as much as 26 inches in isolated areas. At Hye, Blanco County, 23.35 inches fell in 48 hours with 20.40 inches of that falling in 24 hours. At Comfort, Kendall County, the unofficial storm total was 25.10 inches (Orton, 1966, p. 12-14). Again the greatest rainfall magnitudes and intensities were in immediate proximity to the Balcones Escarpment, a fact which tends to confirm the triggering mechanism and localizing effect of the escarpment.

As a result of the floods Lake Travis rose 57 feet behind Mansfield Dam. This one storm contributed 713,130 acre-feet of floodwaters to the lake (*idem*). It represented the largest and potentially most destructive

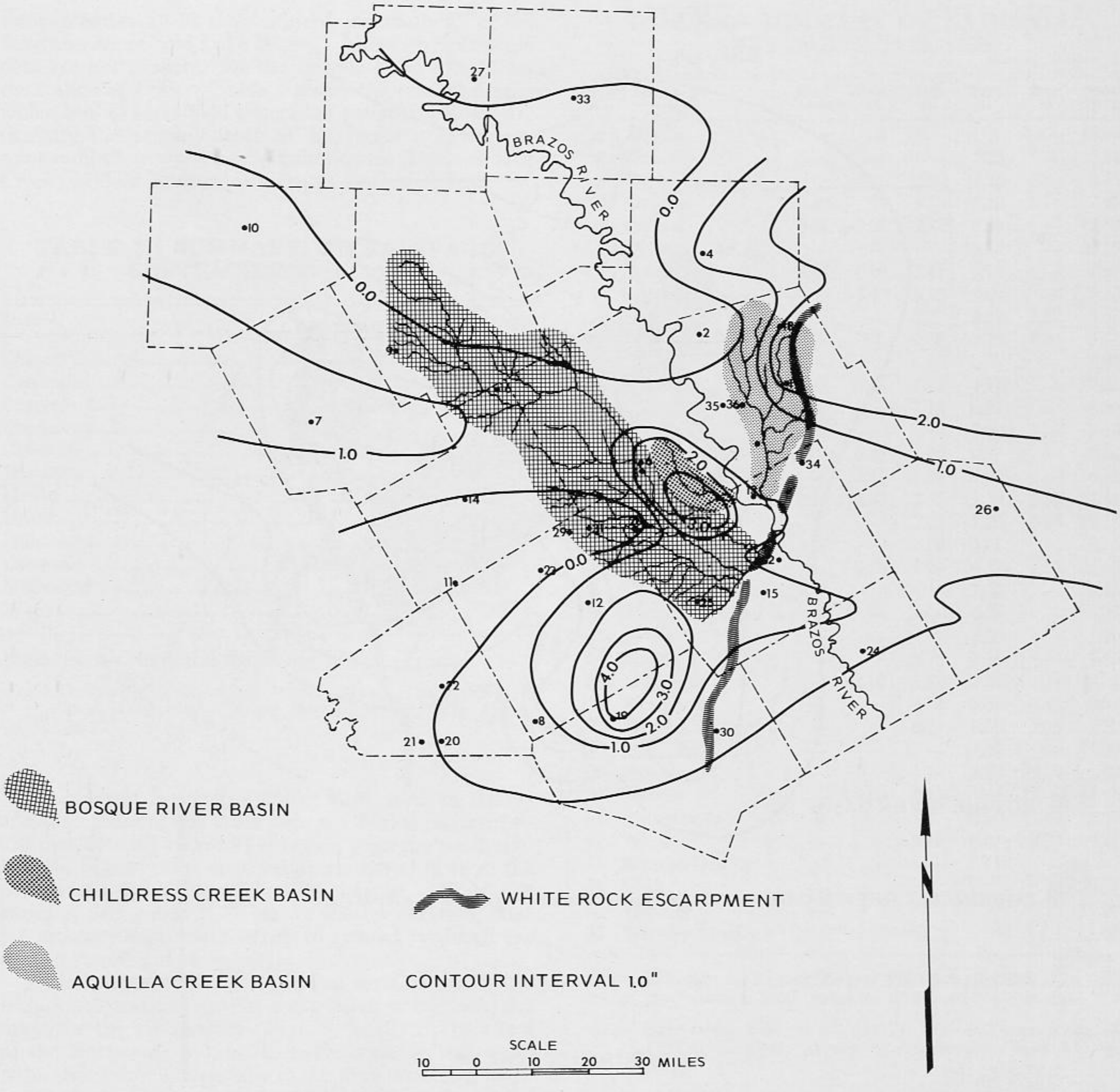


Fig. 9. 24-hour isohyetal map, September 26, 1936.

flood of the Colorado River since the first European settlement of this region.

Similar storms are possible within the Bosque River basin. If such a storm occurred in that basin the flood waters could exceed the flood storage capacity of Lake Waco, and flooding would occur within the Bosque basin and the Brazos River. Since the conservation pool capacity of Lake Waco is 190,000 acre-feet and the maximum design water surface storage capacity is 828,300 acre-feet, the amount of excess flood waters from a flood of the above magnitude would discharge 74,830 acre-feet into the Brazos River.

THUNDERSTORM, SEPTEMBER 25-28, 1936, BRAZOS RIVER, WACO, TEXAS

On September 27, 1936, the largest recorded flood on the Brazos River occurred at Waco, Texas. These flood waters were derived from thunderstorms. Although total rainfall depths were high, they were not excessive. The major cause of flooding in the City of Waco was discharge of previously stored flood waters from a "flood control" structure coincidental with the arrival of flood waters from Childress and Aquilla Creeks immediately upstream.

The flood waters of September 27, 1936, resulted from two separate storms each of which produced ex-

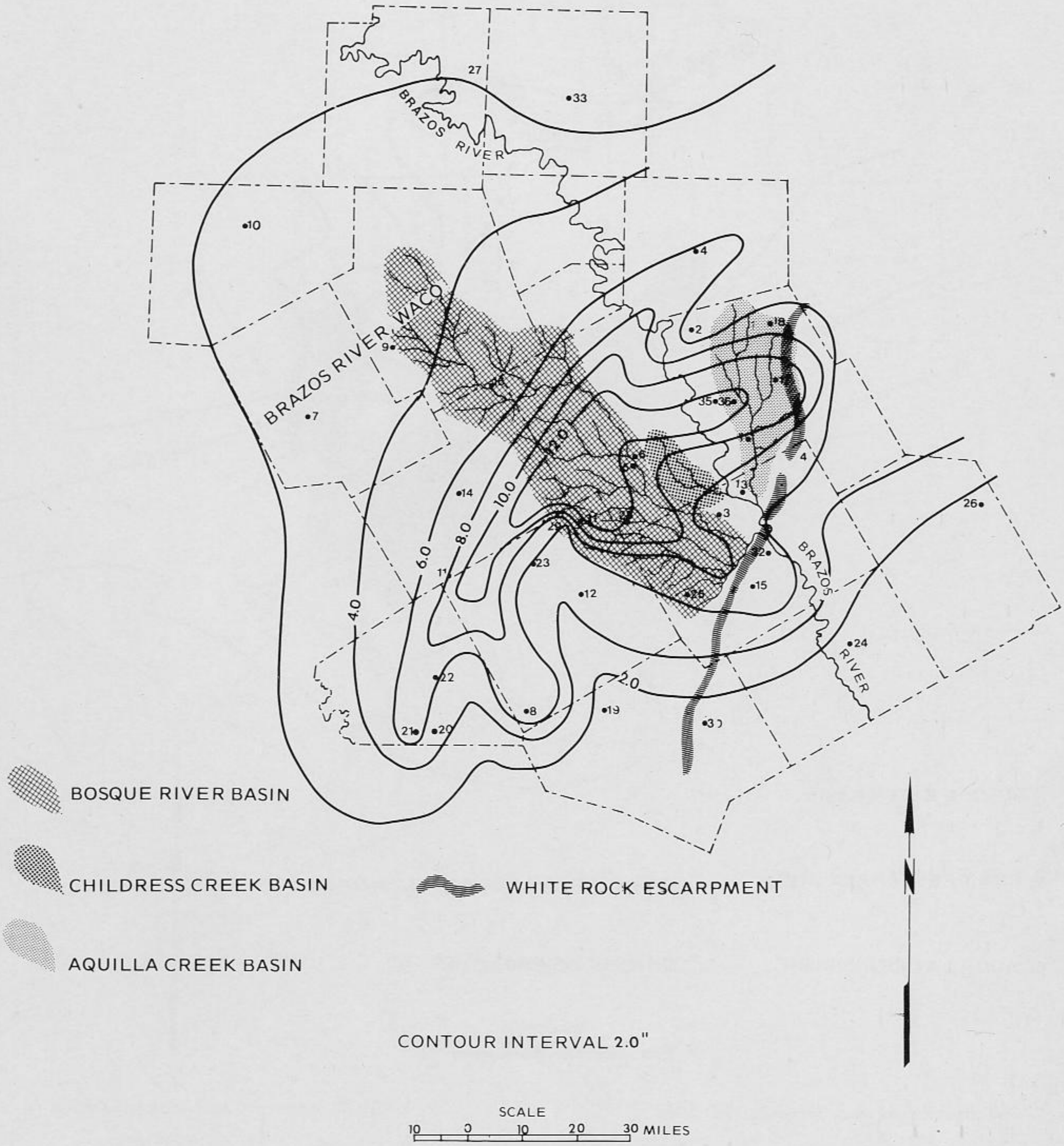


Fig. 10. 24-hour isohyetal map, September 27, 1936. Note time relationships of peak discharges.

cessive runoff. The first rains occurred on September 13-18, as the result of warm moisture-laden air moving in from a stationary low in the Gulf of Mexico and rising over cold dense air of a cold front moving eastward from eastern New Mexico across northern Texas (Dalrymple, *et al.*, 1937, p. 66-67). Though rains were intense they produced little flooding because previous months were dry and thus initial infiltration was high (*idem*, p. 63, 69). Runoff did take place, as is indicated by the hydrographs of the Brazos River at Glen Rose, the Bosque River at Clifton, and the Brazos River at Waco, indicating that ground saturation had been achieved (Fig. 7). Rainfall data for the area of the Bosque basin is shown in Table 3. This precipitation was a critical factor in flood generation at Waco for two reasons. First, antecedent moisture prior to the flood-producing rains of September 25-28 was high, maximizing runoff. Second, flood waters derived from the September 13-18 rains utilized essentially all of the flood storage of "old Lake Waco." Although hydrologic data are not available for the Bosque basin other than the station at Clifton, Table 3 shows the rainfall depths which lead to high flood generation potential. Note particularly the rainfall depth at McGregor which gives some indication of the precipitation on the basins of Hog Creek, Middle Bosque, and South Bosque Rivers.

TABLE 3. SUMMARY OF RAINFALL, SEPTEMBER 13-18, 1936

Station	Total Depth
Clifton*	4.47
Comanche	7.88
Copperas Cove	4.50
Dublin*	7.41
Gatesville	3.66
Hamilton	5.30
Hewitt	0.99
Hico*	1.85
Hillsboro	1.34
Lampasas	8.07
McGregor*	4.93
Waco	1.02

*Indicates stations within the Bosque basin.

From Dalrymple, Tate, *et al.* (1937) Major Texas floods of 1936, U.S. Geol. Survey Water-Supply Paper 816, p. 26-27.

The rains of September 25-28, 1936, were of similar origin to those of the week before. Warm moist tropical maritime air entered the region from the southeast. A front of cold polar continental air moved in from the northwest across the Texas Panhandle. While the storm of September 25-28 was of shorter duration, rainfall of heavy depth over saturated ground produced excessive runoff (*idem,* p. 68).

Table 4 summarizes precipitation for this storm and includes all stations used in compilation of the isohyetal maps for the 1936 storm (Figs. 8, 9, 10). The effect of the Bosque or White Rock Escarpment was again to localize rainfall, especially in the days preceding maximum storm development. Rainfall totals for the period of September 25-28 do not approach the magnitudes of storms which have previously been described. This shows the effect of high antecedent moisture as a principle flood-producing factor for this storm. It also indicates that record storms are not required to produce record flooding. This is particularly true when a major cause of flooding is release of water from flood-control structures.

Analyses of hydrographs (Fig. 11) show several significant factors. First, the nearly simultaneous flood peaks at Glen Rose and Waco indicate that the flood peak at Waco had its origins from tributary basins substantially south of Glen Rose. The contribution of the flood wave at Glen Rose was merely to prolong the recession side of the curve. Travel time of a flood peak from Glen Rose to Waco is approximately 20 hours (Figs. 7, 11).

TABLE 4. SUMMARY OF RAINFALL, SEPTEMBER 19-28, 1936

Sta. No.	Station	Sept. 19-24*	Sept. 25	Sept. 26	Sept. 27	Sept. 28	Sept. 25-28
1	Aquilla	—	—			—	10.00
2	Blum	—	—	—	5.75	—	5.75
3	China Springs	—	—	3.00	6.75	—	9.75
4	Cleburne	0.30	—	1.10	6.16	—	7.26
5	Clifton	0.03	0.60	2.72	9.31	—	12.63
6	Clifton (1 mi. n.)	—	—	—	10.10	—	10.10
7	Comanche	0.04	0.10	1.45	3.14	—	4.69
8	Copperas Cove	—	1.45	0.45	6.60	—	8.50
9	Dublin	0.07	—	0.27	3.30	1.00	4.57
10	Eastland	0.34	T	0.38	2.75	0.44	3.57
11	Evant	—					6.00
12	Gatesville	0.33	0.58	1.71	4.77	—	7.06
13	Gholson	—	—	1.10	6.90	—	8.00
14	Hamilton	—	—	—	7.00	—	7.00
15	Hewitt	—	0.25	1.02	6.77	—	8.04
16	Hico	—	0.62	0.84	4.92	—	6.38
17	Hillsboro	0.10	0.30	2.35	11.30	1.50	15.45
18	Itasca	—	—	2.03	7.20	0.90	10.13
19	Killeen	—	—	4.00	1.75	—	5.75
20	Lampasas	—	0.78	0.04	4.33	1.50	6.65
21	Lampasas (4 mi. w.)	—	—	—	7.50	—	7.50
22	Lampasas (10 mi. n.)	—	—	—	6.25	—	6.25
23	Levita	—	—	—	5.60	—	5.60
24	Marlin	—	T	0.25	1.38	—	1.63
25	McGregor	—	2.10	1.52	6.20	—	9.82
26	Mexia	—	—	0.74	0.85	0.43	2.02
27	Mineral Wells	—	—	0.37	2.00	1.35	3.72
28	Mosheim	—	—	—	11.00	—	11.00
29	Pancake	—	—	—	6.00	—	6.00
30	Temple	—	0.03	0.53	1.63	1.96	4.15
31	Turnersville	—			12.00	—	12.00
32	Waco	—	—	0.97	6.03	2.25	9.25
33	Weatherford	7.65	—	—	—	—	—
34	West	—					9.00
35	Whitney	—					11.00
36	Whitney (4 mi. e.)	—					11.00

* "—" indicates zero precipitation, "T" indicates less than 0.01 inches precipitation, blank indicates no record for that date.

After Dalrymple, Tate, *et al.* (1937) Major Texas floods of 1936, U.S. Geol. Survey Water-Supply Paper 816, p. 26-33.

Record flooding at Waco resulted from discharges of Aquilla and Childress Creeks and from the Bosque system by way of the spillway of old Lake Waco. Flood waves from these streams arrived simultaneously immediately north of Waco. The cause of this simultaneity is both natural and man-made. Figure 10 is an isohyetal map of the storm of September 27. Heavy rainfall over Aquilla, Childress, and lower Bosque basins produced heavy runoff. As a result, flood waters were released from Lake Waco to accommodate flood waters approaching from the second storm. This sudden discharge from Lake Waco entered the Brazos River at the same time as the flood discharges from Aquilla and Childress Creeks were arriving (Fig. 11). The flood hydrograph of the Brazos River at Waco and the discharge hydrograph of Lake Waco Dam give

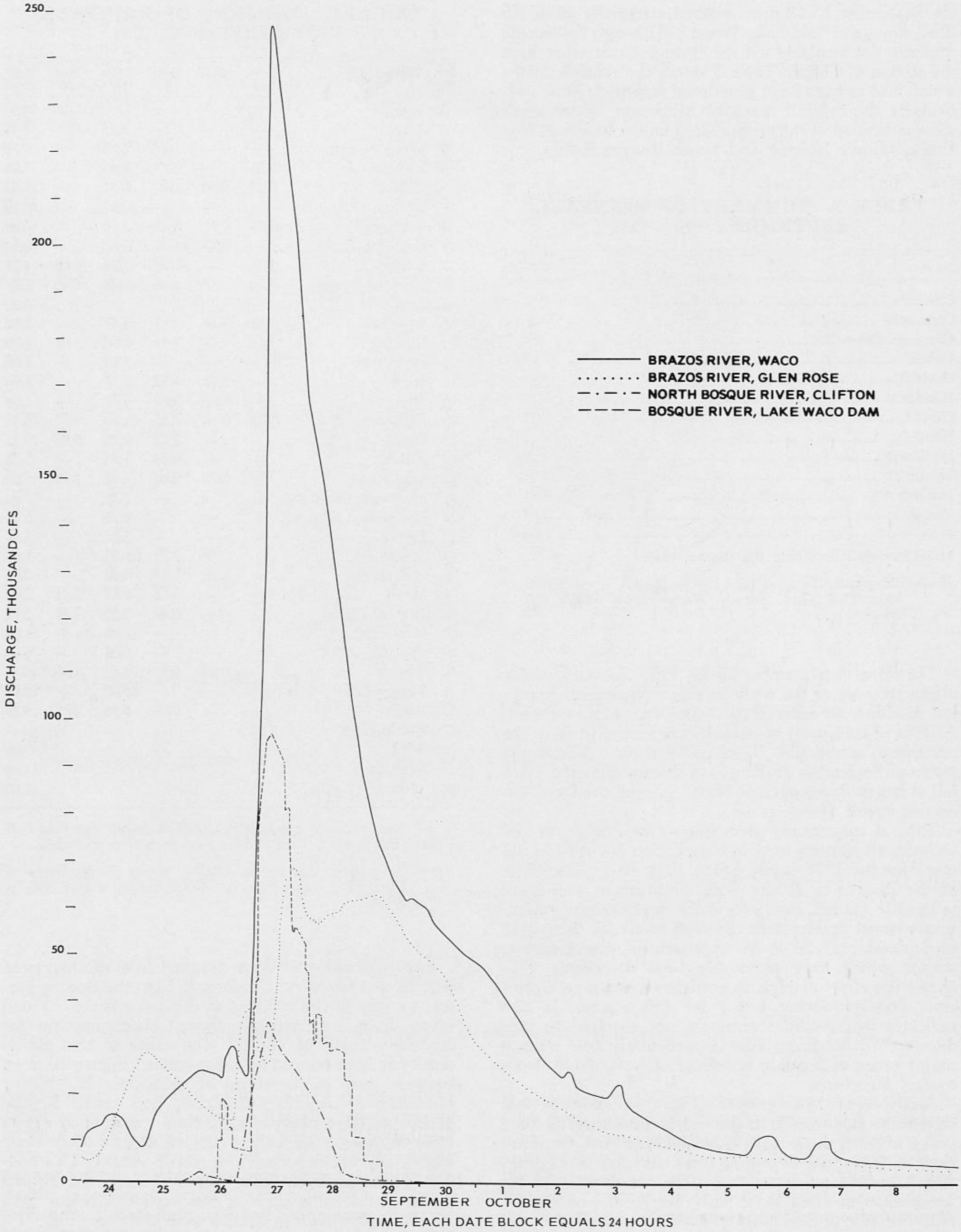


Fig. 11. Hydrographs, central Texas gaging stations, September 24 to October 9, 1936.

strong evidence that both the discharge and stage of the flood at Waco were in large part the result of a human decision.

While human error can be blamed as the cause of this flood, the ultimate cause is the philosophy underlying existing methods of flood control. The release of flood waters from Lake Waco was merely the follow-through of such a philosophy. The idea that floods are sufficiently predictable so that flood waters can be safely stored and discharged is often proven fallacious, as was evidenced in 1936. Maximum flooding is generated with less than record rains when antecedent moisture is high, therefore the time of highest susceptibility to massive and destructive flooding will be immediately after initial impoundment of flood waters. Thus the period of minimum flood protection from a flood-control structure occurs at the same time when maximum flood potential exists. This was the case in September 1936, and conditions today are not radically different despite the flood-control potential of Lake Whitney on the Brazos and new Lake Waco on the Bosque.

The likelihood of recurrence of such a flood is dependent upon the probability of the causes of the flood. Meteorological conditions which produced the flood precipitation are relatively common in central Texas, and are, in fact, the primary rain producers for this area. Because of the nature of rainfall records, storms of this magnitude are of uncertain probability. However abnormal monthly rainfall $\geqq$ 10.00 inches would have a four percent probability of occurrence in any one year (Griffith and Orton, 1968, p. 160). Frequently such abnormal rainfall is the result of the impact of a severe storm on a more normal rainfall period. Therefore if storm probability and excessive rainfall probability are approximately equal, then it was a 25-year storm which produced the "100-year flood," and this fact emphasizes the importance of antecedent moisture as a major factor in peak flooding.

Currently there are two flood-control structures above Waco: Lake Waco on the Bosque River and Lake Whitney on the Brazos River. Lake Waco was completed on June 24, 1965. Original conservation storage capacity was 152,500 acre-feet with an additional storage capacity of 573,900 acre-feet for flood storage (Dowell and Petty, 1973, p. 12/19.0/A-E). However since completion, the conservation pool freeboard has been raised ten feet, thus lowering flood storage capacity to 536,400 acre-feet, a net reduction of 6.5%.

The "controlled" discharge from "old Lake Waco" in 1936 was 210,000 acre-feet, as measured from the discharge hydrograph. Present Lake Waco has a flood storage capacity capable of retaining the amount of water discharged from the old lake in the 1936 flood. However, discharge potential for the new lake is greater than that of old Lake Waco, emphasizing the possibility of even greater floods derived from release of flood storage in the present Lake Waco.

Lake Whitney was completed on April 18, 1951. Conservation storage capacity is 627,100 acre-feet with an additional potential for storage of 1,372,400 acre-feet of flood waters (*idem*, p. 12/18.0/A). Figure 11 shows that the storage capacity of Lake Whitney would have had little effect on the floods at Waco, since the main flood wave was generated downstream from Lake Whitney. Flood water retention by Lake Whitney could have altered the recession side of the hydrograph. Poorly planned release of flood waters from Lake Whitney combined with release of flood waters from Lake Waco could generate a flood of greater magnitude than any ever recorded on the Brazos River before this time.

Currently, a storage and flood control dam is being constructed on Aquilla Creek. This structure could reduce the height of floods like that of 1936. However, it too increases the potential for a "flood control" generated flood.

CURRENT FLOOD MODEL DATA FOR CENTRAL TEXAS

During progress of this study initial investigations revealed a minimum of data, procedures and models directly applicable to flood potentials in the Bosque basin. However, existing models developed elsewhere can be modified to apply to the local area, and therefore are presented to serve as standards for the flood potential model which is offered.

INTERMEDIATE REGIONAL AND STANDARD PROJECT FLOODS

The U. S. Army Corps of Engineers in preparation for *Flood Plain Information, Brazos and Bosque Rivers, Waco, Texas* (1970, p. 30) computed Intermediate Regional Flood (IMF) and Standard Project Flood (SPF) for both Bosque and Brazos Rivers at Waco.

The results of that study are summarized in Table 5. These values resulted from application of two different procedures. The IMF, or one percent flood, is based on a flood record of 123 years for the Brazos and a 90-year record for the Bosque (*idem,* p. 27-28). The results are somewhat questionable because of an inadequate statistical data base and because at least one flood was not a natural flood. Statistical validity of flood prediction is generally considered to require a data base of ten independent samples, each with a length of the desired prediction period (Wisler and Brater, 1959, p. 333). Thus, 1000 years of records would be required to establish a statistically valid 100-year flood. The only reasonably accurate prediction for the Brazos and Bosque Rivers is one for the 12.3-year recurrence interval for the Brazos and nine-year recurrence interval for the Bosque system. Valid prediction of an intermediate regional flood on the basis of currently available data is inadequate and likely to result in significant errors (*idem*). More importantly, the 1936 maximum flood of the Brazos at Waco was not the result of maximum storm, but apparently the result of human error, and it is hence not a valid data point.

The Standard Project Flood is a model computed by the Corps of Engineers and the ESSA Weather Bureau (Corps of Engineers, 1970, p. 29). "The SPF is defined as the largest flood that can be expected from the most severe combination of meteorological and hydrological conditions that are considered reasonably characteristic of the geographic region involved" (*idem*). Storm estimates for the Bosque drainage area compiled by the Corps of Engineers are summarized in Table 5. The SPF is a product of the Standard Project Storm (SPS) and is 40 to 60 percent of the Maximum Probable Flood (MPF). The MPF is a product of the Maximum Probable Precipitation (MPP) (Dalrymple, 1964, p. 25.26-25.31). Since the 31-inch estimate of MPP for this area has been exceeded at least once during the Thrall-Taylor storm of 1921, the magnitude of the MPF would appear reasonable for disaster planning. However, such flood magnitudes are not used in flood calculations in the central Texas area.

THE MAXIMUM PROBABLE FLOOD

Spillways of Lake Waco and Lake Whitney were apparently designed to pass the maximum probable flood (MPF). Table 6 shows the values for the MPF and SPF for selected rivers in the central Texas area.

Table 7 gives discharge per unit area for the SPF and MPF of each basin. When compared with Table 2, it is apparent that such discharges have been exceeded on various occasions and in various basins. This indicates that floods of MPF magnitude have occurred at least three times in the central Texas region. The lack of such occurrence in any given basin does not mean that such floods will not occur there. Spillway design anticipates such floods and is undertaken to protect the dam. In the event of maximum possible floods entering a lake whose flood storage capacity was already utilized, the effect is as though there were no flood control structure. Among the major weaknesses of flood control lakes is their inability to control truly major floods, while at the same time they encourage a false sense of security in those who live below such structures.

FLOOD MODELS AND FLOOD PREDICTION IN THE BOSQUE BASIN

Several different procedures are currently in use for flood modeling and flood prediction. Each method has limitations particularly in application to the Bosque basin. However, various methods offer useful approaches to the current study. Several methods used in the current investigation are summarized below.

RATIONAL FORMULA

The rational formula is defined as:

$$Q = CIA$$

where: Q = peak discharge, cfs; C = runoff coefficient; I = rainfall intensity, in/hr; and A = drainage area, acres.

This equation is empirical and is based on the following assumptions:

1. The rate of runoff resulting from any rainfall intensity is a maximum when this rainfall intensity lasts as long or longer than the time of concentration.

2. The maximum runoff resulting from a rainfall intensity, with a duration equal to or greater than the time of concentration, is a simple fraction of such rainfall intensity; that is, it assumes a straight line relation between Q and I, and Q = O when I = O.

3. The frequency of peak discharges is the same as that of the rainfall intensity for the given time of concentration.

4. The relationship between peak discharges and size of drainage area is the same as the relationship between duration and intensity of rainfall.

5. The coefficient of runoff is the same for storms of various frequencies.

6. The coefficient of runoff is the same for all storms on a given watershed (Krimgold, 1946, p. 214-226).

TABLE 5. FLOOD CHARACTERISTICS OF THE BRAZOS AND BOSQUE RIVERS

CHARACTERISTIC	MAGNITUDE OF OCCURRENCE	
	Standard Project Flood	Intermediate Regional Flood
Maximum Conditions, Brazos River		
Peak discharge, cfs	457,700	95,000
Height of rise, feet	52	31.8
Rate of rise, feet per hour	1.2	1.8
Duration of flooding, hours	230	16
Main channel velocity, feet per second	19	11
Overbank velocity, feet per second	6	5
Maximum Conditions, Bosque River		
Peak discharge, cfs	325,000	50,000
Height of rise, feet	52	Controlled
Rate of rise, feet per hour	3.5	Controlled
Duration of flooding, hours	70	Controlled
Main channel velocity, feet per second	12	9
Overbank velocity, feet per second	4	2

After Corps of Engineers (1970) Flood plain information, Brazos and Bosque Rivers, Waco, Texas: Fort Worth District, Corps of Engineers, p. 30.

TABLE 6. ESTIMATED VALUES OF MAXIMUM PROBABLE FLOOD (MPF)

Lake	River	Maximum Spillway* Discharge Capacity cfs	MPF** cfs	SPF***	SPF/MPF Ratio
Whitney	Brazos	700,000	700,000	457,700	0.6539
Waco	Bosque	563,300	563,300	325,000	0.5770
Proctor	Leon	452,500	452,500	278,513	0.6155
Belton	Leon	650,000	650,000	400,075	0.6155
Stillhouse Hollow	Lampasas	686,000	686,000	422,233	0.6155

* Spillway discharge information from: Dowell and Petty, 1973, p. 12/18.0/D, 12/19.0/D, 12/23.0/D, 12/24.0/C, and 12/25.0/D.

** Maximum Probable Flood discharge was assumed to be that of the maximum discharge capacity for each reservoir.

*** The SPF discharges for the Brazos and Bosque are those computed for Waco (see Table 5). The remainder were computed by multiplying the average SPF/MPF ratio of the Brazos and Bosque times the MPF of the other rivers.

TABLE 7. DISCHARGE PER UNIT OF DRAINAGE AREA, STANDARD PROJECT AND MAXIMUM PROBABLE FLOODS

Station	Drainage Area (contributing) sq mi	SPF cfs	SPF cfs per sq mi	MPF cfs	MPF cfs per sq mi
Whitney Dam	8,706	477,700*	55	700,000	80
Waco Dam	1,670	325,000	195	563,300	337
Proctor Dam	1,265	278,513	220	452,500	358
Belton Dam	3,560	400,075	112	650,000	183
Stillhouse Hollow Dam	1,318	422,233	320	686,000	521

* The SPF given is actually the SPF of the Brazos at Waco, but in terms of drainage area the increase in discharge per unit area is negligible.

Although this formula has been used for flood prediction for basins of many square miles, it is normally limited to areas of 100 to 200 acres or less (Dalrymple, 1964, p. 25.5). It can be considered for larger basins if proper values of the variables can be obtained. The factor causing greatest error is selection of a proper coefficient of runoff. Also the effect of antecedent moisture radically alters the applications of points 3, 5, and 6 above.

To apply the rational formula to the Bosque basin the equation is written as:

$$CI = \frac{Q}{A} \quad \text{or} \quad CI = \frac{Q}{A_1 \times 640}$$

where: Q, C, and I are the same as before, and, $A = A_1 \times 640$ with A_1 = area in sq. mi. (640 = number of acres in a sq. mi.).

Next, certain basic assumptions are made. They are:

1. The Maximum Probable Flood should be calculable by the rational formula by reason of points 5 and 6 above.

2. The discharge of the MPF for the Bosque basin above Lake Waco Dam is 563,300 cfs (Table 6).

3. The Thrall-Taylor rains were of MPP depth and would therefore be of MPP intensity.

4. Since the MPF and the area of the Bosque basin are known and the intensities of the Thrall-Taylor rains vary within a fixed range, then it is reasonable to estimate the runoff coefficient of the Bosque basin.

5. The runoff coefficient of the Bosque basin should be comparable to those used by hydraulic engineers in their application of the rational formula.

For estimation, the following values were used:

$Q = 263{,}000$ cfs, $A_1 = 1670$ sq mi,
$I = 15.60$ in/hr to 1.59 in/hr.

The runoff coefficient varied from 0.331 for rainfall intensities of 38.2 inches in 24 hours to 0.0338 for rainfall intensities of 1.30 inches in five minutes.

A comparison of these values with those on Table 8 shows that a storm of Thrall-Taylor magnitude over the Bosque basin would produce the Maximum Probable Flood. Even at lower rainfall intensities the runoff coefficient does not exceed ranges compatible with the drainage area of the Bosque basin.

UNITED STATES GEOLOGICAL SURVEY FLOOD MAGNITUDE-FREQUENCY MODEL

The standard method utilized by the U. S. Geological Survey for estimation of flood frequency and magnitude, is that of Dalrymple (1960) modified by Benson (1962). Since that time the U. S. Geological Survey has engaged in an active program of applying these methods to each state. Flood frequency and magnitude for rivers of the State of Texas have been calculated utilizing these methods (Patterson, 1963).

Data for this model are obtained from annual flood series of peak discharges recorded at point gaging sta-

TABLE 8. VALUES OF RUNOFF COEFFICIENT C

Type of drainage area	Runoff coefficient, C
Lawns:	
Sandy soil, flat, 2%	0.05-0.10
Sandy soil, average 2-7%	0.10-0.15
Sandy soil, steep 7%	0.15-0.20
Heavy soil, flat, 2%	0.13-0.17
Heavy soil, average, 2-7%	0.18-0.22
Heavy soil, steep, 7%	0.25-0.35
Business:	
Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential:	
Single-family areas	0.30-0.50
Multi units, detached	0.40-0.60
Multi units, attached	0.60-0.75
Suburban	0.25-0.40
Apartment dwelling areas	0.50-0.70
Industrial:	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30
Streets:	
Asphaltic	0.70-0.95
Concrete	0.80-0.95
Brick	0.70-0.85
Drives and walks	0.75-0.85
Roofs	0.75-0.95

After Chow, Ven Te (1964) Runoff, in Handbook of Applied Hydrology, Ven Te Chow, ed.: McGraw-Hill, New York, p. 14.8.

tions in various drainage areas. These are coordinated by curve fitting and curves define mappable units. A hydrologic area is defined as an area in which the ratio of mean annual flood discharge to drainage area is constant. A second mapping unit, the flood frequency region, is defined as an area in which ratio of discharge to mean annual flood is correlative to frequency of discharge (Patterson, 1963, p. 8-12). The hydrologic area of the Bosque basin is four and the flood frequency region is C, as defined by Patterson (*idem,* Pls. I, II). Figures 12 and 13 give the curves for this region.

Two factors are apparent from these figures. The first is the limitation of flood prediction to the 50-year, or two percent, flood. Second is the upper and lower limits of the mean annual flood basin area curve. Although it would seem quite simply a matter of extrapolation, any values derived from such would not be reliable, nor is it recommended (*idem*, p. 20).

An example of the use of these curves is given here to determine the 50-year flood at the gaging station at Clifton, Texas.

1. Determine the drainage area above the gaging station.	971 sq mi
2. From Figure 12 determine the mean annual flood.	26,300 cfs
3. Determine the ratio between the the 50-year flood and the mean annual flood from Figure 13.	5.3
4. Multiply step 2 by step 3 for the discharge of the 50-year flood.	139,390 cfs

By this method the magnitude of discharge for any flood frequency (up to 50 years) can be determined for a given basin provided the basin drainage area is known.

Table 9 gives the 50-year and 100-year flood discharges for the gaged points in the Bosque basin and the streams which had the greatest flood input during the 1936 flood on the Brazos River at Waco, Texas.

From Table 9 it is apparent that a number of streams have not had floods comparable to the 50-year flood as calculated by this method. There are an even greater number which have not experienced the predicted 100-year flood. Also note the discrepancy in values of the one percent (Intermediate Regional Flood; 100-year flood) calculated by this method for the Bosque and that calculated by the Corps of Engineers (Table 5). Table 11 gives the 50- and 100-year estimated discharges for some of the smaller significant streams in the North Bosque basin. Note particularly that Meridian Creek has a higher estimated 100-year flood peak than the flood peak estimated by the Corps of Engineers for the entire Bosque basin. This discrepancy may be due to errors in either or both of the methods.

For example the flood graphs are based on limited data. Although the method was designed to extend the utility of the data, mapping units encompass areas that may be dissimilar in soils, climate, vegetation, geology, land use, etc. and therefore will be dissimilar in hydrologic properties. Hydrologic area four (*idem,* Pl. II) covers areas of outcrop of highly stratified rocks ranging from dense limestones to porous sandstones. Over this region land uses range from open prairie to row crop cultivation to heavily forested regions to urban pavements. It is unlikely that the ratio between mean annual flood size to basin area is the same throughout this region.

Flood frequency region C presents similar questions. Areas mapped as C range from the basin of the Sabine River to trans-Pecos, Texas, and from the High Plains to the mouth of the Nueces River at Corpus Christi. It is probable that flood frequency regions encompassing areas of highly dissimiliar hydrologic properties may result in inaccurate prediction.

Another problem is in the prediction of low probability floods. Although many of the predicted 50-year flood values exceed 100-year values derived by other methods, floods in excess of the 50-year flood cannot be predicted without excessive extrapolation.

The major limitation to the use of this method is caused by its inability to predict flood volumes. Flood control is based upon storage of flood waters rather than upon flood wave characteristics, hence knowing the vol-

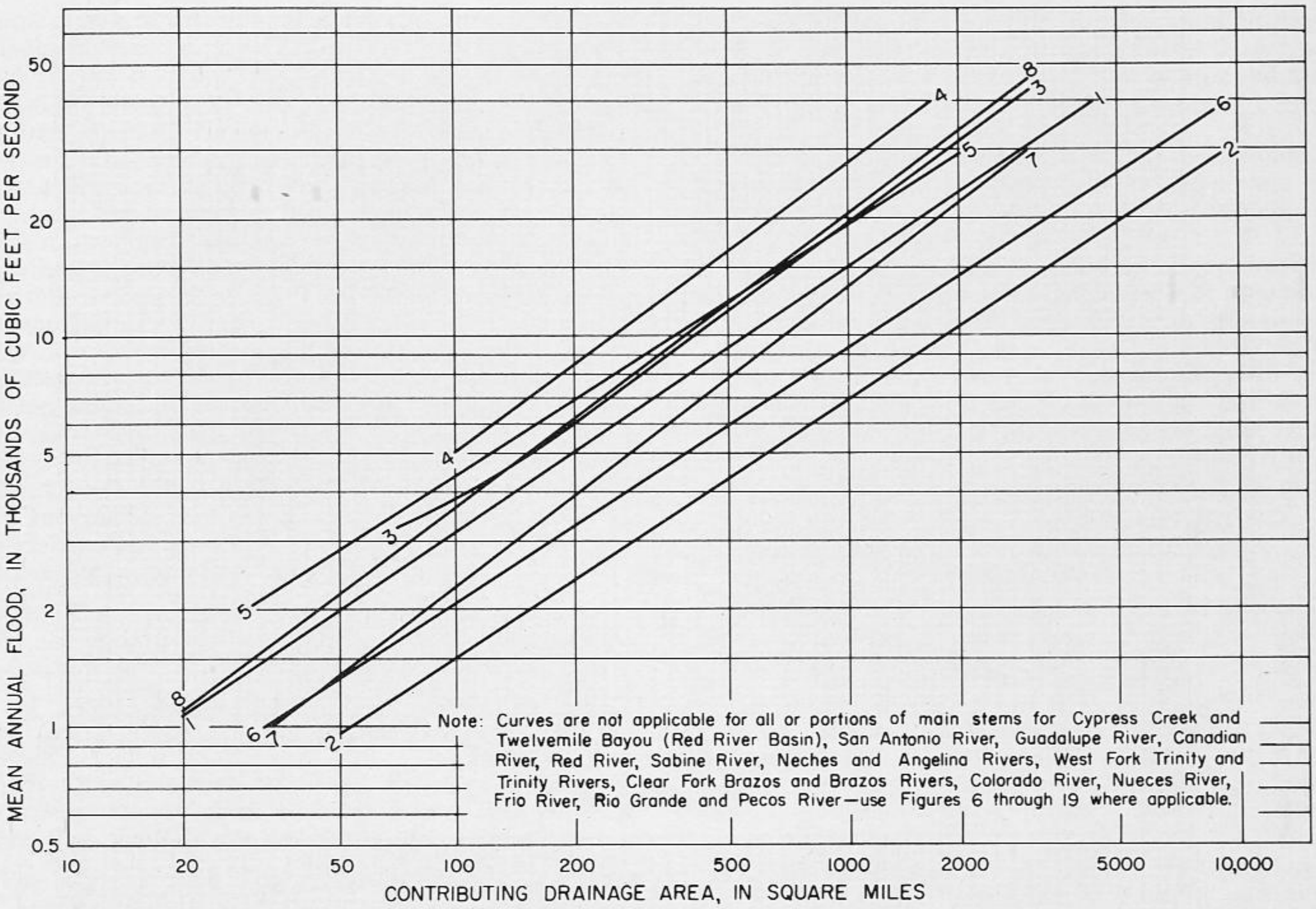
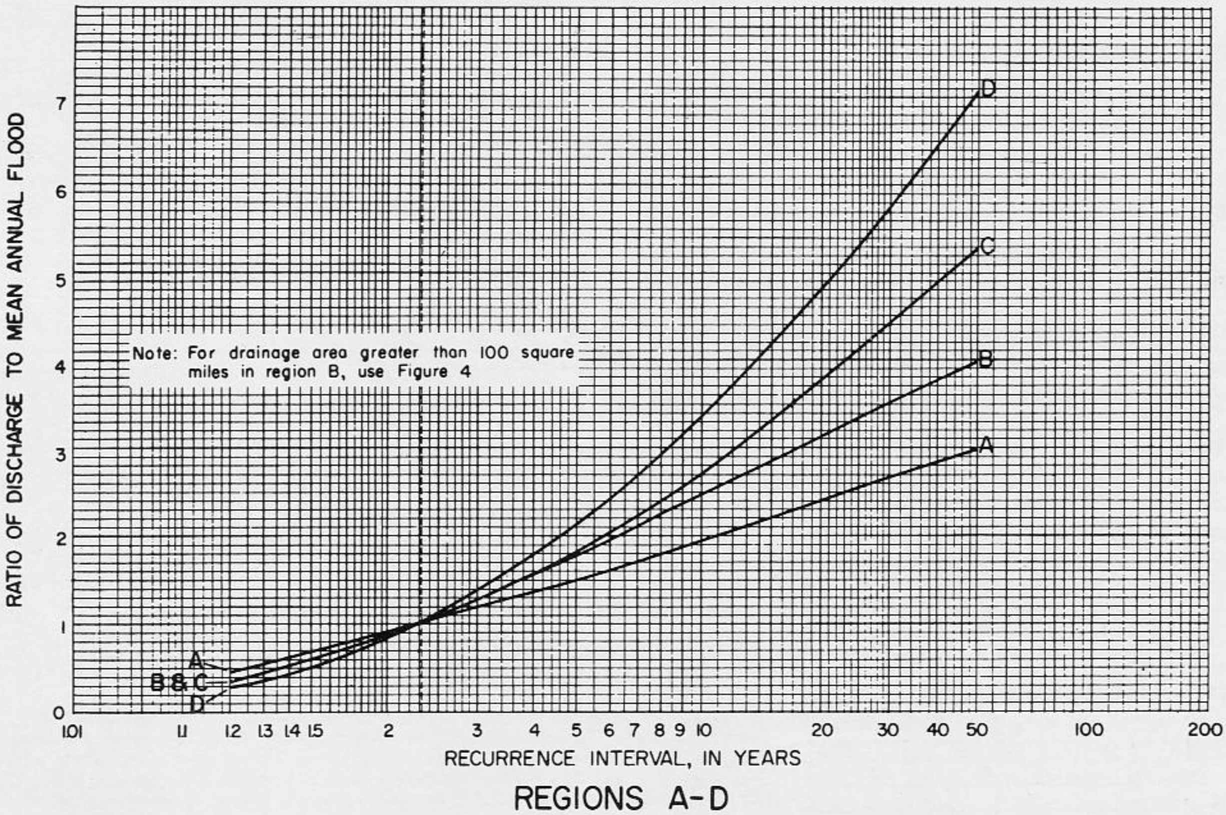


Fig. 12. Variations of mean annual flood with drainage area in hydrologic areas 1 through 8. *From* Patterson, 1963, Texas Water Commission Bull. 6311, p. 15.

TABLE 9. ESTIMATED DISCHARGES OF 50- AND 100-YEAR FLOODS FOR GAGED STATIONS ON BOSQUE BASIN AND SELECTED ADJACENT STREAMS

Stream	Station	Drainage Area sq mi	Maximum Recorded Flood, cfs (Date)	Mean Annual cfs	50-Year Flood cfs	Q_{50}/Q_{Max}	100-Year Flood cfs	Q_{100}/Q_{Max}
N. Bosque	Stephenville	92.4	49,000 (19 May 55)	*	*	*	*	*
N. Bosque	Stephenville	93.3	40,000 (23 May 52)	*	*	*	*	*
Green Cr.	Dublin	3.18	9,910 (30 Apr 56)	*	*	*	*	*
Green Cr.	Dublin	11.6	18,900 (23 May 52)	*	*	*	*	*
Green Cr.	Alexander	45.5	55,800 (23 May 52)	*	*	*	*	*
N. Bosque	Hico	358	87,800 (23 May 52)	12,800	67,840	0.77	87,040	0.99
N. Bosque	Clifton	971	92,800 (4 Oct 59)	26,300	139,390	1.50	178,840	1.93
N. Bosque	Valley Mills	1,149	107,000 (4 Oct 59)	30,000	159,000	1.49	204,000	1.91
Hog Creek	Crawford	78.2	15,400 (4 Oct. 59)	*	*	*	*	*
Middle Bosque	McGregor	182	32,600 (16 June 64)	7,820	41,446	1.27	53,176	1.63
S. Bosque	Speegleville	388	54,500 (14 June 27)	13,600	72,080	1.32	92,840	1.70
Bosque	L. Waco Dam	1,660	96,000 (27 Sep 36)	39,000	206,700	2.15	265,200	2.76
Aquilla Cr.	Aquilla	309	34′ (stage) (31 Aug 87)	11,400	60,420	—	77,520	—
Aquilla	Gholson	372	84,500 (26 Sept 36)	13,200	69,960	0.83	89,760	1.06
Childress Cr.	China Springs	79	47,000	*	*	*	*	*

* calculation of this information would require extrapolation beyond reliability of data base.
— no discharge was recorded for this flood and therefore this cannot be calculated.



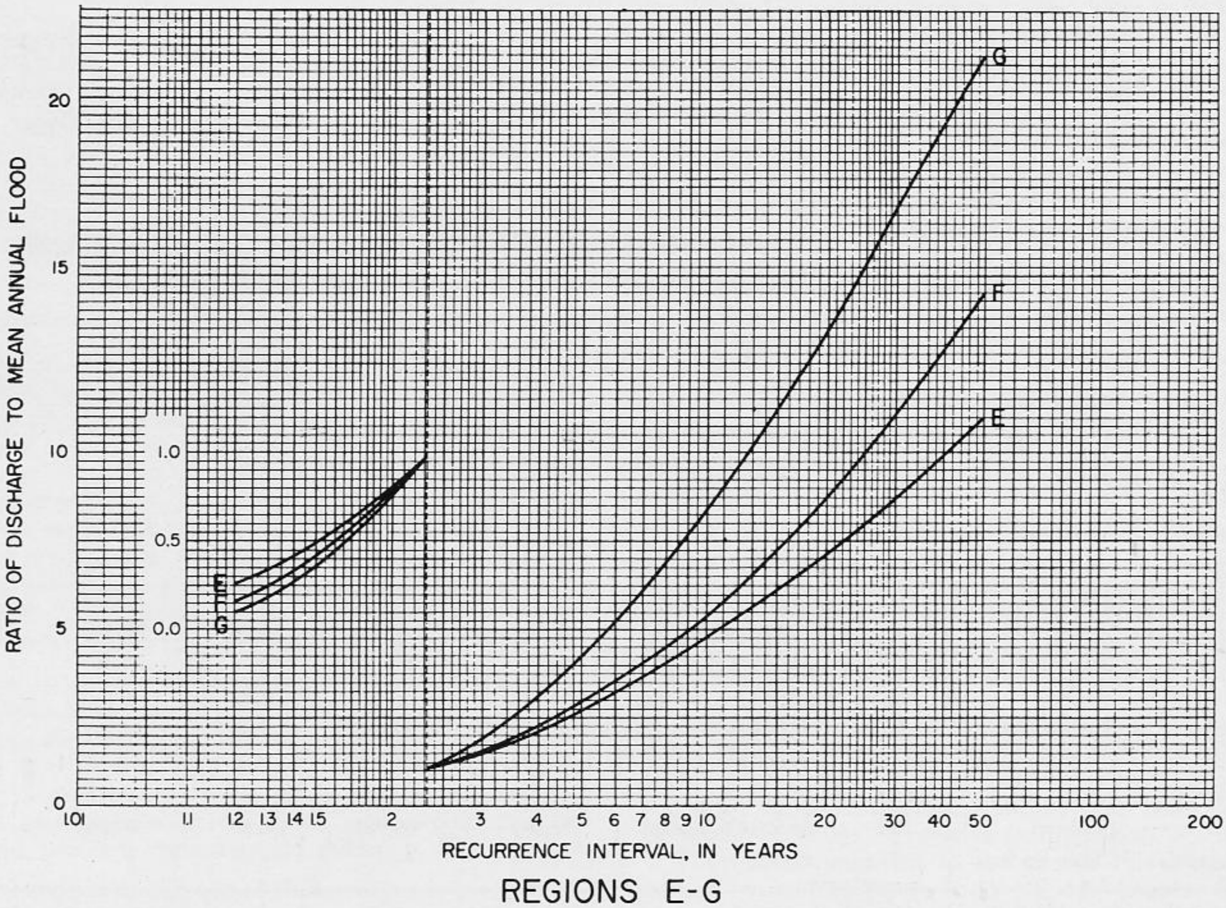


Fig. 13. Frequency of annual floods by regions. *From* Patterson, 1963, Texas Water Commission Bull. 6311, p. 13.

ume of a flood is more critical than knowing peak flows. If the Hydrologic Area/Flood Frequency Region method is correct, and if the discharges are much greater than those predicted by other means, then the question arises, are the volumes estimated by other methods in error to the same degree? The answer must come from some other method.

An estimate for the flood volume for the Bosque basin has been based on the dimensionless hydrograph method utilizing data from Meier's study of three small basins in central Texas (1964). By comparison of these basins with the Bosque basin, the hydrograph for Pin Oak Creek (Hill and Limestone Counties; *idem,* p. 15, 51) was considered most representative of hydrographs in the Bosque basin, and the Pin Oak Creek dimensionless hydrograph was utilized to develop a model hydrograph for the 100-year flood calculated by the U. S. Geological Survey method.

To generate the hydrograph it was necessary to determine the time of rise. In order to do this the following assumptions were made:

1. The rate of rise for the 100-year flood would not be significantly different from the Standard Project Flood.

2. Once overbank conditions exist there is a direct or nearly direct stage-discharge relationship.

3. If an overbank stage and discharge are known, the stage for any given discharge greater than that and less than the SPF can be calculated.

The height of the SPF is 52 feet at 325,000 cfs (Table 5). Surface water records indicate a stage of 39.8 feet at a discharge of 69,000 cfs for the Bosque River at Waco on October 4, 1959 (U. S. Geological Survey, 1963, p. 220). From this it was calculated that at 265,200 cfs the flood height would be 49 feet and the time of rise to flood peak would be 14 hours at a rate of 3.5 feet per hour (Table 5).

Table 11 gives the coordinates of the dimensionless hydrograph of Pin Oak Creek and the coordinates of the predicted 100-year flood with a peak discharge of 265,200 cfs and time of rise of 14 hours.

The volume of the flood is given by the area under the curve (Fig. 14), and this volume could be produced by 4.23 inches of runoff from the entire Bosque basin. Assuming a ten percent loss of rainfall to infiltration, a 4.7-inch rain could produce this amount of runoff.

Other 100-year predicted flood hydrographs were constructed utilizing data from other basins more simi-

TABLE 10. ESTIMATED DISCHARGES OF 50- AND 100-YEAR FLOODS UNGAGED STREAMS IN THE NORTH BOSQUE RIVER BASIN

Stream	Station	Drainage Area sq mi	Mean Annual cfs	50-Year Flood cfs	100-Flood Year cfs
Green Cr.	Mouth	104	5,200	27,560	35,360
Duffau	Mouth	90*	4,650	24,645	31,620
Meridian	Mouth	187	8,000	42,400	54,400
Neils	Mouth	142	6,600	34,980	44,800

* Normally extrapolation for this would be beyond the reliability of the curve; however, the basin size is sufficiently close to the 100 square mile cut off and the basin is significant enough to warrant the calculation.

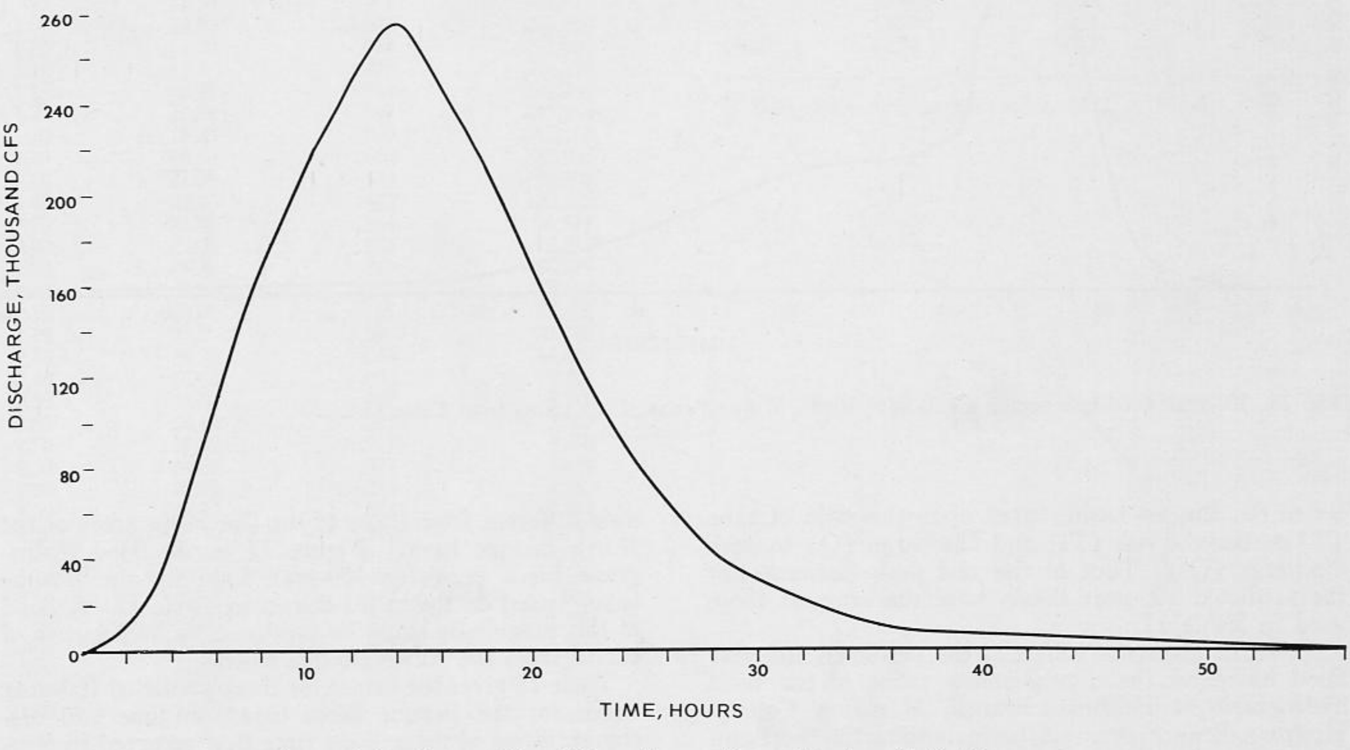


Fig. 14. 100-year flood hydrograph for Bosque River, Waco, Texas. Data points from Table 11.

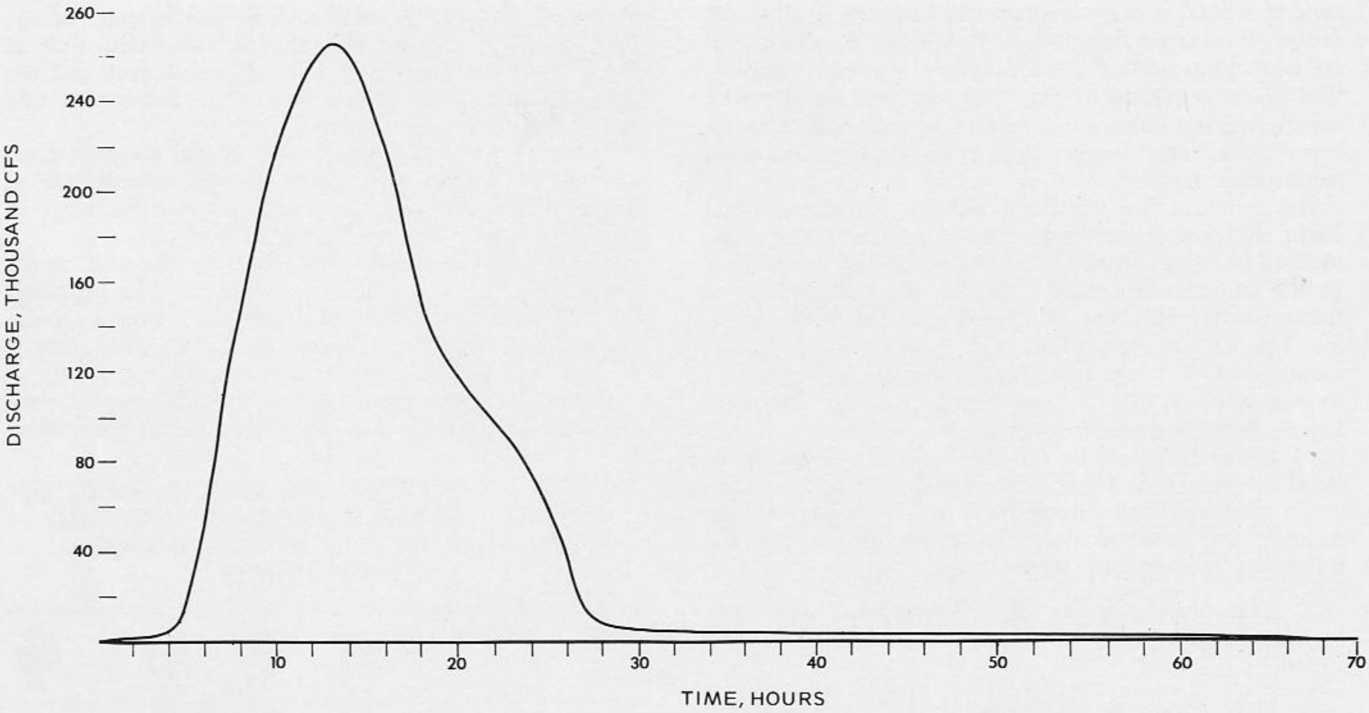


Fig. 15. 100-year flood hydrograph for Bosque River, Waco, Texas. Data points from Table 12.

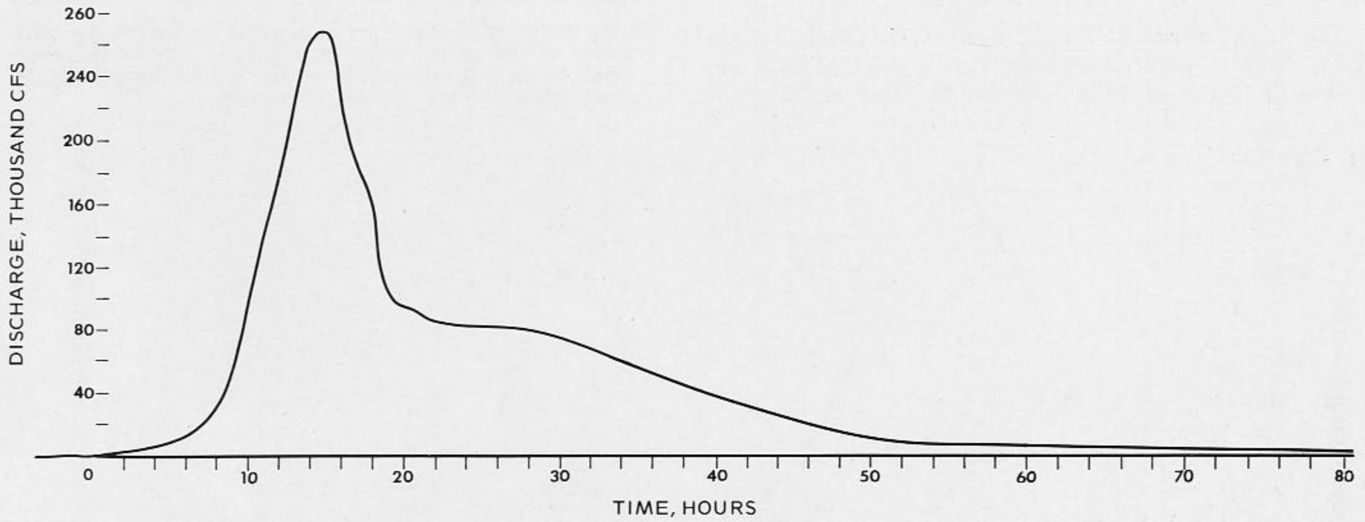


Fig. 16. 100-year flood hydrograph for Bosque River, Waco, Texas. Data points from Table 13A.

lar to the Bosque basin, based upon the ratio of time (T) to time of rise (T_P) and Discharge (Q) to peak discharge (Q_P). Time of rise and peak discharge for the predicted 100-year floods were the same as those used in Table 11.

Table 12 gives the values of the predicted 100-year flood based on the dimensionless ratios of the flood hydrograph of Hoffman Branch, Hamilton County. Hoffman Branch drains a basin heading in the Lampasas Cut Plain. The geology, soils, and land use are little different from those of the Cut Plain areas of the North Bosque basin. Figure 15 is the flood hydrograph for a predicted 100-year flood for the Bosque basin, based on the ratios shown in Table 12. A flood of this magnitude could be produced by 3.02 inches of runoff from the entire Bosque basin.

Table 13 gives the values for three predicted 100-year floods for the Bosque basin based on time and discharge ratios of three flood rises that occurred in September, 1936. Figures 16, 17, and 18 are the flood hydrographs for these synthesized floods. Although there is considerable variance in shape and volume among the hydrographs, the runoffs required to produce them were equally as low as those of the predicted flood hydrographs in Tables 11 and 12. For Figure 16 the runoff is 3.50 inches, for Figure 17 the runoff is 2.02 inches, and for Figure 18 the runoff is 3.71 inches.

From the above it may be seen that regardless of the model used, the runoff necessary to produce a 100-year flood, as defined by the U. S. Geological Survey, is 4.23 inches or less, and may be as little as 2.02 inches. If such small runoff values are capable of producing floods of greater magnitude than the largest ever seen on the Brazos River at Waco, it would appear only reasonable to consider such floods in flood planning for the Waco area and throughout the Bosque basin.

However, extrapolation beyond the 100-year discharge is risky at best and other methods are required in order to determine magnitudes of floods of even greater discharge.

TABLE 11. DIMENSIONLESS HYDROGRAPH FOR PIN OAK CREEK, HILL AND LIMESTONE COUNTIES, AND FLOOD HYDROGRAPH OF THE CALCULATED 100-YEAR FLOOD OF THE BOSQUE RIVER AT WACO

T/T_p*	T_{14} hours	Q/Q_p*	$Q_{265,200}$ cfs
0	0	0	0
.05	.70	.007	1,856
.10	1.40	.021	5,569
.15	2.10	.045	11,934
.20	2.80	.080	21,216
.30	4.20	.169	44,819
.40	5.60	.318	84,334
.50	7.00	.484	128,357
.60	8.40	.635	168,402
.70	9.80	.768	203,674
.80	11.20	.871	230,989
.85	11.90	.916	242,923
.90	12.60	.953	252,736
.95	13.30	.991	262,813
1.00	14.00	1.000	265,200
1.05	14.70	.994	263,609
1.10	15.4	.975	258,570
1.15	16.10	.940	249,288
1.20	16.80	.897	237,884
1.30	18.20	.800	212,160
1.40	19.50	.690	182,988
1.50	21.00	.569	150,899
1.60	22.40	.462	122,522
1.70	23.80	.364	96,533
1.80	25.20	.284	75,317
1.90	26.60	.219	58,079
2.00	28.00	.159	42,167
2.10	29.40	.113	29,968
2.20	30.8	.082	21,746
2.30	32.20	.055	14,586
2.40	33.60	.035	9,282
2.50	35.00	.027	7,160
2.60	36.40	.021	5,569
2.70	37.80	.017	4,508
2.80	39.20	.013	3,448
2.90	40.60	.012	3,182
3.00	42.00	.011	2,917
3.10	43.40	.0105	2,785
3.20	44.80	.010	2,652
3.30	46.20	.008	2,122
3.40	47.60	.007	1,856
3.50	49.00	.005	1,326
3.60	50.40	.004	1,061
3.70	51.80	.003	796
3.80	53.20	.002	530
3.90	54.60	0	0

* Meier, 1964, p. 42.

TABLE 12. DIMENSIONLESS HYDROGRAPH FOR HOFFMAN BRANCH, HAMILTON COUNTY, AND FLOOD HYDROGRAPH OF THE CALCULATED 100-YEAR FLOOD OF THE BOSQUE RIVER AT WACO, TEXAS

T/T_p*	T_{14} hours	Q/Q_p*	$Q_{265,200}$ cfs
0	0	0	0
.167	2.34	.003	796
.333	4.66	.023	6,000
.500	7.00	.348	92,290
.667	9.34	.607	184,844
.833	11.66	.929	246,371
1.000	14.00	1.000	265,200
1.167	16.34	.781	207,121
1.333	18.66	.523	138,700
1.500	21.00	.397	105,284
1.667	23.34	.310	82,212
1.833	25.66	.171	45,349
2.000	28.00	.020	5,304
2.167	30.34	.015	3,978
2.333	32.66	.010	2,652
2.500	35.00	.009	2,387
2.667	37.34	.008	2,122
2.833	39.66	.007	1,856
3.000	42.00	.005	1,326
3.167	44.34	.004	1,061
3.50	49.00	.003	796
3.833	53.66	.002	530
4.167	58.34	.002	530
4.487	62.82	.002	530

* Data derived from Schroeder, 1972, p. 44-46.

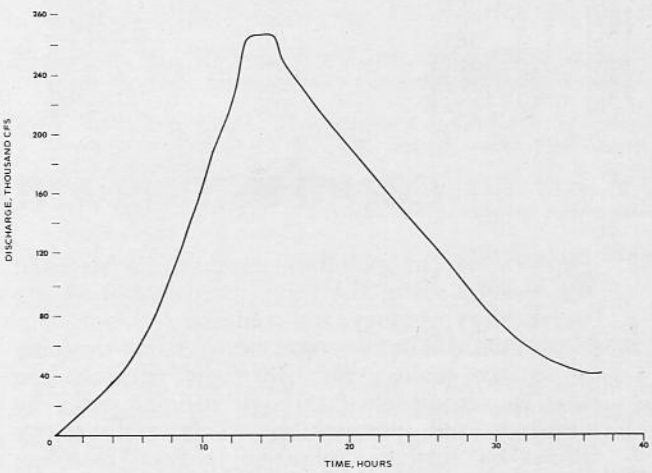


Fig. 17. 100-year flood hydrograph for Bosque River, Waco, Texas. Data points from Table 13B.

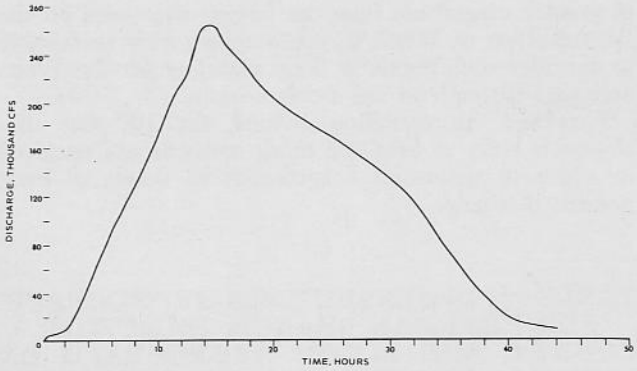


Fig. 18. 100-year flood hydrograph for Bosque River, Waco, Texas. Data points from Table 13C.

TABLE 13. DIMENSIONLESS HYDROGRAPHS FOR NORTH BOSQUE RIVER, CLIFTON, TEXAS, AND FLOOD HYDROGRAPHS OF THE CALCULATED 100-YEAR FLOOD OF THE BOSQUE RIVER AT WACO, TEXAS

T/T_p	T_{14} hours	Q/Q_p	$Q_{265,200}$ cfs
16-22 Sept 36*			
0	0	0	0
.111	1.55	.005	1,326
.278	3.89	.012	3,182
.389	5.45	.022	5,834
.500	7.00	.047	12,464
.611	8.55	.182	48,266
.722	10.11	.391	103,693
.833	11.66	.652	172,910
.944	13.22	.975	258,570
1.000	14.00	1.000	265,200
1.056	14.78	1.000	265,200
1.111	15.55	.902	239,210
1.278	17.89	.548	145,330
1.389	19.45	.354	93,881
1.444	20.22	.354	93,881
1.500	21.00	.336	89,107
1.722	24.11	.319	84,599
2.056	28.78	.285	75,582
2.278	31.89	.239	63,383
2.722	38.11	.157	41,636
3.056	42.78	.102	27,050
3.389	47.75	.067	17,768
3.722	52.11	.037	9,812
4.056	56.78	.017	4,502
5.056	70.78	.006	1,591
5.722	80.11	.005	1,326
25-26 Sept 36*			
0	0	0	0
.222	3.11	.096	25,459
.444	6.22	.250	66,300
.667	9.34	.520	137,904
.889	12.45	.800	212,160
1.00	14.00	1.000	265,200
1.111	15.55	1.000	265,200
1.222	17.11	.930	246,636
1.556	21.78	.670	177,684
2.222	31.11	.250	66,300
2.444	34.22	.171	45,349
2.556	35.78	.154	40,841
26-27 Sept 36*			
0	0	0	0
.056	.78	.010	2,652
.111	1.55	.012	3,182
.167	2.34	.032	8,486
.278	3.89	.137	36,332
.389	5.45	.294	77,969
.500	7.00	.450	119,340
.556	7.78	.519	137,639
.611	8.55	.582	154,346
.667	9.34	.631	167,341
.722	10.11	.695	184,314
.833	11.66	.795	210,834
.944	13.22	.916	242,923
1.000	14.00	1.000	265,200
1.056	14.78	1.000	265,200
1.111	15.55	.951	252,205
1.167	16.34	.916	242,923
1.278	17.89	.847	224,624
1.389	19.45	.795	210,834
1.611	22.55	.718	190,414
1.833	25.66	.631	167,341
1.944	27.22	.585	155,142
2.056	28.78	.539	142,943
2.167	30.34	.490	129,948
2.278	31.89	.429	113,771
2.389	33.45	.337	89,372
2.500	35.00	.237	62,852
2.611	36.55	.149	39,515
2.722	38.11	.075	19,890
2.778	38.89	.054	14,321
2.833	39.66	.048	12,730
2.944	41.22	.039	10,343
3.056	42.78	.033	8,752
3.167	44.34	.027	7,160
**	**	**	**

* The three dimensionless hydrographs were derived from three separate rises occurring on these dates (Dalrymple, 1937, p. 79).

** No end point is given because the data from which the data were derived did not extend to a period of no flow.

CONCLUSIONS AND RECOMMENDATIONS

1. Of the seven factors influencing flood discharges in the Bosque basin, the three most significant are meteorology, geology, and land use.
2. For initial qualitative reconnaissance, the mapping of surface geology for hydrologic purposes can best be accomplished through defining units by lithology and permeability. This methodology allows for further application to flood modeling techniques utilized by the Soil Conservation Service.
3. In the Bosque basin, the concentration of impermeable bedrock in the lower portion of the basin provides a greater flood input into the Brazos River through runoff quantity and basin proximity.
4. Increased urbanization in the lower portions of the Bosque basin will compound its already high flood potential through decreased time of rise, increased peak discharge (by as much as 300 percent), increased stage, increased frequency, and increased volume of runoff.
5. Of the three types of flood-producing storms, the

tropical cyclone has the greatest potential for producing maximum flooding in the Bosque basin, but has the least probability of occurrence. The thunderstorm has the highest incidence of occurrence in the Bosque basin, but by physical limitations produces the smaller floods. The tropical wave presents the most significant potential flood threat because of the near tropical cyclone capacity for precipitation and near thunderstorm frequency of occurrence.

6. The Bosque Escarpment has the capacity to not only localize rainfalls, but also the thermodynamic capacity to "trigger" rainfalls from unstable meteorological conditions.
7. Historical rains and floods in central Texas have been among the greatest in magnitude and intensity of any area in the United States. Storms equal to any or all of these storms may reasonably be expected to occur with the Bosque basin.
8. The flood of September 25-28, 1936, on the Brazos River at Waco was caused by simultaneous arrivals of flood waves from Aquilla and Childress Creeks, coupled with directed discharges from stored flood waters in Lake Waco. The flood-control philosophy which caused this flood is still in effect, and with even larger flood-control structures the capacity for even greater floods of this type is compounded.
9. The Intermediate Regional Flood estimates for the Bosque and Brazos basins at Waco are based on insufficient data. As such their effectiveness as inputs for disaster planning is questionable.
10. Flood modeling of the Bosque basin indicates that the 100-year flood for the Bosque basin is larger than any flood seen to date. This flood could be produced by 2.02 to 4.23 inches of runoff from the basin.
11. It is recommended that the Standard Project Flood and the Maximum Probable Flood guidelines be used for flood disaster planning.
12. If a percentage probability is desired for planning purposes, it is recommended that probabilities be limited to meteorological conditions and the flood designs be developed utilizing the Soil Conservation Service techniques.

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