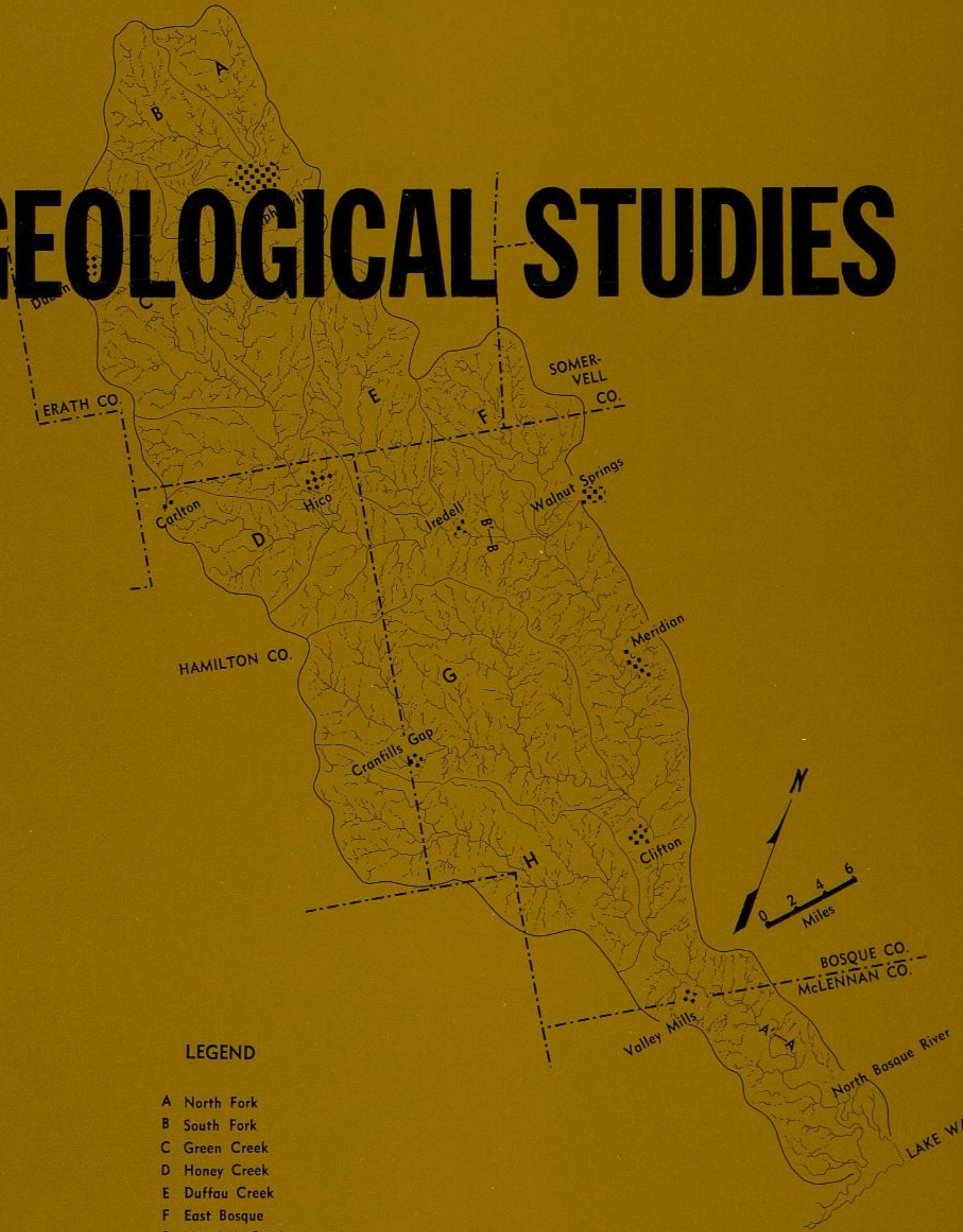
BAYLOR GEOLOGICAL STUDIES



SPRING 1969

Bulletin No. 16

The North Bosque Watershed
Inventory of a Drainage Basin

CLEO V. PROCTOR, JR.

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

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

Objectives of Geological Training at Baylor

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

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The North Bosque Watershed Inventory of a Drainage Basin

CLEO V. PROCTOR, JR.

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Spring, 1969

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.

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Inventory of a Drainage Basin

CLEO V. PROCTOR, JR.

ABSTRACT

The geomorphology of the four physiographic regions within the North Bosque watershed is directly related to the properties of the rocks outcropping within those regions, and a dynamic equilibrium exists between erosional energy and topography. Landforms are being downwasted at the same rate, and differences in relief and form can be explained in terms of spatial relationships rather than evolutionary development through time.

Because of the location of the North Bosque watershed, flood discharges reaching the astounding magnitude of 500,000 second feet can be expected during a long period of record.

Sheet erosion is the major sediment producer in the North Bosque watershed, and the Paluxy Formation is the dominant contributor to this type of erosion. Sheet erosion lowers the land surface by a maximum of approximately 0.095 centimeter per year. Solution is also important as a landscape modification agent and lowers the land surface by approximately 0.0012 centimeter per year.

The North Bosque watershed is in the erosional development stages of inequilibrium and equilibrium. Quantitative analyses of geomorphic parameters indicate that Meridian Creek and Honey Creek basins are presently losing drainage in their headwaters to the Leon River.

In the North Bosque watershed several empirical relationships have been found to exist between geomorphology, hydrology, and erosional energy. Channel length and drainage basin area are related as $\log L_1 = 0.1778 + 0.5882 \log D_a$. Drainage area and discharge are related as $\log Q = -0.7348 + 1.0159 \log D_a$. Relief ratios are conservatively related to annual sediment yield as $\log S_1 = -1.0372 + 231.54 R_r$.

INTRODUCTION[1]

This is the study of the geomorphology of the North Bosque watershed, Central Texas. It is primarily concerned with the exogenous processes as they shape the Central Texas landscape. Ideally, the factors which have controlled landform development in Central Texas can be considered in simple terms. The land surface in any area is composed of rocks with particular chemical and physicals properties. Because these exposed rocks were formed at greater depths, they are not in equilibrium with the weathering environment, and decomposition begins. This wasting of the land surface is expedited by the mechnical action of water, debris, ice, and air, and where a surface slope exists the products of weathering are removed by erosion. By this process various landforms, typical of the region and the mechanisms of formation, are created.

The shape or form of the landscape may vary from region to region, depending upon the properties of the rock and the type of erosional agents. However, if the mechanics and products of weathering remain constant —in equilibrium—as the land surface is reduced, the landforms should remain the same though the areas occupied by uplands and lowlands will change. These fac-

[1]A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1967. Professors O. T. Hayward and L. F. Brown, Jr., Department of Geology, were consulted during research and manuscript preparation.

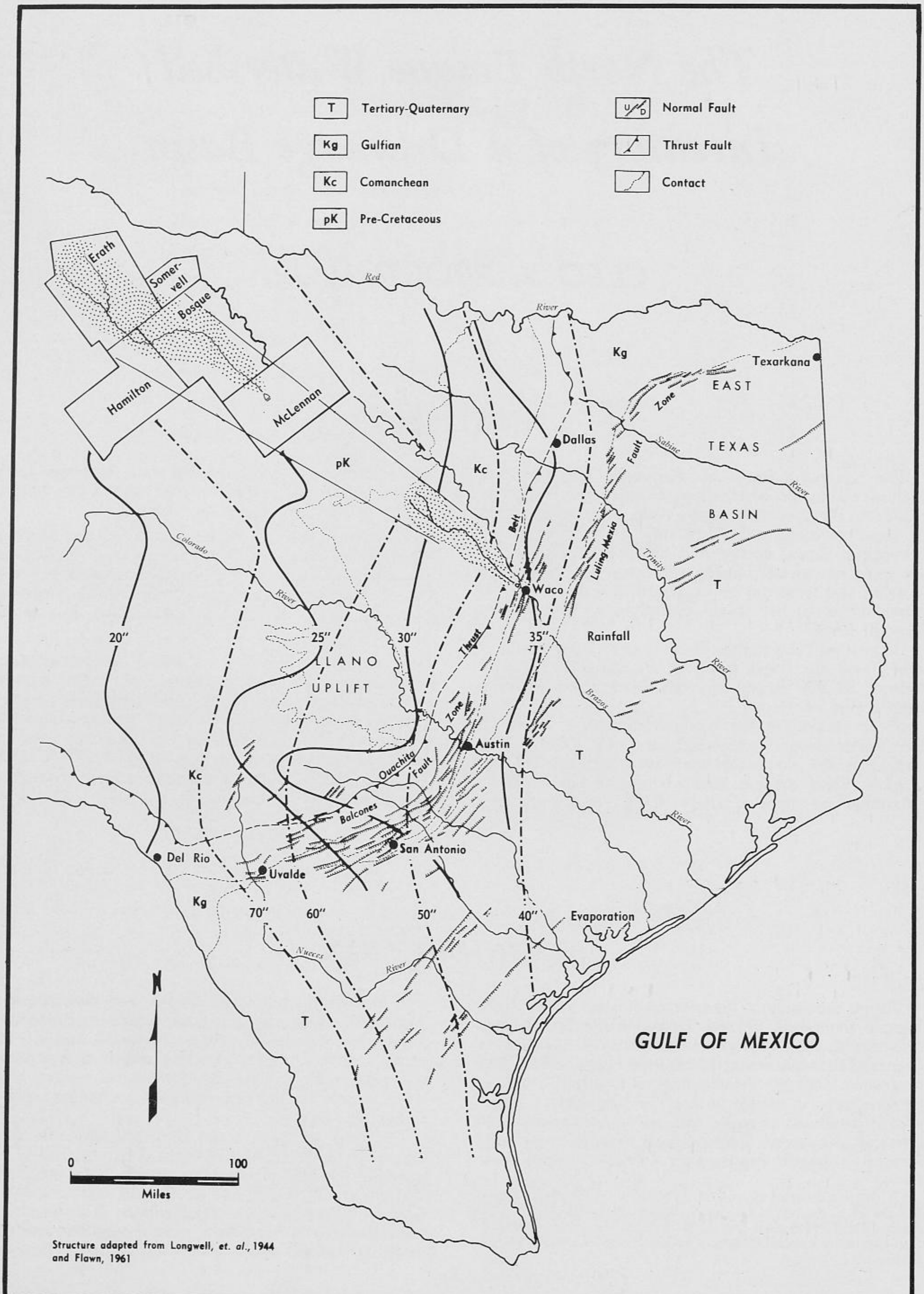


Fig. 1. Location, rainfall, and evaporation map.

tors account for the internal homogeniety of the major geomorphic provinces of Central Texas, and the marked differences between adjacent provinces.

Three major theories regarding the development of landscapes have been advanced by geomorphologists. The first of these is the cycle theory by William Morris Davis. Davis proposed in 1899 that valleys develop by deepening (and wasting of the sides) through three distinct stages: youth, maturity, and old age. This sequence of stages he called a geomorphic cycle, and the end product is a peneplain (Davis, 1922).

The influence of William Morris Davis on geomorphology was unquestionably greater than any other individual. In development of the cycle theory, he observed that the basic principles underlying the evolution of landforms are a function of the structure of the rocks (including their composition and structural attitude), processes acting upon them, and time over which these processes have been active. The interrelation of these three factors results in specific landform development.

Walther Penck, a critic of Davis' cycle theory, proposed his slope development theory in the 1920's. He viewed the development of a drainage basin as a function of the development of the individual slopes it contains. According to Penck, the slopes recede individually owing to the various denudation agents (Scheidegger, 1962, p. 14).

Most recently John T. Hack (1960) in his "dynamic equilibrium theory" extended the work of G. K. Gilbert and proposed that every slope and every channel in an erosional system is adjusted to every other slope and channel. When erosional energy and topography are in equilibrium, all elements of the topography are downwasted at the same rate. Difference in relief and form may be explained in terms of spatial relations rather than in terms of an evolutionary development through time (*idem*). It is this theory by Hack which best applies to the evolution of the North Bosque watershed.

PURPOSE

The purpose of this investigation is to analyze the relationship between geomorphic processes and geology in the North Bosque watershed. This watershed forms a convenient unit of regional size, suitable for evaluation of processes and formation of landforms in the Central Texas region.

The interpretation of geomorphic history is presently being extended from the purely descriptive interpretations of the past to a more quantitative interpretation through concentration on geomorphic processes.

In order to interpret the rate and processes of denudation of the North Bosque watershed, the following specific problems are considered: (1) drainage net geometry as related to lithology and structure; (2) water and sediment sources: (3) geochemical character of the surface waters; (4) flow and sediment transport rates; (5) stream channel gradients and their relationship to outcropping rocks; (6) hillslope development (mechanics, controls and denudation rates); (7) ratios of upland to valley floor for individual basin areas; and (8) the physical and chemical properties of the outcropping rocks.

LOCATION

The North Bosque watershed of Central Texas is located on the eastern margin of the Texas Craton, northwest of the Balcones fault zone (fig. 1). The North Bosque River originates about 20 miles northwest of Stephenville, in Erath County, and terminates in Lake Waco, McLennan County. The basin area is approximately 1290 square miles and is bounded by the Leon River drainage to the southwest and the Brazos River drainage to the north and northeast.

PROCEDURE

Because existing topographic maps of the North Bosque watershed are inadequate in coverage, Texas Highway Department county maps, prepared by photogrammetric methods, were used in the compilation of drainage system data. These maps were checked for accuracy against high altitude photographs and corrected wherever necessary. Elevation control was established from U.S.G.S. topographic quadrangle maps, 1:24000 and 1:62500 scale. U.S. Army Map Service 1:250000 series maps were used for those regions where larger scale maps were not available.

The outcropping geologic formations were mapped on high altitude aerial photographs (1:69000), field-checked, transposed onto U.S.G.S. topographic maps, and projected onto the base map. Elevation data for gradients of first order streams were obtained from hand-level surveys. A cross-profile section illustrating the relationship of geology and channel development of the North Bosque River channel was surveyed with plane table and alidade. Additional elevation data were taken from U.S.G.S. topographic maps.

Stream channel lengths were measured by map planimeter. Drainage areas of individual basins were determined from the drainage map, by use of a compensating polar planimeter, and the mean values of repeated sets of measurements were recorded.

In order to determine the geochemical character of the surface waters of the North Bosque watershed, water samples were taken at four significant locations in the North Bosque River and at one location in Meridian Creek, a major tributary to the North Bosque River. Analyses of these five samples were performed to determine the total dissolved solids and the percentage of the total of several ions.

PREVIOUS WORK

Earlier work on the geomorphology of the Central Texas area is entirely descriptive and includes papers by Loughridge, Hill, and Taff.

In 1884 the first comprehensive report on the topographic features of the state of Texas, accompanied by maps showing the distribution of soils and a brief discussion of the geology of the area, was published by the Federal Government in the Tenth Census of the United States (Loughridge, 1884).

In 1892 J. A. Taff described the topography developed on the Glen Rose Limestone and Paluxy Sand in the Central Texas region.

R. T. Hill (1901) in his classic study, *Geography*

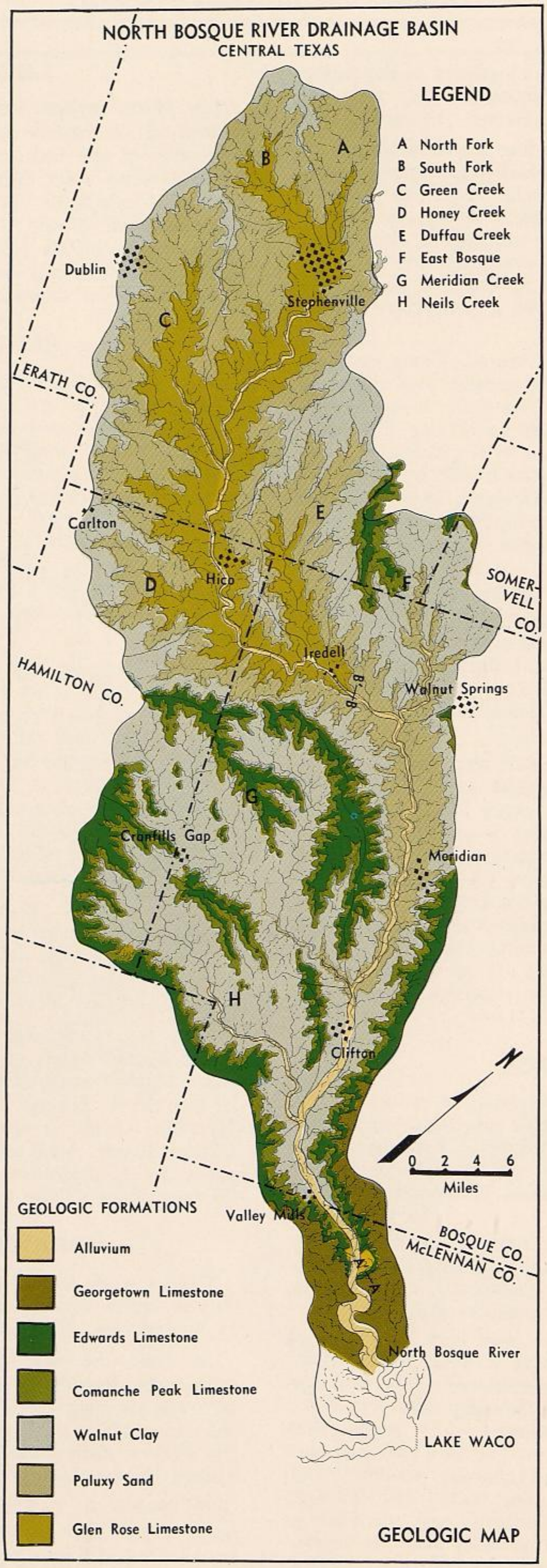


Fig. 2. Geologic map of the North Bosque watershed.

and Geology of the Black and Grand Prairies of Texas, logically divided the Central Texas region of this report into its natural physiographic regions—the Fort Worth Prairie and the Lampasas Cut Plain. In topographic, geologic, economic, and cultural aspects Hill's report is the most comprehensive ever attempted for the Central Texas region, but this too is entirely descriptive in its approach.

Most recent regional geologic studies of importance, used in the preparation of this report, include those by Atlee (1962), Brown (1963), Frost (1963), Boone (1966), Jones (1966), and Rodgers (1966).

Quantitative studies include only streamflow records and limited soil erosion rate studies undertaken by the U.S. Soil Conservation Service. Streamflow data for the North Bosque River and its tributaries have been recorded only since 1923, by the Water Resources Division of the U.S. Geological Survey.

An extensive search of the geologic literature discloses no quantitative analyses of the geomorphology of the Central Texas area. However, such studies of other regions of the United States have been undertaken, and those used in preparation of this study are mentioned in the following paragraphs.

The major impetus for studies in quantitative geomorphology was provided by Horton (1945), who set forth many of the principles now applied to drainage-basin studies. Subsequent investigators, notably Leopold and Miller (1956), Leopold and Langbein (1962), Leopold, Wolman, and Miller (1964), Strahler (1950, 1952, 1954, 1958) and several of Strahler's students (Schumm, 1956; Morisawa, 1962, 1964), Hack (1957, 1960), Bush (1961), Hadley and Schumm (1961), Scheidegger (1962), Lustig (1965), and Brice (1966), have enlarged these concepts, introduced new parameters, and extended the approach to a wider variety of geographic regions. Of these, the papers by Schumm (1956), Bush (1961), Hadley and Schumm (1961), Morisawa (1962, 1964), Lustig (1965), and Brice (1966) most closely paralled the principle purpose of the present study.

Schumm (1956) found that in the badland region of Perth Amboy, New Jersey, the relationship between channel lengths, drainage-basin area, and stream-order number are dependent on the constant of channel maintenance (the minimum drainage area required for channel maintenance). This constant of channel maintenance is in turn dependent on relative relief, lithology, and climate (*idem*). Schumm also concluded that topographic differences can be explained by the variance of infiltration rates of the formations on which they form, and that this distinction can apply generally to differences between arid and humid topography.

Bush (1961) measured hydraulic, basin, and geologic characteristics of 16 selected streams in Central Pennsylvania. He observed that the distribution of rock types and their relative positions along the length of a stream tend to govern the rate of change of channel slope and bed load size.

Hadley and Schumm (1961) found that an interrelationship exists between topographic and hydrologic characteristics of small drainage basins. Both relief ratio (elevation difference in the basin divided by basin length) and drainage density (stream length per unit drainage area) are fairly reliable quantitative measures for approximating the hydrologic characteristics (*idem*).

Analysis of quantitative geomorphic characteristics of watersheds in the Appalachian Plateau indicates that horizontal or planimetric aspects conform to Horton's laws, but control by structure and lithology governs vertical or gradient aspects (Morisawa, 1962).

In observing the origin and development of drainage systems, Morisawa (1964) suggested that the manner and rate of drainage development, as well as stream morphology, depend upon the slope of the initial land surface and type of material.

Lustig (1965) proposed a method of estimating the long-term sediment yield of the Castaic watershed, California, in the general absence of hydrologic data. The estimate is based upon a comparison of geomorphic parameters between the Castaic watershed and watersheds in the San Gabriel Mountains for which long-term sediment-yield data are available.

Brice (1966) evaluated the geomorphic properties of Medicine Creek basin, Nebraska and found that relief ratio, frequency of first-order streams, and the percentage of area in uplands have the highest correlation with runoff and sediment discharge.

CLIMATE

The climate of the North Bosque watershed lies within the modified Koppen region, Cfa—subtropical humid climate (Trewartha, 1954). However, the study area is near the dry margin of this climate belt since the mean annual precipitation ranges from 30-35 inches and mean annual water losses vary from 30-32 inches (fig. 1).

Mean annual precipitation is well distributed, with the larger average monthly rainfall occuring in April, May, June, September and October. Individual rains of excessive amounts occur dominantly in the spring months. The temperature averages from 45°F in January to 85°F in July. Daily temperature average is approximately 70°F during maximum precipitation, thus, limiting evaporation and intensifying erosion. Because of this rainfall effectiveness, the North Bosque watershed lies within the maximum soil construction belt, which occurs in a band between the 60 and 100 ratio (rainfall/evaporation x 100).

Regional climatic influence on the various sub-basins of the North Bosque watershed is relatively uniform. However, effective local climate is greatly altered by topography and compass orientation. High runoff on steep slopes, in effect, creates an arid local climate and conversely, less runoff and increased seepage on flatter, low-lying areas create more humid local climates. These effects may be seen in both soil types and plant communities on slopes of varying gradients.

Differential climates on opposite sides of valleys may be a function of their compass orientation. Diurnal fluctuations of temperature, plus differential insolation of north- and south-facing slopes, may be comparable to differences of several degrees of latitude so far as the local climate is affected (Leopold, *et al.*, 1964, p. 367). This causes north-facing slopes to be several degrees steeper, in a given formation, than equivalent south-facing slopes.

Weather extremes are quite pronounced in Central Texas and associated areas. The orographic effect of the Balcones escarpment (fig. 1) is the dominant physical factor influencing these extremes.

The forced ascent up the escarpment by easterly waves of moist tropical air has contributed to the release of some of the heaviest rains in Texas weather history, including the great Thrall, Texas storm of September 9-10, 1921, when 36.40 inches fell within an 18-hour period (Orton, 1966). In fact, flood-producing storms are more frequent along this escarpment than in any other region in the United States (Hoyt and Langbein, 1955).

The storm which occurred near D'Hanis, Texas on May 31, 1935, was one of the most intense small-area short duration storms on record. Its production of 22 inches in 2 hours and 45 minutes is the world's record for that time. This storm was of the thunderstorm "cloudburst" type resulting from northward flow of moist tropical air from the Gulf of Mexico which underwent convergence as the isobaric pattern changed from anticyclonic over the Gulf of Mexico to straight over Texas (Morgan, 1966). It appears possible that this convergence was localized by the orographic lifting effect of the Balcones fault zone of this region. As a result of this storm Seco Creek, near D'Hanis, Texas, had a peak flood discharge of approximately 260,000 cfs (cubic feet per second). This flow was derived from an extremely small basin area of only 160 square miles.

Small, short-lived hurricanes are also the cause of heavy storm rainfall in Texas. On June 25, 1954, a hurricane of minor intensity—"Alice"— entered Mexico about 85 miles south of Brownsville, Texas. "Alice" subsequently traveled up the Rio Grande valley to the lower Pecos and Devils River watersheds and released rains over this area.

Almost unbelievable flows of water came racing down the draws and arroyos that drain into the Devils River and the lower Pecos River, and on into the Rio Grande River immediately above Del Rio, Texas. The flow at the mouth of the Pecos River of almost one million cfs was eight times any previous flow during a long record (Myers, 1966). This is an extreme illustration of the fact that storm experience over a single basin alone is not a dependable indicator of what might occur over that basin in the future. The Pecos River record through 1953 gave no hint of what was to come in 1954.

On September 10, 1921, the Little River, formed by the confluence of the Lampasas and Leon rivers, the basins of which bound the North Bosque watershed on the west, had a peak flood discharge of 647,000 second feet (Brown *et al.*, 1962, p. 106). This flow was derived from a basin area of approximately 7,000 square miles, lying immediately west of the area of this investigation. Two additional floods, in 1852 and December, 1913, of the same magnitude as the 1921 flood have been recorded in the Little River basin (Water Resources Data, 1965, p. 285). Even though no flow of this magnitude has ever been recorded for the North Bosque watershed, there appears to be no question that such flows are not only possible but to be expected over a long period of record.

GEOLOGY

The North Bosque watershed is located on the structurally stable Texas craton (fig. 1). Rocks exposed in the watershed are Lower Cretaceous (Comanchean Series) strata and Recent alluvium which covers the valley floors of the North Bosque River and its major tributaries (fig. 2). The Cretaceous strata exposed in the watershed strike north-northeast and dip southeastward at 12 to 27 feet per mile (fig. 3). The Cretaceous rocks are, in descending order, the Washita Group, Fredericksburg Group, and Trinity Group (fig. 4).

The Washita Group is composed of three formations, of which only the lower two, the Del Rio Clay and the Georgetown Formation, crop out in the study area. The four formations of the Fredericksburg Group (Edwards Limestone, Comanche Peak Limestone, Walnut Clay, and Paluxy Sand) and the uppermost formation of the Trinity Group, the Glen Rose Limestone, crop out in the study area.

The geology and soils of the North Bosque watershed can be discussed most appropriately for purposes of this report by subdividing the area into 4 physiograpic regions with their associated surface deposits. These are the Washita Prairie, Lampases Cut Plain, Paluxy Cross-Timbers, and Glen Rose Prairie.

A generalized description of the rock units exposed in and characteristic of these physiographic regions is given in figure 4, and the distribution of the rock units within the basin is shown on the geologic map (fig. 2). The rock units and their physiographic regions are as follows:

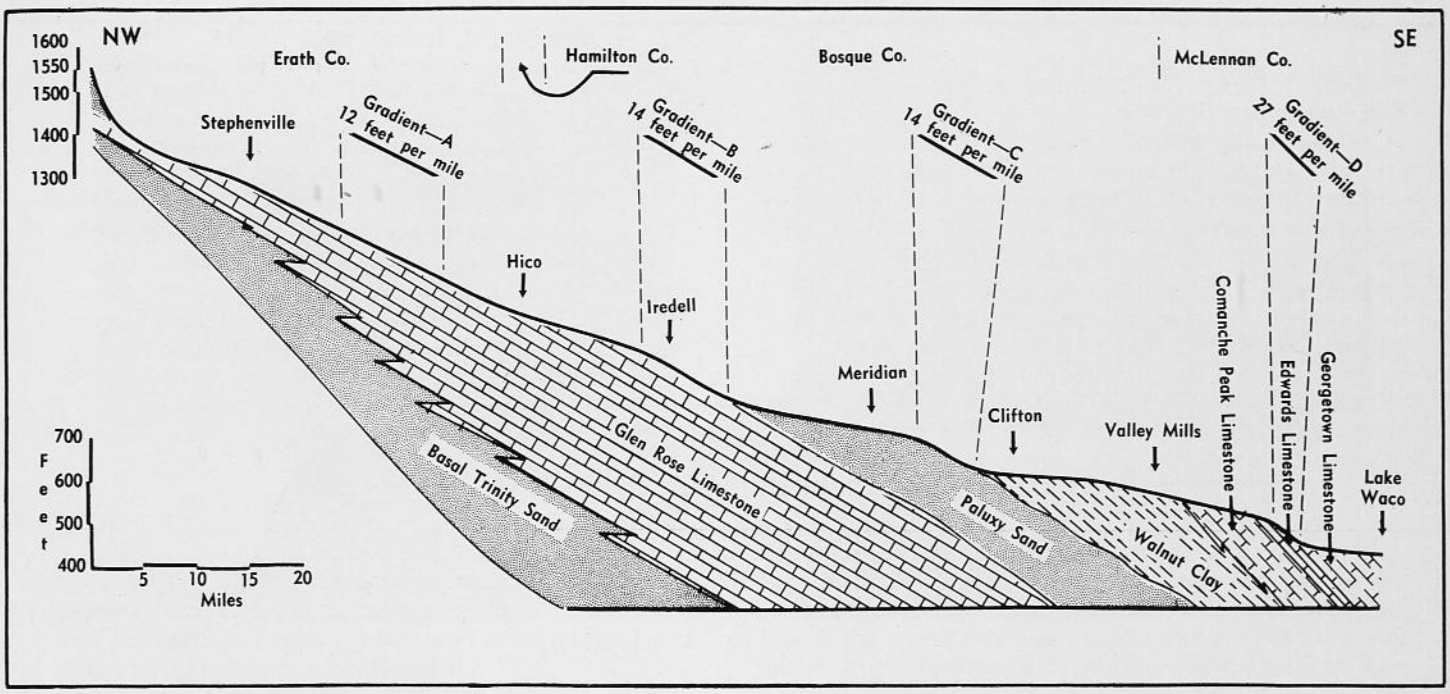


Fig. 3. Longitudinal profile of the North Bosque River. Gradients: A,B,C,D consequent to local lithologic dip. Average gradient of the North Bosque River 9.3 feet per mile.

ROCK GROUPS	PHYSIOGRAPHIC REGIONS
Georgetown Formation	Washita Prairie
Edwards Limestone Comanche Peak Limestone Walnut Clay	Lampasas Cut Plain
Paluxy Sand	Paluxy Cross-Timbers
Glen Rose Limestone	Glen Rose Prairie

SURFACE DEPOSITS

Deposits of Recent alluvium distributed along the North Bosque River valley and its major tributaries occupy a relatively small part of the basin (fig. 2). A terrace level of approximately 30 to 50 feet above low-water stage has the greatest distribution and prevails throughout most of the four physiographic regions. Terraces of the Glen Rose Prairie and Paluxy Cross-Timbers regions occur in patches somewhat disconnected from each other and show much less continuity than those of the Washita Prairie and Lampasas Cut Plain regions.

The unconsolidated deposits of alluvium and colluvium significantly reflect the characteristics of the rock units from which they were derived (fig. 4). All terrace deposits of the North Bosque River system are composed chiefly of limestone gravels and fossil remains. The only silicious material is the quartz sand-size material derived from the Paluxy Formation.

Soils of the Catalpa series are dominant on the surface deposits of the North Bosque watershed. These soils are dark to light grayish-brown clay loam and vary in thickness from zero to thirty inches (Soils Manual-Texas). Where these soils are not actively cultivated, the mesquite tree is prominant as the characteristic vegetational cover.

The Catalpa series soils are extremely fertile. Even though the bottomlands supporting these soils are occasionally flooded, they are highly favorable for crop production. Cotton, corn, and sorghums are the most extensively cultivated crops.

WASHITA PRAIRIE

Physiography

The Washita Prairie occupies the extreme downstream portion of the North Bosque watershed. Because of the limited areal extent within the North Bosque basin and relative sparsity of drainage channels, the Washita Prairie is the least important of the four physiographic regions of the North Bosque watershed.

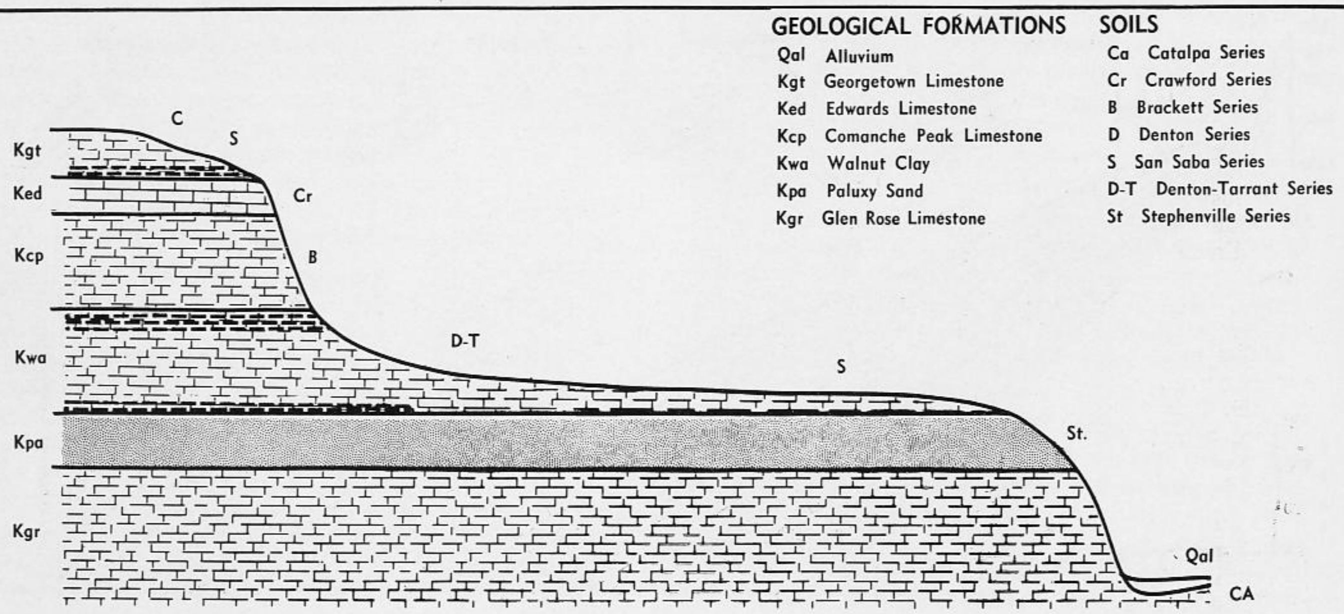
The general appearance of the Washita Prairie is that of an uplifted prairie in which the uplands are poorly dissected. The differential weathering of the clays of the Del Rio Formation and alternating marl and limestone beds of the Georgetown Formation give the Washita Prairie a characteristic topography of rolling hills and flat uplands (fig. 5). Rounded benches are prominent where relatively resistant limestone beds crop out. Relief is low, generally only in tens of feet.

Stream channels in the Washita Prairie are relatively far apart and are distinguished by V-shaped cross-sectional profiles. Much of the area is in broad, relatively flat divides. The hillslopes and valley walls have a distinct upward convexity.

Soils

Over most of the North Bosque watershed, soils of the Washita Prairie are derived from limestones and shales, yielding variation categorized under Crawford and San Saba soil series.

The limestone soils are dark reddish-brown stony clays ranging in thickness from 0 to 30 inches. The shale-derived soils are characterized by 0 to 54 inches



SYSTEM	FORMATION	DESCRIPTION	SOILS
QUATERNARY	Alluvium	Chiefly limestone gravels and fossil fragments. Silicious material: sand-sized quartz grains from the Paluxy Formation and chert fragments from the Edwards Formation.	Catalpa. Soils developed on floodplains of streams draining calcareous upland soils. 0" - 60".
CRETACEOUS	Georgetown Limestone	Thin wavy-bedded and nodular limestone beds interbedded with silty, calcareous shales and clays. Rounded limestone benches and receding clay zones characterize topography. Springs and seeps numerous wherever outcrop area is large.	Crawford. Dark reddish-brown stony clay soils. 0" - 30". San Saba. Dark gray granular clay soils. 0" - 54".
	Edwards Limestone	Massively bedded limestone with alternating marl beds and gray-to-white massive reef limestone. Forms resistant ledges on the crest-slopes and controls the topography of the Lampasas Cut Plain. The principal perennial aquifer of this area.	Crawford. Accumulation of noncalcareous residual material derived from the overlying Georgetown Formation and the Edwards Formation. 0" - 30".
	Comanche Peak Limestone	Chalky nodular fossiliferous limestone in fairly massive beds. Forms steep mid-slopes of the Lampasas Cut Plain. Weathers rapidly and is seldom found without the overlying protective Edwards Limestone cap.	Brackett. Light-colored calcareous lithosols which form on chalky limestones and marls with slopes greater than 5%. 0" - 12".
	Walnut Clay	Composed of alternating clays, nodular marly limestones, and massive shell beds. Occupies the lower slopes and valley floors of the Lampasas Cut Plain. Massive shell beds form rounded topographic benches.	Denton-Tarrant. Calcareous granular soils developed on moderately sloping areas and dark grayish-brown clays developed on hard limestones.
	Paluxy Sand	Composed of uncemented friable fine- to medium-sized quartz sand. Easily disaggregates and contributes abundant sediments to the North Bosque System. Streams lose water to the Paluxy Formation causing channels to become choked with sediment.	Stephenville. Soils with friable sandy clay loam and sandy clay subsoils. 0" - 40".
	Glen Rose Limestone	Composed of thin- to medium-bedded hard limestone beds alternating with marly limestone beds. The benched topography developed by the differential weathering of alternating limestone and marl beds forms gentle convex hillslopes in the Glen Rose Prairie.	Denton-Tarrant. Similar to Walnut Clay soils. Calcareous lithosols of the Tarrant series develop on resistant limestone beds, and soils of the Denton series form on marl beds.

Fig. 4. Lithologies of the North Bosque watershed.

Fig. 5. Washita Prairie.

Fig. 6. Lampasas Cut Plain.

of dark gray granular clay (Soils Manual—Texas). A thick vegetational cover of short grasses such as buffalo and gramas, tall bunch grasses, and scattered live oaks characterize both these soil types.

The Crawford and San Saba soil series are moderately fertile and are suited for cultivation of small grains, cotton, sorghums, and corn. However, the Washita Prairie soils of the North Bosque watershed are uncultivated and used almost exclusively for grazing purposes.

LAMPASAS CUT PLAIN

Physiography

The Lampasas Cut Plain is located upstream adjacent to the Washita Prairie and occupies the middle portion of the North Bosque watershed. Geomorphically, the Lampasas Cut Plain is the largest and thus the most important of the four physiographic regions represented in the North Bosque watershed.

The Lampasas Cut Plain is a highly dissected plain (fig. 6) with well integrated drainage channels (fig. 8). Broad, flat basin divides and interfluvial hills are capped by the resistant Edwards Limestone, with an overlying cover of Kiamichi Shale on the larger upland (over ¼ mile wide areas). The less resistant Comanche Peak Limestone forms the steep concave slopes below the Edwards cap, and the Walnut Clay is exposed on the lower slopes and valley floors.

Valleys of the Lampasas Cut Plain are broad, well developed features occupied by amply integrated systems of drainage channels. Occasional rounded benches, maintained by relatively resistant oyster beds in the Walnut Clay, give these valleys the appearance of gently rolling prairies. Local relief between the flat-topped, steep-sloped basin divides and broad, flat valley floors is 150 to 200 feet.

The Lampasas Cut Plain ". . . is so intimately related to and dependent upon the occurrence and erosion of one geologic formation—the Edwards limestone—that it is difficult to describe it without bearing in mind the vast extent of this formation. . . ." (Hill, 1902, p. 78). The characteristic hillslope topography of the Lampasas Cut Plain is chiefly a result of the physical and hydraulic properties of the Edwards Formation.

Because of the physical resistance to weathering of the Edwards Limestone prominent ledges are formed and maintained where this formation is exposed on crests and slopes of the divides and interfluvial hills of the Lampasas Cut Plain. A significant aspect of the weathering characteristics of this formation, its hydraulic character, may be equally important in the maintenance of these prominent ledges.

The Edwards Formation acts as a perennial aquifer accepting water from rainfall on the highlands and contributing water to springs and seeps which form the wellsprings of the North Bosque drainage system. Field observations indicate that essentially all these springs and seeps are located in the base of the Edwards Formation. Sapping at the base of the Edwards Formation removes support from beneath the overlying ledge, through the weathering and erosion of the softer Comanche Peak Limestone and Walnut Clay (fig. 7).

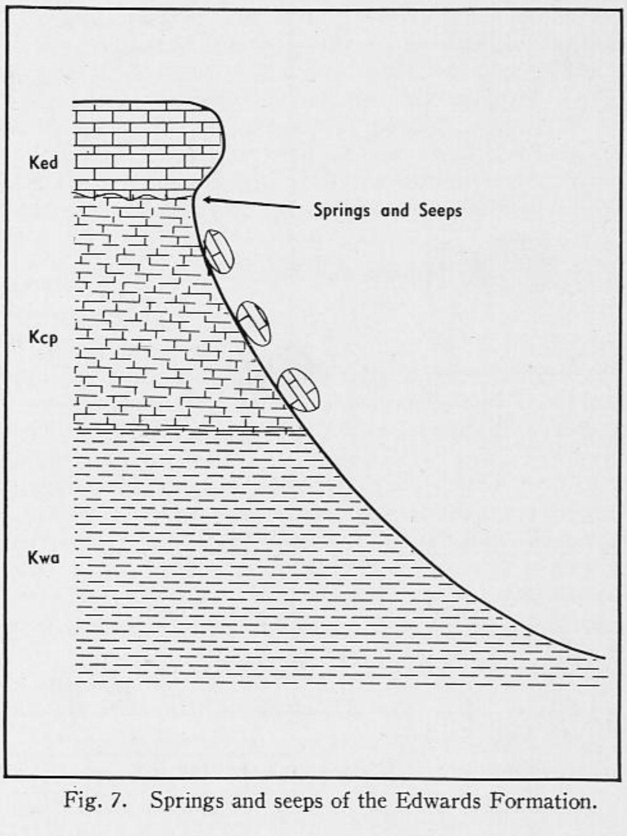


Fig. 7. Springs and seeps of the Edwards Formation.

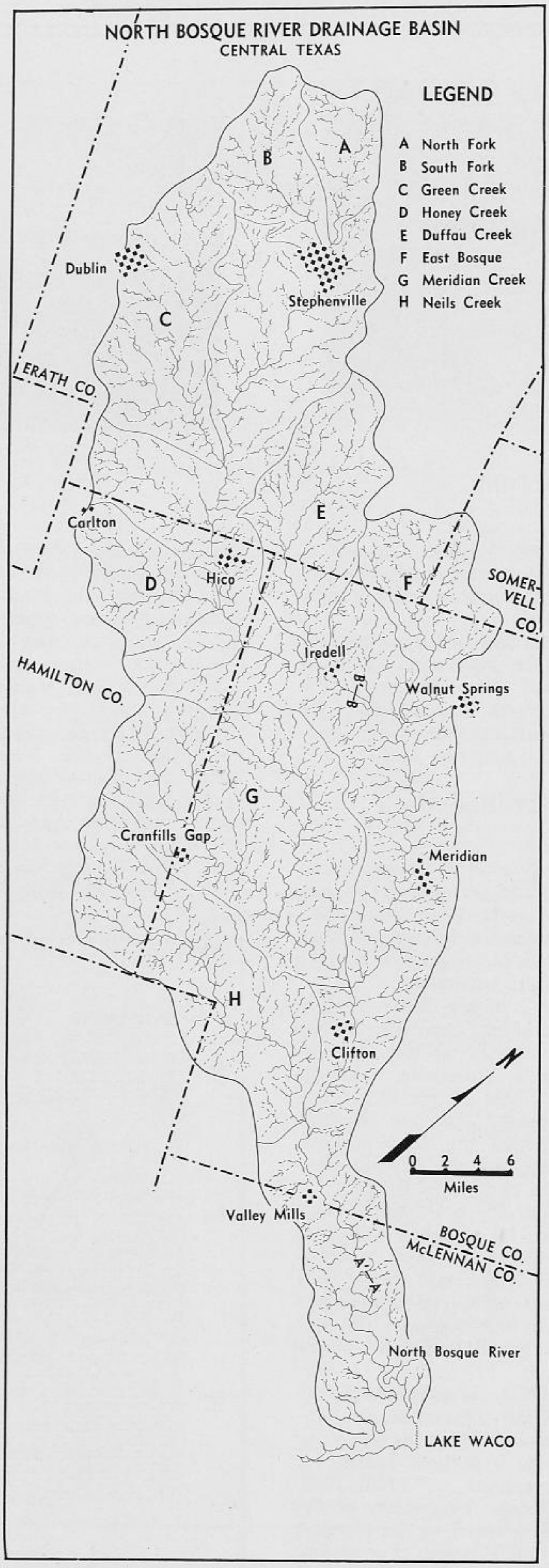


Fig. 8. Location and drainage map of the North Bosque watershed.

As sapping continues beneath the Edwards Limestone, prominent overhangs are formed, which subsequently fail, scattering blocks of Edwards debris over the lower slopes and valley walls.

The position of the spring line insures that weathering and erosion are constantly active on the Comanche Peak midslopes and Walnut footslopes, but on the Edwards crest slopes, it is active only during periods of precipitation and overland flow.

SOILS

Soils of the Lampasas Cut Plain show remarkable correlation with the overlying geologic formations.

Soils developed on the Edwards Formation, the Crawford series, are apparently the product of accumulation of non-calcareous residual material derived from the overlying Kiamichi Shale. Crawford soils range up to 30 inches in thickness and support a variety of native grasses and small trees such as bluestem and gramas, Texas wintergrass, buffalo grass, live oak, and post oak (Brown, 1963). However, wherever overgrazing has occurred, the juniper tree is normally the only vegetational cover.

In the North Bosque watershed Crawford soils of the Edwards Formation are chiefly shallow phase and unsuitable for cultivation. About 80 percent of the area is used for poor grazing land and only 20 percent for cultivation of small plots of cotton, small grains, sorghums, and corn.

The poorly developed Brackett soil series develops on the Comanche Peak Formation. These light-colored calcareous lithosols form on soft, chalky limestone and marl and usually occur on slopes steeper than 5 percent. The development of arid microclimates on the steep mid-slopes, due to moisture loss by runoff, retards soil formation (usually limiting the soil thickness to less than 12 inches) and limits plant cover. The most characteristic vegetation occuring on Comanche Peak soils is the Spanish or Texas oak tree and a scattering of bluestem grasses (Brown, 1963).

The poor Brackett soils in the North Bosque watershed are never cultivated and frequently have very little vegetational cover other than a few scattered Spanish oak trees. This area is used chiefly as pasturage for sheep and goats.

Mature soils of the San Saba and Denton series develop in thickness up to 54 inches on the gentle slopes of the Walnut Clay (Soils Manual—Texas). A thick vegetational cover consisting of a wide variety of grasses and scattered groves of live oak trees characterize the soils of the Walnut Formation.

Approximately one half to two thirds of the area covered by the soils of the Walnut Formation in the North Bosque watershed are cultivated and used for growing cotton, sorghums, small grain, and corn. These soils are quite productive and therefore highly prized as farmlands.

PALUXY CROSS-TIMBERS

PHYSIOGRAPHY

The Paluxy Cross-Timbers is located in an area extending from the middle portion of the North Bosque watershed to the headwaters of the basin.

The outcrop area of the Paluxy Sand forms the physiographic region called the Paluxy Cross-Timbers.

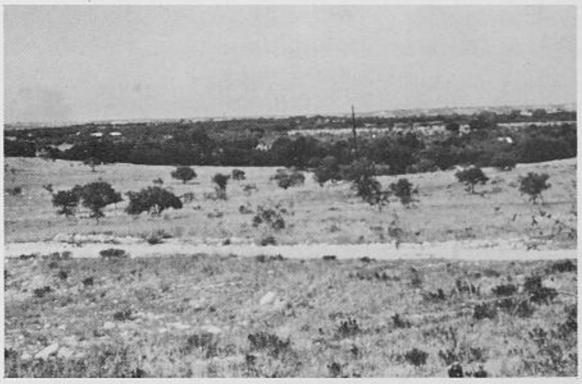


Fig. 9. Paluxy Cross-Timbers.

The friable sands of the Paluxy Formation readily disaggregate, resulting in topography characterized by gentle slopes and gently rolling hills (fig. 9) occasionally capped by thin marl or oyster beds of the overlying Walnut Formation. Intrabasinal relief is measured in tens of feet, and in the Paluxy Cross-Timbers basin divides are low and indistinct.

Streams of the Paluxy Cross-Timbers tend to lose water to the porous sand bed causing stream channels to become choked by sand. As a result, stream channels are broad and indistinct throughout the region.

SOILS

Soils of the Windthorst series developed in the Paluxy Cross-Timbers are the accumulation products of fine-grained siliceous detritus from the underlying sand strata mixed with colluvial clays derived from the overlying Walnut Formation.

These light-brown to reddish-brown soils range up to 38 inches in thickness and support a fairly heavy vegetational cover of stunted post-oak, live-oak, coarse bunch grass, and short (buffalo) grass (Soils Manual—Texas). Approximately half the Paluxy Cross-Timbers soils are cultivated for peanuts, peaches, sorghums, corn, and cotton. In places considerable areas formerly cultivated have been retired, due to lowered productivity induced by exhaustive production and erosion.

GLEN ROSE PRAIRIE

PHYSIOGRAPHY

The Glen Rose Prairie occupies the central portion of the upper half of the North Bosque watershed. It consists of rolling, gently sloped hills and conspicuous topographic benches (fig. 10) developed in the outcrop area of the Glen Rose Limestone. Differential weathering of the alternating limestone and marly clay beds of the Glen Rose Formation has produced a "typical Glen Rose" benched topography. The marly clay beds erode to form gentle convex slopes and resistant limestone beds, support benches, and cap hills.

Basin divides of the Glen Rose Prairie are broad, flat surfaces with relatively steep convex hillslopes (fig. 11). Relief between divides and valley floors ranges from a few feet to 100 feet.

Drainage patterns are well defined and dendritic (fig. 8), and valleys tend to be narrow and precipitous with steep gradients.

Fig. 10. Glen Rose Prairie.

Fig. 11. Glen Rose hillslopes.

Soils

Soils developed in the Glen Rose Prairie are similar to those of the Walnut Clay. The Denton series normally occurs up to 34 inches thick on the gentle slopes underlain by marl and clay beds and the shallow-phase (less than 6 inches thick) Denton and Denton-Tarrant complex on the resistant limestone benches (Soils Manuel—Texas).

A moderate cover of prairie grasses is supported by these soils. The chief use of the Glen Rose Prairie soils is for pasture land. Occasional small areas have been cultivated, mainly in oats and wheat.

SEDIMENT SOURCES

Topography of the North Bosque watershed is almost entirely the product of fluviatile dissection of horizontally bedded marine limestones, shales, and sands. The erosional products of this dissection, both physical and chemical, are carried to the North Bosque River and out of the region by running water. While the mechanics of erosion and transport of sediment by water are everywhere essentially the same, the place or type of erosion is dependent upon the topographic position and material cohesion of the eroding surface or bank.

Three major types of erosion are responsible for the sediment being transported in the North Bosque watershed—sheet erosion, gully erosion, and streambank cutting. Of these, sheet erosion is the major sediment producer in the North Bosque watershed, while gully erosion is confined mainly to the Lampasas Cut Plain, and streambank cutting is found only in the Lampasas Cut Plain and Paluxy Cross-Timbers regions. Rates of erosion may be expressed in terms of sediment yield per square mile per year, to form a basis of comparison between drainage areas.

Sheet Erosion

Sheet erosion is the removal of soil and weathered rock material by surface flow not concentrated in well-defined channels. Sheet erosion generally approaches a maximum in areas where bedrock is at or near the surface on relatively steep hillslopes and may increase markedly where weathered mantle is thick.

In the basins of the Paluxy Cross-Timbers and Glen Rose Prairie regions sheet erosion is at a maximum (Hadley and Schumm, 1961), and produces annual sedimentation rates of approximately 2.0 acre-feet per square mile of drainage basin area (Manford, 1959, p. 33). (Equivalent to 0.095 centimeter per year, if distributed evenly over the Paluxy Cross-Timbers and Glen Rose Prairie.)

In sedimentation rate studies conducted by the Soil Conservation Service in the Green Creek watershed (fig. 8-C) sediment yields were calculated to be: 97 percent from sheet erosion, 1 percent from modern gullies, and 2 percent from channel erosion. Average annual yield of sediment per square mile is 1.21 acre-feet (Soil Conservation Service, 1954). This amount is equivalent to 0.058 centimeter per year, if distributed evenly over the Green Creek watershed.

Gully Erosion

Sediment contribution from gully erosion in the North Bosque watershed is minimal. Gullies now being cut are limited mainly to local areas on the footslopes and alluvial valley floors of the Lampasas Cut Plain. However, gully trenches are of importance to the overall sediment yield of the North Bosque watershed in that locally they form efficient channels for transporting material derived from sheet erosion active on the upland areas.

Annual sedimentation rates from sheet and gully erosion in the Lampasas Cut Plain range from 0.72 (Brune, 1956) to 0.35 (Manford, 1959) acre-feet per square mile of drainage basin area. This amount is equivalent to 0.012 to 0.034 centimeter per year, if distributed evenly over the Lampasas Cut Plain.

Streambank Erosion

Valley floors of the major tributary streams in the North Bosque watershed contain alluvial deposits eroded from upland areas. These deposits are subjected to erosion where stream shifting or widening causes undercutting of the alluvial banks.

Principal valleys of the Lampasas Cut Plain have broad, alluvial floors on which streams are free to meander. However, in areas of the Glen Rose Prairie, stream channels are entrenched in bedrock and lateral shifting is of minor importance.

Appreciable sediment contributions from bankcutting occur only where recent alluvial cutbanks are exposed to stream action. Generally, these conditions are only local in extent, occurring principally in the Lampasas Cut Plain and Paluxy Cross-Timbers areas.

GEOCHEMISTRY

GENERAL CONSIDERATIONS

Water which runs off the land and drains into the North Bosque River frequently carries with it large quantities of sediment in suspension. In addition to materials carried in suspension, quantities of material are also carried in solution in both surface and ground water which flows into the stream. It is this latter solution load which is most often ignored.

The quantity of material removed in this process of "solvent denudation," as it is sometimes called, can be quite large. Computations based on records of surface-water quality for the 1950 water year published by the U.S. Geological Survey (Water-Supply Papers 1186-1189) show that from 70 to 86 tons of soluble matter were carried on the average from each square mile of drainage area of the James River above Richmond, Virginia; the Iowa River above Iowa City, Iowa; the Colorado River above Grand Canyon, Arizona; and the Similkameen River above Oroville, Washington. Higher rates were observed for certain streams draining limestone terraines in humid areas, and lower rates are typical of certain streams in the Great Plains and in arid regions. A rate of solvent denudation of 80 tons per square mile per year is roughly equivalent to lowering of the land surface by one foot in each 20,000 years by this process (Hem, 1959).

In order to apply concepts of geochemistry to the hydrologic regime of the North Bosque River, it is necessary to understand the relations among the various components of the system—the chemical character of the water, the mineralogy of the environment, and the circulation of the water. A consideration of the principal hydro-chemical processes may be helpful in clarifying some of these relationships.

1. Wind blowing over the ocean carries sodium, chloride, and other substances landward;
2. as the water vapor condenses, nitrogen, oxygen, and carbon dioxide of the atmosphere dissolve and are taken to the ground in rain and snow;
3. additional carbon dioxide dissolves as water percolates through soil rich in organic matter;
4. minerals dissolve and release many cations and anions;
5. sulfide minerals oxidize to provide sulfate and some other constituents;
6. cations in the solution are exchanged for those in the soil and rocks;
7. sulfate in solution is bacterially reduced and carbon dioxide is generated;
8. minerals are precipitated as solubility products are exceeded; and
9. the water is returned to the atmosphere by evaporation or transpiration leaving behind the chemical products, or the water returns to the ocean as streamflow or groundwater discharge, carrying dissolved and suspended matter with it (Davis *et al.*, 1959).

This simplified description of the hydro-chemical cycle covers only the most important processes. It is emphasized that most of the reactions shown may be reversed if the chemical or physical environment of the solution changes. This is especially true for reactions involving carbon dioxide, carbonic acid, and the carbonates. This is because of the instability of the compounds formed, the ease with which carbon dioxide passes in and out of solution, and the complex part played by organisms in the carbon cycle.

A mineral sampling program was undertaken in the North Bosque watershed to determine approximate rates of solvent denudation of this basin.

SURFACE WATER OF THE NORTH BOSQUE WATERSHED

SAMPLING AND ANALYSIS

Samples of surface water of the North Bosque watershed were collected at five locations (fig. 8). Four of these locations were selected to show the dependence of the chemical character of the water on the varied outcropping rocks. An additional sample location (#3) was chosen to determine the chemical contribution of Meridian Creek, one of the major tributaries of the North Bosque River.

Sample Locations

Location 1 At the downstream edge of the outcropping Glen Rose Formation. Most of the headwaters of the North Bosque watershed flow over the Paluxy Sand and Glen Rose Formation to this point.

Location 2 Near the downstream edge of the outcropping Paulxy Sand.

Location 3 Near the mouth of Meridian Creek.

The waters of Meridian Creek originate in the Edwards Limestone and flow over Comanche Peak Limestone, Walnut Clay, and a small area of Paluxy Sand before flowing into the North Bosque River.

Location 4 Near the downstream edge of the Walnut Clay.

Location 5 At the mouth of the North Bosque River, at Lake Waco. The outcropping rocks in this area are the Del Rio and Georgetown formations. However, because of the limited number of tributaries of the North Bosque watershed supported on these formations (fig. 2), it is unlikely that this area contributes greatly to the chemical composition of the waters of the North Bosque watershed.

Water analyses were determined by titration with approximate indicators (Appendix). Concentrations of the following ions were determined:

Calcium	Bicarbonate
Magnesium	Carbonate
Iron	Chloride
Sulfate	

Calcium

Calcium is dissolved from almost all rocks, but the highest concentrations are usually found in waters that have been in contact with limestone, dolomite and gypsum. Most waters associated with granite or silicious sands contain less than 10 ppm (parts per million) of calcium; waters in areas where rocks are composed of dolomite and limestone contain from 30 to 100 ppm; and waters that have been in contact with gypsum lithologies may contain several hundred parts per million.

In the North Bosque watershed the principal sources of calcium are the limestones of the Glen Rose, Comanche Peak, and Edwards formations.

Magnesium

Magnesium is an important component of carbonate rocks, where it may occur as dolomite, the double carbonate with calcium, or as magnesite ($MgCO_3$). In the North Bosque watershed the principal source of magnesium is belived to be the Paluxy Formation and to a lesser extent the Edwards Formation, though dolomitic limestones also occur in the Glen Rose Formation.

Iron

The element iron (Fe) is one of the most abundant constituents of rocks and soils. It is more abundant in hydrolyzates than in resistates and precipitates. The principal source of iron in the North Bosque watershed is the Paluxy Formation. Iron, probably as pyrite or siderite, is a principal pigment of all the unweathered rocks in the area, and ferric iron as limonite characteristically stains weathered exposures buff or tan.

Sulfate

Sulfur occurs in water largely in the completely oxidized form (S^{+6}). Under some conditions, sulfur may be present as sulfide (S^{-2}), as in the form of dissolved hydrogen sulfide. However, surface waters subject to thorough oxidation are normally free from sulfide. In the North Bosque watershed organic marls of the Glen Rose Formation are considered to be the primary sources of sulfate, and water derived from the Glen Rose Limestone is typically high in both sulfate and sulfide.

Carbonate and Bicarbonate

In these analyses, alkalinity values are reported in terms of equivalent amounts of carbonate, bicarbonate, and hydroxide (if present). In general, because of the relative abundance of carbonate minerals, and because

Table 1. Analyses of water samples of the North Bosque watershed.

Sample Location	1		2		3		4		5	
	ppm	epm	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Calcium	45.6	2.28	63.2	3.16	12.4	0.62	80.0	4.00	76.0	3.80
Magnesium	19.2	1.60	12.0	1.00	0.4	0.03	13.4	1.12	4.8	0.40
Iron	----	----	----	----	----	----	----	----	----	----
Sulfate	----	----	----	----	<10.0	----	----	----	----	----
Bicarbonate	212.3	3.48	205.0	3.36	131.8	2.16	203.7	3.34	217.2	3.56
Carbonate	----	----	7.2	0.24	7.2	0.24	----	----	----	----
Chloride	100.0	2.82	60.0	1.69	40.0	1.13	60.0	1.69	40.0	1.13

carbon dioxide which enters into equilibrium with them in water solution is readily available, bicarbonate and carbonate are to be expected in most surface waters. The presence of hydroxide ions in natural water in amounts sufficient to affect the alkalinity determinations directly is very rare, unless the water is artificially contaminated (Hem, 1959). In the North Bosque watershed major sources of carbonate are the limestone of the Glen Rose, Comanche Peak, Edwards, and Walnut Clay formations. The Paluxy Sand is likewise cemented with $CaCO_3$, and *all* the shales are typically calcareous.

Although alkalinity data may suggest the presence of definite amounts of carbonate, bicarbonate, or hydroxide, the ions have not been directly determined as such, and the results may include the equivalent of all or part of such other anions which may hydrolize—silicate, phosphate, borate, and possibly fluoride (Hem, 1959).

The usual stream water has little apparent carbonate alkalinity and in theory should have a pH below 8.2 if it contains an appreciable amount of calcium. Generally, alkalinity reported as carbonate is present in amounts less than 10 ppm. In waters high in sodium, higher values are sometimes encountered, but concentrations over 50 ppm are extremely unusual (Hem, 1959).

CHLORIDE

In natural waters, chloride is the most widely distributed member of the halogen group. In dilute solutions it is present as dissociated chloride ions.

The most important source of chloride in natural waters is sedimentary rock, especially the evaporites. Chloride may be present in resistates as the result of inclusion of connate water, and its presence is to be expected in any incompletely leached deposit laid down under the sea or in a closed basin where chloride was present. The primary source of chloride in the North Bosque watershed is the Glen Rose Formation.

RESULTS OF WATER ANALYSES

Results of water analyses of surface water samples of the North Bosque watershed are presented in table 1. The equivalent parts per million of the various ions are diagrammatically illustrated in figure 12. The total concentration of the ions tested and the percentages of individual ions are presented in table 2.

One of the most obvious results of these analyses is the consistency of the total concentration of the ions tested over the entire North Bosque watershed. This consistency is probably due to the combination of similar lithology over the watershed and fairly uniform dilution of the surface waters by ground-water throughout the watershed.

Bicarbonate is the predominant ion in the water analyzed. The percentages range from 56.3 percent for sample #1 to 64.2 percent for sample #5. This consistent enrichment of bicarbonate ion is to be expected, considering the high concentration of calcium carbonate in the outcropping rocks of the North Bosque watershed.

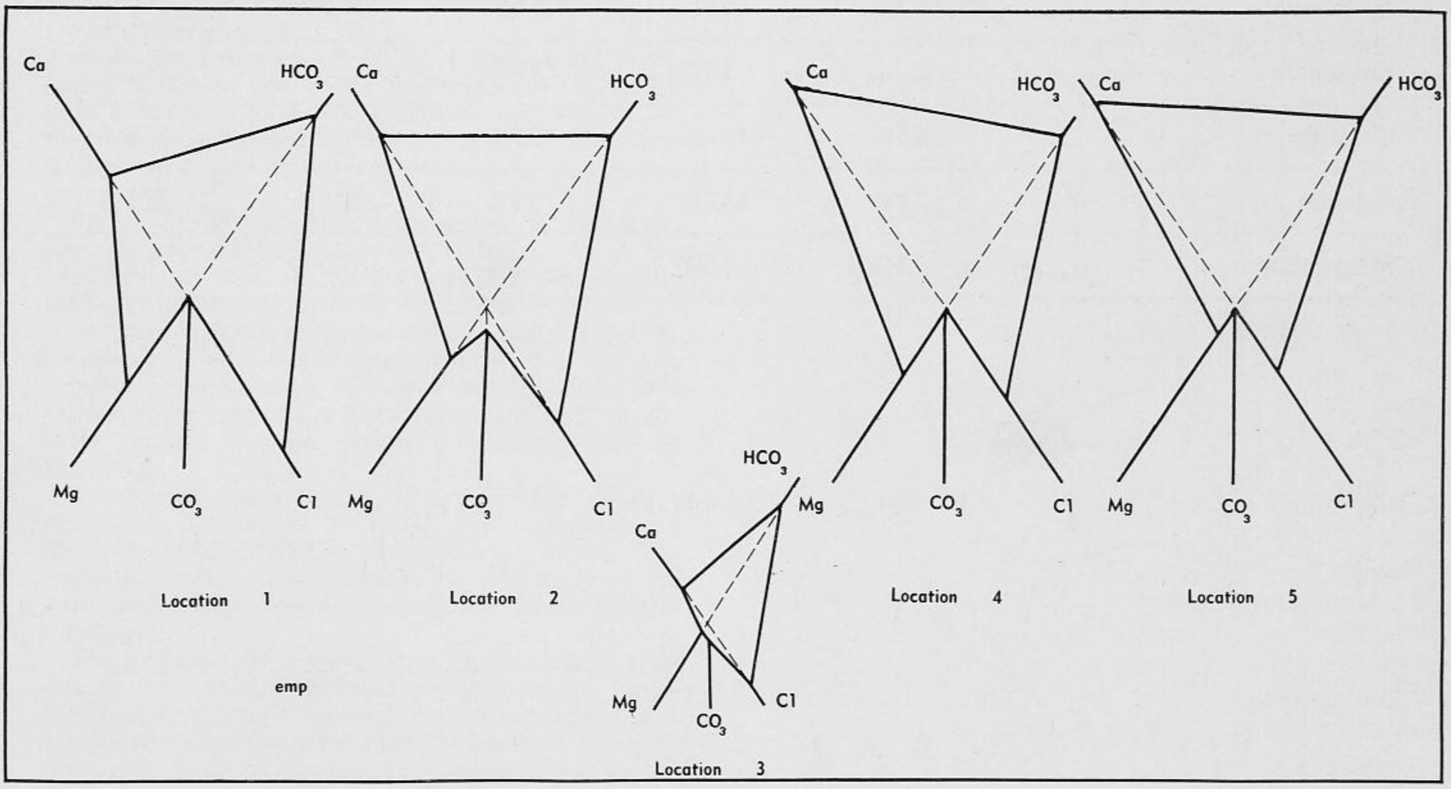


Fig. 12. Diagrammatic presentation of equivalent parts per million of the ions analyzed in the surface water of the North Bosque watershed.

The percentages of calcium range from 12.1 percent for sample #1 to 22.5 precent for sample #5. This enrichment of calcium is compatible with the enrichment of bicarbonate ions. As noted earlier, in the $CO_2 + H_2O + CaCO_3$ system so long as a sufficient supply of carbon dioxide is available, only the first dissociation step ($CaCO_3 + H^+ = Ca^{++} + HCO_3$) takes place and carbonate ions are not present in solution. Under these conditions calcium carbonate is attacked and calcium and bicarbonate ions are put into solution. The deficiency of carbonate ions in the waters analyzed also substantiates this interpretation.

The chloride anion is a substantial constituent of the waters of the North Bosque watershed. The percentages of chloride range from 26.5 percent for sample #1 to 11.8 percent for sample #5. The marine shales and marls which crop out in the North Bosque watershed are the principal sources of chloride in the surface waters. Saline marine waters, trapped in the strata of the North Bosque watershed since deposition, are also probable chloride sources. These waters are flushed out in areas where faults or fractures permit easy access of the formation waters to the land surface. Similar conditions in studies of streams of the southern Coast Ranges in California have been reported (Davis, 1961, p. 22).

In the water samples analyzed, the relative enrichment of chloride toward the headwaters of the North Bosque watershed can be attributed to the higher chloride concentration in the marls of the Glen Rose Formation than in the other exposed rocks of the watershed. The abundant fractures in the limestone of the Glen Rose Formation also afford avenues for the migration of trapped saline formation waters to the surface.

The Paluxy Sand is higher in magnesium-bearing minerals than the other exposed rocks of the North Bosque watershed, and because of its outcrop position in the watershed (fig. 2), it contributes magnesium only to the surface waters of the upper portion of the North Bosque watershed. The decrease in abundance of magnesium ions from the headwaters to the mouth of the North Bosque River is attributed to the geographic position of the Paluxy Sand.

In terms of landscape modification, the dissolved solids present in the samples, if representative of average stream flow of 235 cfs, would result in removal of approximately 83,000 tons of solids per year from the North Bosque watershed and lowering of the landscape —by solvent action alone—by one foot in 25,000 years.

Table 2. Total concentration of ions tested and percentages of individual ions.

Sample	1	2	3	4	5
Total Concentration—ppm	377.23	347.51	192.54	357.33	338.00
Bicarbonate	56.3%	59.0%	68.6%	57.2%	64.2%
Carbonate	------	2.1%	3.8%	------	------
Chloride	26.5%	17.2%	20.9%	16.9%	11.8%
Calcium	12.1%	18.2%	6.5%	22.4%	22.5%
Magnesium	5.1%	3.5%	0.2%	3.5%	1.5%

BASIN GEOMORPHOLOGY

One of the earliest and most important quantitative studies of basin geometry was that of Horton (1945), who was able to show that simple geometric relations exist in a drainage basin between such parameters as steam order, number, length, and slope.

The principal utility of these values, as expounded by Horton, is in the comparison of basins and streams of different sizes—in different terrains. By these parameters, basin can be compared with basin for stage of development, stability of stream geometry, and effect of geology on geomorphic evolution.

In order to understand the geomorphology of the North Bosque watershed, it is essential to first understand the fundamental concepts and terminology used in geomorphology. Those terms necessary to this study are defined in the following section. Application of these terms and concepts, as related specifically to the North Bosque watershed, appears in subsequent sections.

Various characteristics of an area, from which a stream receives water, control factors which affect streamflow including, as the most important of these factors, *infiltration rate, evaporation rate,* and *basin geometry.* Of the geometric properties, streamflow is most directly related to *drainage area, stream length, channel frequency, basin shape,* and *basin relief.*

The *drainage area* of any basin may be defined as the surface area which contributes water to a channel or set of channels.

Basin shape directly affects the collection and distribution of stream flow within any watershed. Although it is difficult to numerically express the relation between basin shape and hydrology, several basin shape factors have been formulated for use in quantitative geomorphology.

Miller (1952) selected a dimensionless circularity ratio to express basin shape. Circularity, C, is the ratio of basin area, A_b, to the area of a circle having the same perimeter, A_c or $C = A_b/A_c$.

Schumm (1956) suggested an elongation ratio, E, for use as a basin shape factor. This factor is the ratio between d, the diameter of a circle with the same area as the basin, and L_m, the maximum length of the basin parallel to the principal drainage line, or $E=d/L_m$.

These basin shape factors, E and C, have shown a significant correlation to runoff for watersheds in the Appalachian plateau (Morisawa, 1962). The elongation ratio, E, was chosen for this study as the most useful basin shape factor in the North Bosque watershed.

The *drainage net* is the pattern of channels or tributaries and master streams in a drainage basin. Ideally, the drainage net includes all the minor rills which are definite watercourses. In practice, however, the visible detail of the mapped drainage net is dependent on the scale used to trace the drainage channels. Thus, the smaller the scale, the less detailed is the mapped representation of the drainage net.

Drainage density refers to the degree of channel development within a basin. Drainage density is the average length of streams within the basin per unit of basin area: $D_d = \frac{L}{A_d}$, where D_d is drainage density, L is the total length of the streams, and A_d is the area of the basin. Poorly drained basins have drainage densities as low as 0.73; well-drained basins may have drainage densities of 2.74, or four times as great (Horton, 1945 p. 283). Drainage density is most directly related to *infiltration capacity* of the soil or country rock and erosional resistance of the basin surface.

Stream order is a measure of the relative position of a stream in the hierarchy of tributaries. Using a map of a certain scale, the first-order streams are those which have no tributaries (fig. 13). The second-order streams are those which have as tributaries only first-order streams. In designating a second-order stream, however, it must extend headward to the tip of the longest tributary which drains into it. Third-order

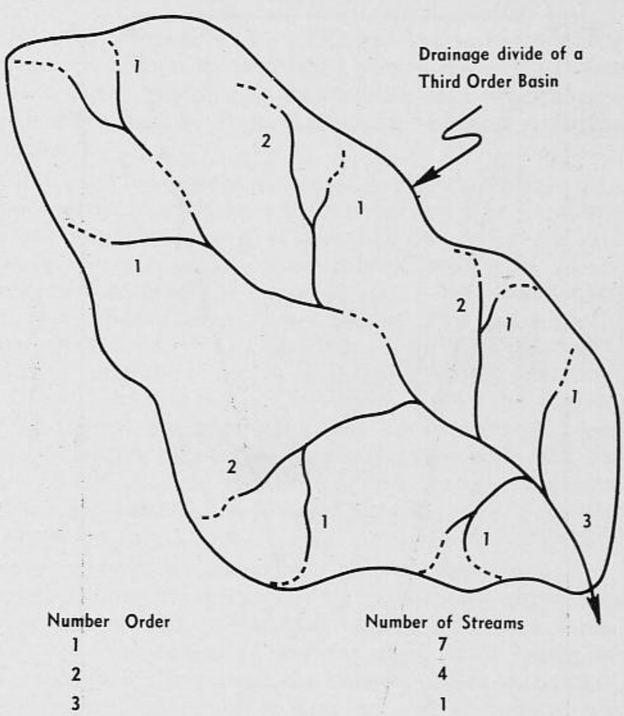


Fig. 13. Tributary order number, basin order, and number of streams of a given order.

streams receive as tributaries only first- and second-order streams and they are also considered to extend headward to the end of the longest tributary.

In this study, streams of the North Bosque watershed are classified under the system devised by Horton. First-order streams are the smallest unbranched tributaries visible on a map drawn to a scale of 1:126,720. On this basis the North Bosque River is a seventh-order stream and the North Bosque watershed becomes a seventh-order basin.

Horton (1945) also suggested that definite relations exist among stream order, number of streams, and stream length. Figure 14 illustrates the simple geometric relationships existing among these three variables. As shown, stream order varies as the log of stream length, as the log of number of streams, and as the log of basin area.

Bifurcation ratio is the ratio of the number of streams of a given order to the number of streams in the next lower order in any drainage basin. If numbers of streams of a given order are plotted against stream order for any basin, as in figure 14, the slope of the curve is the bifurcation ratio. Among many examples of basins in the United States the bifurcation ratio averages about 3.5—ranging from 2 for flat or rolling drainage basins to 3 or 4 for mountainous or highly dissected drainage basins (Horton, 1945, p. 290). For the North Bosque watershed, the range is 3.2 to 5.0.

Stream gradient is a vertical element in drainage-net geometry. Stream gradient is the average slope of a longitudinal stream profile. For selected first order basins in the North Bosque watershed, gradients were determined by survey. For higher order streams in the North Bosque watershed, gradients were obtained from topographic maps.

For any given basin there exists a relationship between stream gradient and stream order. In general, gradient decreases exponentially with increasing stream order. Gradient is also related to stream bed material and drainage area. The equation $S = 18(\frac{M}{A})\ 0.6$, where S is channel slope in feet/mile, M is median size of bed material, and A is drainage area in square miles, expresses this relationship for streams in Virginia and Maryland (Hack, 1957). Thus, for any given drainage area, gradient is directly proportional to the 0.6 power of the mean grain size of bed material. Conversely, for any given grain size of bed material, gradient is inversely proportional to the 0.6 power of the drainage area. This generalization was found to hold roughly true for drainage basins ranging from 0.12 to 370 square miles in Virginia and Maryland (*idem,* p. 61).

The relief ratio of a drainage basin as defined by Schumm (1956) is $R_n = H/L_b$, where H is the difference in elevation between the basin divide and stream mouth and L_b is the maximum basin length measured parallel to the principal drainage line. The relief ratio is a dimensionless number that approximates overall drainage basin surface slope. Relief ratio decreases with increasing basin order. If a basin is developed in litho-

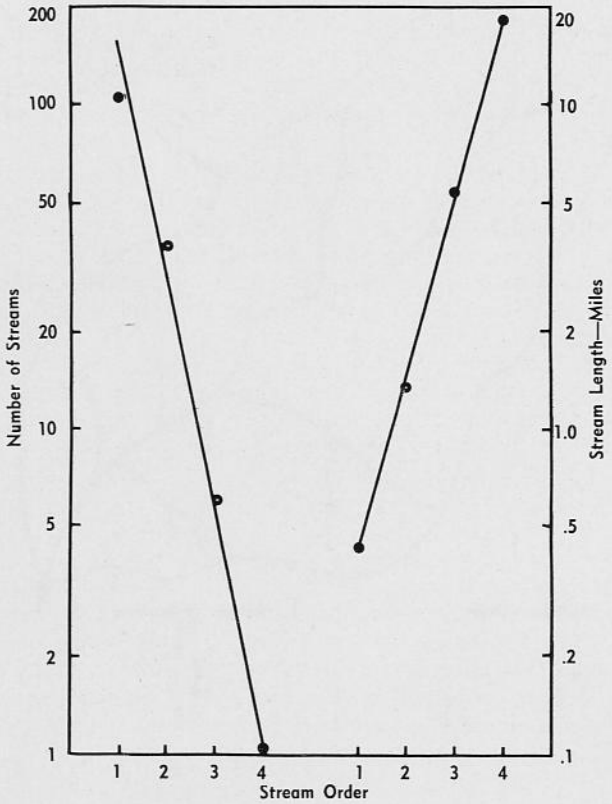


Fig. 14. Geometric relation between stream order, number, and area.

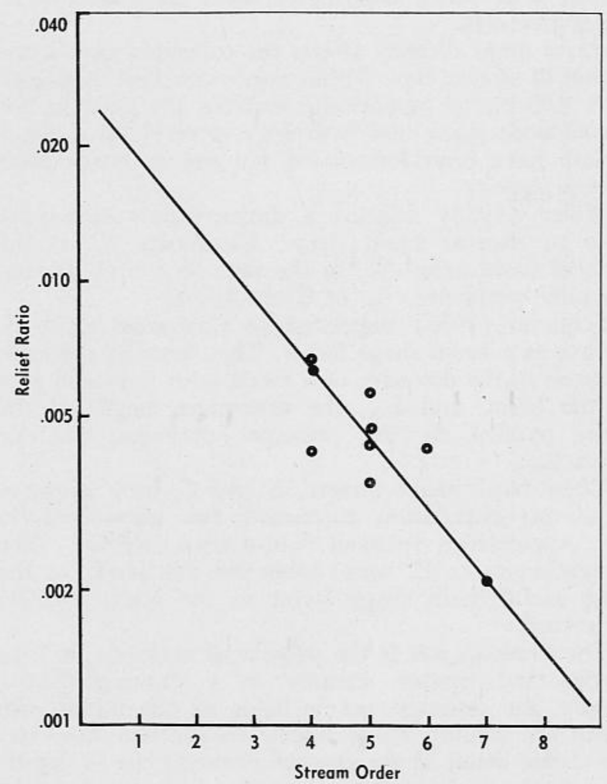


Fig. 15. Relationships between relief ratio and stream order.

logically homogeneous rock, the log of the relief ratio varies directly with stream order (fig. 15).

The relief ratio may prove a useful parameter in estimating sediment loss from small drainage basins. Schumm (1956, p. 613) found a direct relation between mean relief ratio and mean sediment loss for several areas in Utah, New Mexico, and Arizona (fig. 16).

Hypsometric analysis of a basin is a means of equating the stages of development of basins of various sizes. Hypsometric analysis, developed in its dimensionless form by Langbein (1947), yields a curve which shows by its shape the relative proportions of a basin which are occupied by divide lands, slopes, and valley floors. It thus permits comparison of basin with basin to show relative degree of maturity of the landscape.

The hypsometric curve for any basin is developed by assuming the basin to be bounded by vertical sides rising from a horizontal base plane which passes through the stream mouth. The relative height of any part of the basin is the ratio of height of the contour h at that point or for that area, to total basin height H. Relative area is the ratio of horizontal cross-sectional area a of the portion in question to the basin area A. The percentage hypsometric curve is a plot of the continuous function relating relative height y to relative area x (Strahler, 1957, p. 919), $y = f(x)$. Integration of this function—designated the ***hypsometric integral*** (*idem*, p. 1121)—between the limits of $y = 0$ and $y = 1.0$ gives the ratio of the landmass volume remaining with respect to the volume of the entire reference solid.

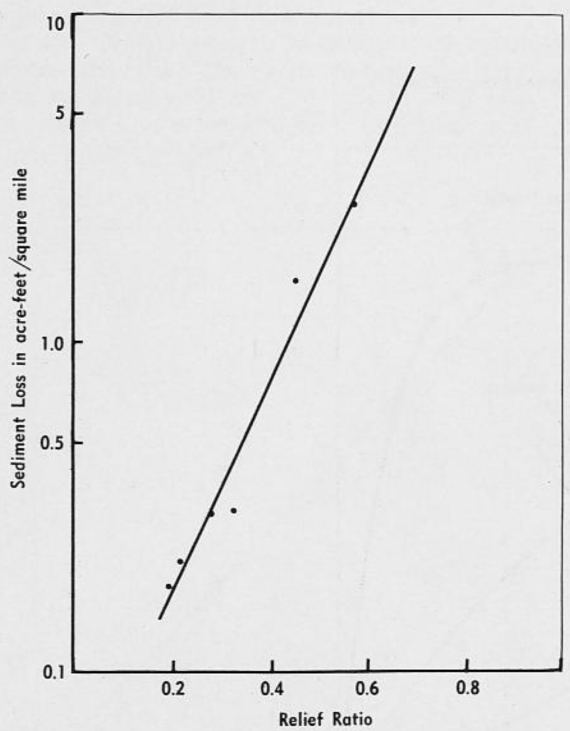


Fig. 16. Relationship between mean annual sediment loss and relief ratio.

The dimensionless character of the relative hypsometric curve makes it useful in comparison of basins. Significant values of the curve are the area below the curve, showing the relative amount of material removed from the basin; inflection points, indicating the relative level at which a change in slope occurs; and the degree of sinuosity of the curve, expressing the distribution of mass within the drainage basin.

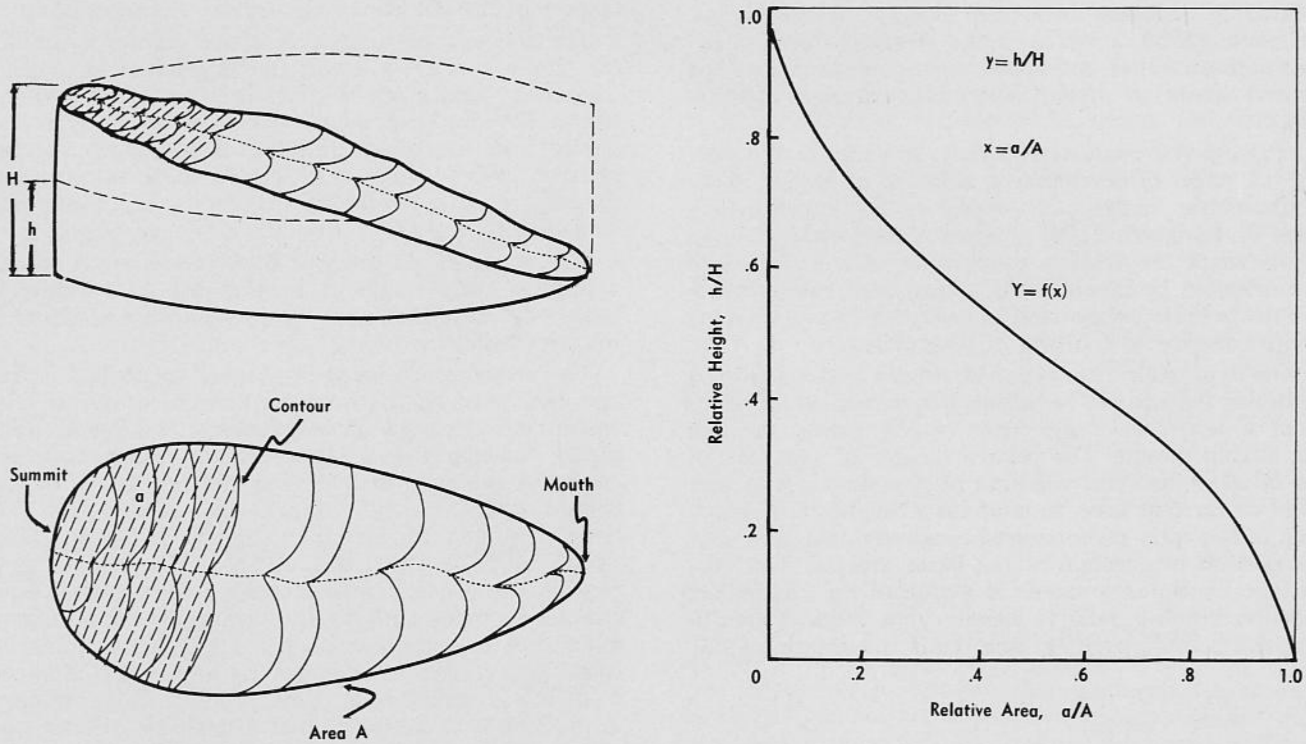
The shape of the relative hypsometric curve varies widely in early stages of development of a drainage basin (fig. 17). However, once equilibrium is attained, it varies little thereafter.

The relationships between channel length and drainage area show the correlations between erosional processes and drainage basin geometry. Figure 18 is a graph showing the relation between progressive increase in drainage area with increasing length of the highest order stream channel. The equation of this curve (fig. 18), for streams in the Shenandoah Valley (Hack, 1957, p. 63), is $L = 1.4\ A_d 0.6$, derived empirically, where L is the length of the highest order channel in miles and A_d the drainage area in square miles. For drainage basins in the northeastern United States the coefficient averages 1.4 and ranges between 1 and 2.5 (Leopold *et al.*, 1964, p. 145). This coefficient is the length of a stream that a drainage area of one square mile can support.

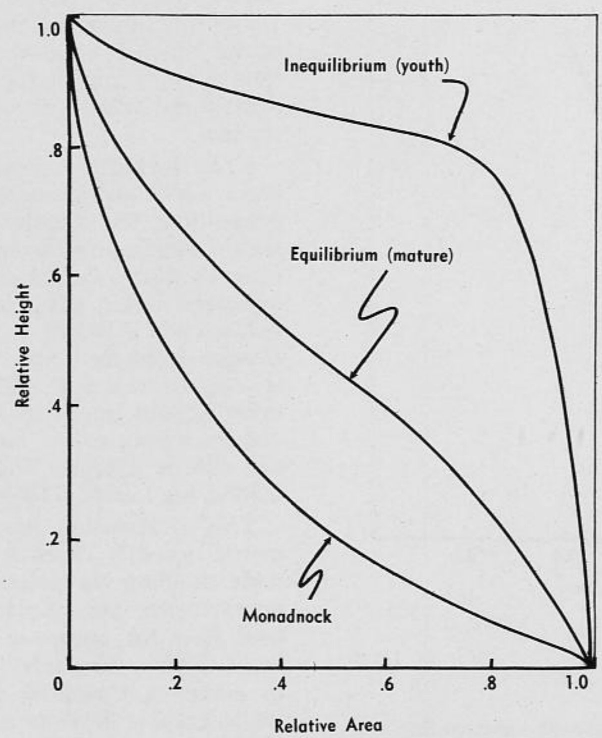
In this study it is believed that channel length-drainage area analysis in the North Bosque watershed is of greater significance if progressive increase in drainage area is related to *cumulative* channel length. Using this procedure, the coefficient for drainage basins of the North Bosque watershed ranges from 0.6 to 2.4; thus for this region for each square mile of drainage area, there will be from 0.6 to 2.4 miles of drainage channel.

If, as the basin expands through erosion, the average basin width and channel length increased in the same proportion, the length of the highest order channel should increase as the square root of basin area. However, as shown by the curve of figure 19, basin length increases faster than basin width. This relationship holds true for basins of all sizes (*idem*). In the North Bosque watershed, the ratio between length and area is: $\log Le = a + b \log Da$, where Le is the highest order stream length in miles and Da is drainage basin area in square miles. The proportionality constants for the North Bosque watershed are $a = 0.1778$, $b = 0.5882$, $\log Le = 0.1778 + 0.5882 \log Da$.

This relationship has value in indicating the geometric growth characteristic of drainage basins, in understanding the processes of channel formation and maintenance, and in establishing the length of overland flow for basins of various sizes. The length of overland flow affects both the amount of water required to exceed a threshold of erosion and to initiate the physiographic development of drainage basins (Horton, 1945).



Model nondimensional hypsometric curve



Erosional cycles

Fig. 17. Model nondimensional hypsometric curve and characteristic erosion cycle curves (*after* Strahler, 1957).

GEOMORPHIC ANALYSIS AND INTERPRETATION

INTRODUCTION

The initial step in this study of the North Bosque watershed was a morphological analysis of eight sub-basins (fig. 2, A through H) in order that the form elements of the basin landscape could be separated, described, and compared from sub-basin to sub-basin. The second step was an attempt to relate the topographic forms to the rates and intensities of denudational processes. Wherever possible these relationships for the North Bosque watershed are in the form of empirical equations, derived from observational data.

The primary objective of these geomorphic measurements is the selection of drainage-basin properties that have a high degree of correlation with runoff and sediment yield. If runoff and sediment yield data exist for a large number of drainage basins in the same region, statistically valid selections may be made. If, as in the North Bosque watershed, runoff and sediment yield are known for only a very limited number of small basins, evaluation of drainage-basin properties must be approached by different methods.

For the North Bosque watershed, morphological properties that show the greatest correlation with runoff and sediment yield are (1) stream frequency, (2) relief ratio, (3) channel gradient, (4) basin area, and (5) hypsometric properties.

SUB-BASINS

The purpose for selecting the eight sub-basins studied was twofold. First, these are the largest basins within the North Bosque watershed and therefore form convenient units of study. Second, these basins embrace all the physiographic provinces that are characterized by the different lithologies and soils of the North Bosque watershed (fig. 2).

The sub-basins range in size from 32.5 square miles (North Fork in the Paluxy Cross-Timbers) to 187 square miles (Meridian Creek in the Lampasas Cut Plain).

North Fork Basin—A

The North Fork basin (fig. 8) is the headward extension of the North Bosque River and occupies a basin area of 32.5 square miles. As shown in figure 2, the greatest part of the basin of the North Fork is underlain by the Paluxy Sand. Hard, macerated limestone ledges in the Walnut Clay form the low indistinct divides and upland areas of this basin. Basin topography consists of rolling hills which characterize the Cross-Timbers area. Relief is low, and the hard limestone ledges of the Walnut Clay form the only distinct topographic features.

Within this basin all the stream channels are drowned

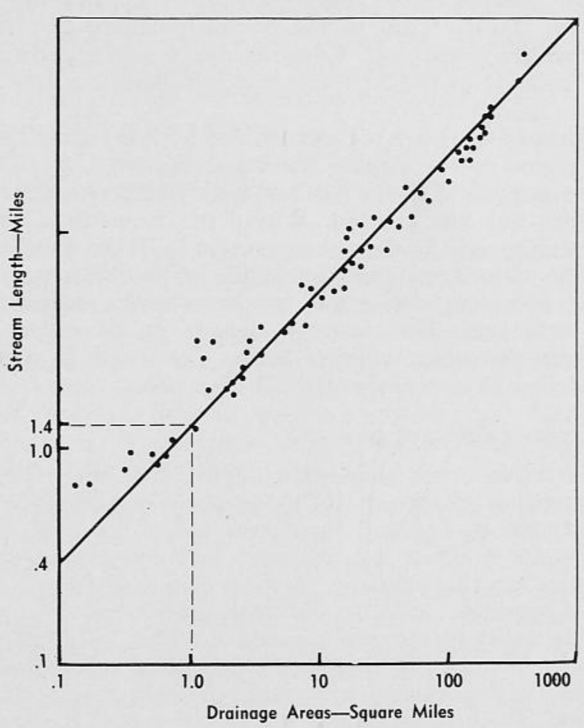


Fig. 18. Relationship of main channel length in miles to drainage area in square miles and length of overland flow in miles (*after* Hack, 1957).

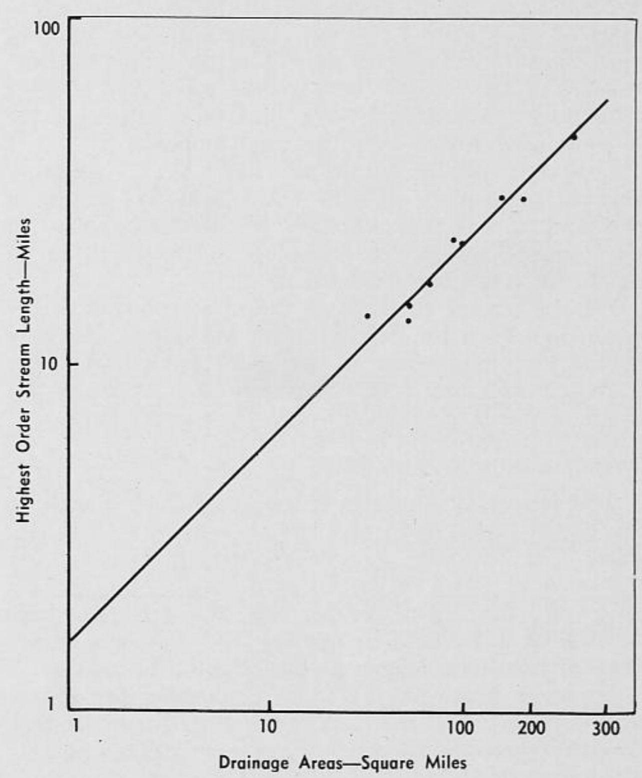


Fig. 19. Relationship between stream length and drainage area for the North Bosque watershed—log length=0.1778+0.5882 log area.

with sand eroded from the Paluxy Formation. The drainage density is 2.0 miles of channel length per square mile of basin. The length of overland flow is approximately 0.2 of a mile, a value fairly consistent throughout the eight basins studied. Most of the streams within this basin are intermittent, with flow persisting only during and immediately following periods of precipitation adequate to initiate overland flow.

South Fork Basin—B

The basin of the South Fork (fig. 8) is similar in size (50.1 square miles) and topography to that of the North Fork. As shown in figure 2 the Glen Rose Limestone occupies more of the South Fork basin, but the Paluxy Sand is still the dominant lithologic unit of the basin.

The hard limestone ledges of the Walnut Clay which occupy the indistinct basin upland maintain the only prominent physiographic features of the basin.

The South Fork basin is better drained than the North Fork basin for it has a drainage density value of 2.2 miles of channel per square mile of basin. The length of overland flow is the same as in the North Fork basin, approximately 0.2 of a mile, and most of the streams in this basin are also intermittent.

Green Creek Basin—C

The Green Creek basin (fig. 8) encompasses an area of 104.4 square miles. The three dominant lithologic units of the basin are Glen Rose Limestone which forms the valley floors, Paluxy Sand which forms the slopes leading to the uplands, and the hard limestone ledges of the Walnut Clay which support the drainage divides or uplands (fig. 2).

Basin topography is somewhat more distinctive than in the North and South Fork basins because of the benching effects of both the Glen Rose Limestone and Walnut Clay. In the lower part of the basin an escarpment of Glen Rose Limestone, approximately 100 feet high, rises above the flood plain. The low rolling hills developed on the Paluxy Sand extend upward to another escarpment supported by the limestone ledges of the Walnut Clay which form the basin uplands.

Drainage density within the basin is 2.3 miles of channel per square mile of basin, and the length of overland flow is approximately 0.2 of a mile. Most of the streams within the basin are intermittent, as in the North and South Fork basins.

All the stream channels in the upper portion of the basin, underlain by Paluxy Sand, are obscure because of the drowning effect of the sand eroded from the Paluxy Formation. A distinctive cultural feature of this basin is the large number of conservation dams.

Honey Creek Basin—D

The Honey Creek basin is topographically similar to the Green Creek basin and has an area of 49.5 square miles. The lithologic units characterizing this basin are the same as those of the Green Creek basin (fig. 2). However, the basin divides are less distinguishable because of a decrease in number and erosional resistance of limestone ledges in the Walnut Formation.

Drainage density is 1.8 miles of channel per square mile of basin, lower than any of the other basins studied. Length of overland flow, 0.3 of a mile, is correspondingly greater for this basin.

The number of streams occupying this basin is proportionately fewer compared with the other seven basins. Basin topography is of low relief and landforms are indistinct except in the lower portion of the basin where the Glen Rose Limestone crops out. Streams are generally intermittent except where a small quantity of perennial flow may be derived from the Glen Rose Limestone.

Duffau Creek Basin—E

Duffau Creek basin, occupying an area of 90.5 square miles (fig. 8), contains the same outcropping rock types as the other basins except that the uplands on the northeastern divide are formed by Comanche Peak and Edwards limestones (fig. 2).

The topography of the lower and middle portions of the basin is similar to that of Honey Creek and Green Creek basins. The Comanche Peak and Edwards limestones occupy an upland area of more than 100 feet above the valley floor.

The drainage channels developed on the Walnut Clay and Paluxy Sand are obscure and characteristically choked with sediments. Drainage density is 2.2 miles of channel per square mile of basin, and length of overland flow is approximately 0.2 of a mile.

The northwestern drainage divide of Duffau Creek basin (fig. 2), separating Paluxy River drainage and North Bosque River drainage, is low and may be breached in the geologically near future. Some of the streams which head in Edwards Limestone flow essentially all year round, drying up only in periods of extended drought.

East Bosque Basin—F

The East Bosque basin, which includes an area of 68.3 square miles (fig. 8), contains the same formations as Duffau Creek basin with the exception of the Glen Rose Limestone (fig. 2). Paluxy Sand is found in the lower portions of the basin, marls and limestone ledges of the Walnut Clay in the middle portions, and the Comanche Peak and Edwards limestones constitute the uplands of the northern and northwestern divides of the basin.

Most of the basin is characterized by low rolling hills developed on the Paluxy Sand and Walnut Clay. The limestone ledges of the Walnut Clay weather to clearly defined but low benches. Where the Edwards Limestone is present in the uplands, relief is 100 to 150 feet.

The majority of stream channels of the basin are almost indistinguishable due to characteristic drowning by sediments. The drainage density is 2.1 miles of channel per square mile of basin. The length of overland flow is approximately 0.2 of a mile.

Meridian Creek Basin—G

Meridian Creek basin is the largest basin studied, encompassing an area of 187.3 square miles (fig. 8). As illustrated in figure 2 the broad valley floors of the basin are occupied by Walnut Clay, and the upland divides are characterized by steep slopes developed on the Comanche Peak and Edwards limestones.

The valley topography consists of rolling hills, underlain by Walnut Clay, with very little local relief. Basin valleys are extremely wide and relatively flat for this region. The Edwards Limestone caps almost all the basin divides and many of the intrabasinal divides (fig. 2).

Seeps and springs originating in the Edwards Limestone contribute water to the tributaries of this basin.

Even in the hottest, dryest periods during this study flow was continuous in streams of second order, and occasionally in streams of first order, originating in the Edwards Limestone.

Because of the lack of flow from streams draining other lithologies of the North Bosque watershed, it is concluded that the Edwards Formation is the major perennial aquifer contributing to the North Bosque drainage system.

The divides on the western periphery of the basin are low and indistinct, and the Edwards Limestone is absent from the divide lands (fig. 2). Because of this low topographic divide and other evidence which will be presented in the following section, it is postulated that the Meridian Creek basin is being reduced by diversion of basin flow into the Leon River drainage.

The drainage density of the Meridian Creek basin is 2.1 miles of channel per square mile of basin, and the length of overland flow is 0.2 of a mile.

NEILS CREEK BASIN—H

The Neils Creek basin, consisting of an area of 142.4 square miles (fig. 8), contains the same rock types as Meridian Creek basin (fig. 2). Topography is similar to that of Meridian Creek basin, although the valleys are not as wide and flat, and intrabasinal divides are less distinct. As in Meridian Creek basin, the Walnut Clay forms the low hills within the valleys, and the Edwards Limestone caps the broad flat uplands.

Because of the presence of Edwards Limestone in the extensive divide lands, this basin is one of the major contributors of perennial flow of the North Bosque system. The drainage density is 1.8 miles of channel per square mile of basin, and the length of overland flow is correspondingly higher, 0.3 of a mile.

One of the most conspicuous geomorphic features of the North Bosque watershed is illustrated in Neils Creek and Meridian Creek basins. This is the uniform slope recession exhibited by the Walnut Clay and Comanche Peak Limestone, where the Edwards Limestone caps the divides. This uniformity of slope suggests that these geomorphic slopes are in equilibrium with the erosional agents acting upon them.

This is, furthermore, an illustration of dynamic equilibrium in geomorphic evolution (Hack, 1960). Even though these features may be in different spatial positions through time, they will yet retain the same topographic characteristics.

QUANTITATIVE ANALYSIS AND INTERPRETATION

Each of the parameters listed in table 3 was obtained as described in the preceding section. These were considered in various combinations to identify possible correlations with erosional rates, sediment yield, and geologic control in the North Bosque watershed. Each of these parameters bears some relation to basin evolution, though the relationship is often subtle and may be difficult to explain.

DISCHARGE AND DRAINAGE AREA

The quanity of discharge is one of the most important factors controlling morphological development of a basin. However, for practical purposes, except where there are gaging stations that have been in operation for many years, this parameter cannot be measured. There are only five gaging stations in the area of study. Four of these are on the North Bosque River (at Stephenville, Hico, Clifton, and Valley Mills) and one on Green Creek.

Nevertheless, a conservative relation has been found to exist in other regions between drainage area and discharge (Hack, 1957, p. 54). Enlargement of drainage area is accompanied by proportional increase in discharge. This relationship is shown by the curve of figure 20, in which the average annual discharge determined at all the gaging stations in the North Bosque watershed and the Hog Creek basin (on the southwestern periphery of the North Bosque watershed) is plotted against the drainage area above these stations. The curve shows that within limits the average annual discharge in cubic feet per second is proportional to the drainage area, measured in square miles.

Two of the plots on the curve in figure 20 require further explanation. Hog Creek drains a basin occupied dominantly by the Edwards Limestone. Since, as this study has shown, this formation is the major perennial aquifer in this region, the high discharge rate to drainage area ratio for the Hog Creek basin is a product of the Edwards Limestone contributing water over an extensive area to the tributaries of this basin. The low ratio of discharge rate to drainage area for the Green Creek basin can be explained by the large number of conservation dams constructed in this basin, and by the high infiltration capacity of Paluxy Sand, which occupies much of the basin.

The relation shown in figure 20, is valid only for average annual discharge, which is probably not the most significant value of discharge controlling basin morphology. Significant departures from this conservative relationship may be found, especially in smaller basins. With these qualifications in mind, an empirical equation for the curve of figure 20 can be formulated and used to determine average annual discharges of the basins within the North Bosque watershed.

Where Q is the average annual discharge in cubic feet per second and D_a is the drainage area in square miles this equation would be:

$$\log Q = a + b \log D_a .$$

For the North Bosque watershed the proportionality constants have the values: $a = -0.7348$, $b = +1.0159$, giving an empirical equation of the form:

$$\log Q = -0.7348 + 1.0159 \log D_a .$$

TABLE 3. Geomorphic parameters and data of the North Bosque watershed.

Basins	Area (Miles)^2	Avg. Annual Discharge cfs	L Miles	Drainage Density $Dd=\frac{L}{A}$	Length of Overland Flow $lo=\frac{A}{2L}$ Miles	Order	Number of Streams Per Order	Avg. Length of Streams Lo Miles	Bifurcation Ratio rb Avg.	Stream Frequency $Fs=\frac{N}{A}$	Elongation Ratio $E=\frac{d}{Lm}$	Gradients For Highest Order Stream Feet/mile	Relief Ratio Lm/Total Relief	Hypsometric Integral	Avg. Annual Sed Losses Acre-feet/mi^2
A. North Fork	32.5	6.5	65.7	2.0	0.2	1 2 3 4 5	L_1= 62 L_2= 19 L_3= 2 L_4= 1 L_5= 1 L= 85	L_1= .34 L_2= 1.50 L_3= 3.10 L_4= 4.4 L_5=14.5	4.0	2.6	d= 6.4 Lm=12.4 E= 0.52	L_5=22.6	.0043	.63	0.95
B. South Fork	50.1	10.0	112.5	2.2	0.2	1 2 3 4 5	L_1= 96 L_2= 26 L_3= 10 L_4= 1 L_5= 1 L=134	L_1= .38 L_2= 1.01 L_3= 2.87 L_4= 6.7 L_5=14.2	4.3	2.7	d= 8.0 Lm=12.8 E= 0.63	L_5=26.5	.0050	.60	1.38
C. Green Creek	104.4	20.9	245.3	2.3	0.2	1 2 3 4 5 6	L_1=219 L_2= 37 L_3= 13 L_4= 5 L_5= 3 L_6= 1 L=278	L_1= .36 L_2= 1.63 L_3= 2.70 L_4= 5.70 L_5= 6.8 L_6=22.5	3.2	2.7	d=11.5 Lm=19.8 E= 0.58	L_6=22.2	.0042	.67	0.90
D. Honey Creek	49.5	9.9	75.3	1.5	0.3	1 2 3 4	L_1= 24 L_2= 5 L_3= 1 L_4= 1 L= 34	L_1= 1.63 L_2= 2.50 L_3= 5.60 L_4=13.3	3.8	0.7	d= 8.0 Lm=11.0 E= 0.73	L_4=30.8	.0057	.61	2.00
E. Duffau	90.5	18.1	200.0	2.2	0.2	1 2 3 4 5	L_1=141 L_2= 41 L_3= 10 L_4= 3 L_5= 1 L=196	L_1= .47 L_2= 1.15 L_3= 3.98 L_4= 7.9 L_5=23.5	3.7	2.2	d=10.7 Lm=19.8 E= 0.54	L_5=19.1	.0036	.52	0.66
F. East Bosque	68.3	13.7	145.0	2.1	0.2	1 2 3 4	L_1=106 L_2= 37 L_3= 6 L_4= 1 L=150	L_1= .43 L_2= 1.34 L_3= 5.32 L_4=17.8	5.0	2.2	d= 9.3 Lm=15.6 E= 0.60	L_4=30.9	.0059	.54	2.30
G. Meridian	187.3	37.5	392.4	2.09	0.2	1 2 3 4 5 6	L_1=196 L_2= 64 L_3= 17 L_4= 3 L_5= 1 L_6= 1 L=282	L_1= .66 L_2= 1.6 L_3= 4.2 L_4= 7.2 L_5=18.0 L_6=30.0	3.3	1.5	d=15.4 Lm=23.6 E= 0.65	L_5=21.7	.0041	.57	0.86
H. Neils	142.4	28.5	251.2	1.8	0.3	1 2 3 4	L_1=137 L_2= 38 L_3= 9 L_4= 1 L=185	L_1= .74 L_2= 1.70 L_3= 5.9 L_4=30.7	5.3	1.3	d=13.5 Lm=25.6 E= 0.57	L_4=21.1	.0041	.54	0.86

Basins	Area in Square Miles	Discharge in Cubic Feet Per Second
North Fork	32.5	6.5
South Fork	50.1	10.0
Green Creek	104.4	20.9
Honey Creek	49.5	9.9
Duffau Creek	90.5	18.1
East Bosque	68.3	13.7
Meridian Creek	187.3	37.5
Neils Creek	142.4	28.5

RELIEF RATIO

Relief ratios for the eight basins studied have values ranging from 0.0036 for Duffau Creek basin to 0.0059 for the East Bosque basin (table 3). Relief ratios, plotted against known sediment loss for areas within the North Bosque watershed, result in the curve shown in figure 21.

Because of the sparsity of data concerning sediment yield for this area, the curve shown is valid only within certain broad limits. Significant departures from this relationship are to be expected, particularly for large basins in varying geological environments.

An empirical equation based on the relationship between relief ratio and sediment yield illustrated in figure 21 can be formulated and used to determine annual sediment yield of basins within the North Bosque watershed. The empirical equation relating relief ratio to average annual sediment losses is:

$$\log Se = a + b\,Rr$$

where Se is the average annual sediment loss in acre-feet per square mile and Rr is the relief ratio.

The proportionality constants for this equation, that apply within the North Bosque watershed, are: $a = -1.0372$ and $b = 231.54$, giving an empirical equation of the form:

$$\log Se = -1.0372 + 231.54\,Rr$$

Basins	Average Annual Sediment Losses Acre-feet/Mile^2
North Fork	0.95
South Fork	1.38
Green Creek	0.90
Honey Creek	2.00
Duffau Creek	0.66
East Bosque	2.30
Meridian Creek	0.86
Neils Creek	0.86

LONG PROFILES

The close relation between the lithology of a basin and the form of the long profile of the highest order stream within that basin suggests that a state of dynamic equilibrium exists between the amount of relief and the form of the erosional channel on the one hand, and the resistance of the bedrock to the forces tending to break it up and remove it on the other. An analysis of a basin in terms of the long profile should show a direct relationship to the discharge (and indirectly to the sediment yield) of that basin.

The long profiles of the highest order streams for the eight basins studied are shown in figure 22 (#1) and figure 23 (#1). Mean gradients for these streams are given in table 3.

Although each of these profiles describes an entire

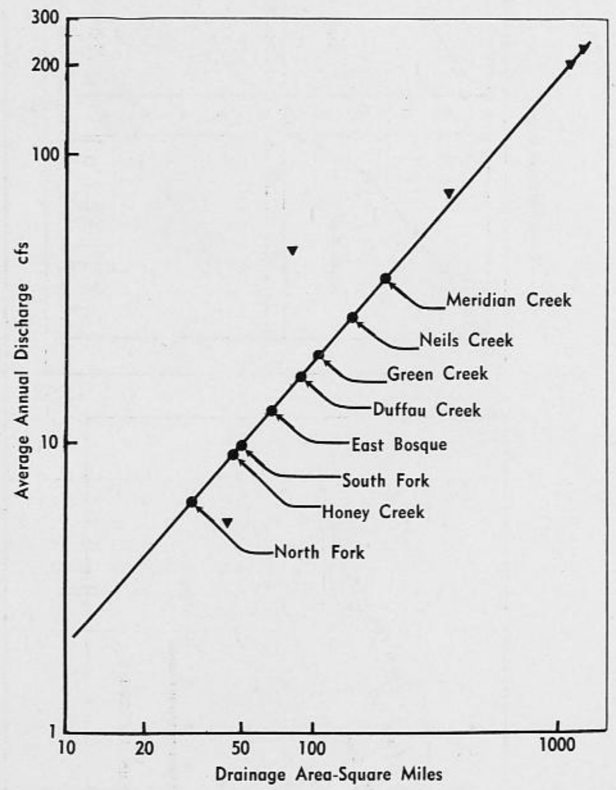


Fig. 20. Relationship between average annual discharge and drainage area for the North Bosque watershed.

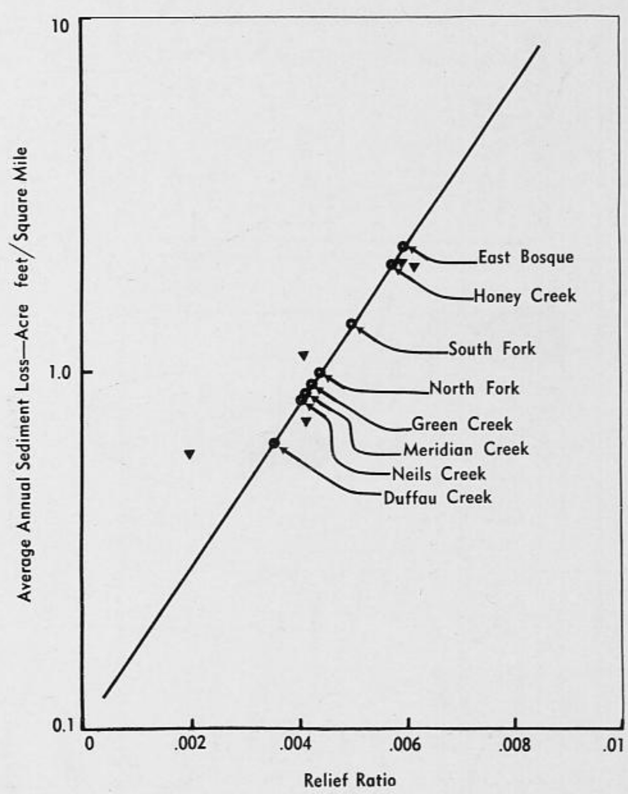


Fig. 21. Relationship between average annual sediment loss and relief ratio for the North Bosque watershed.

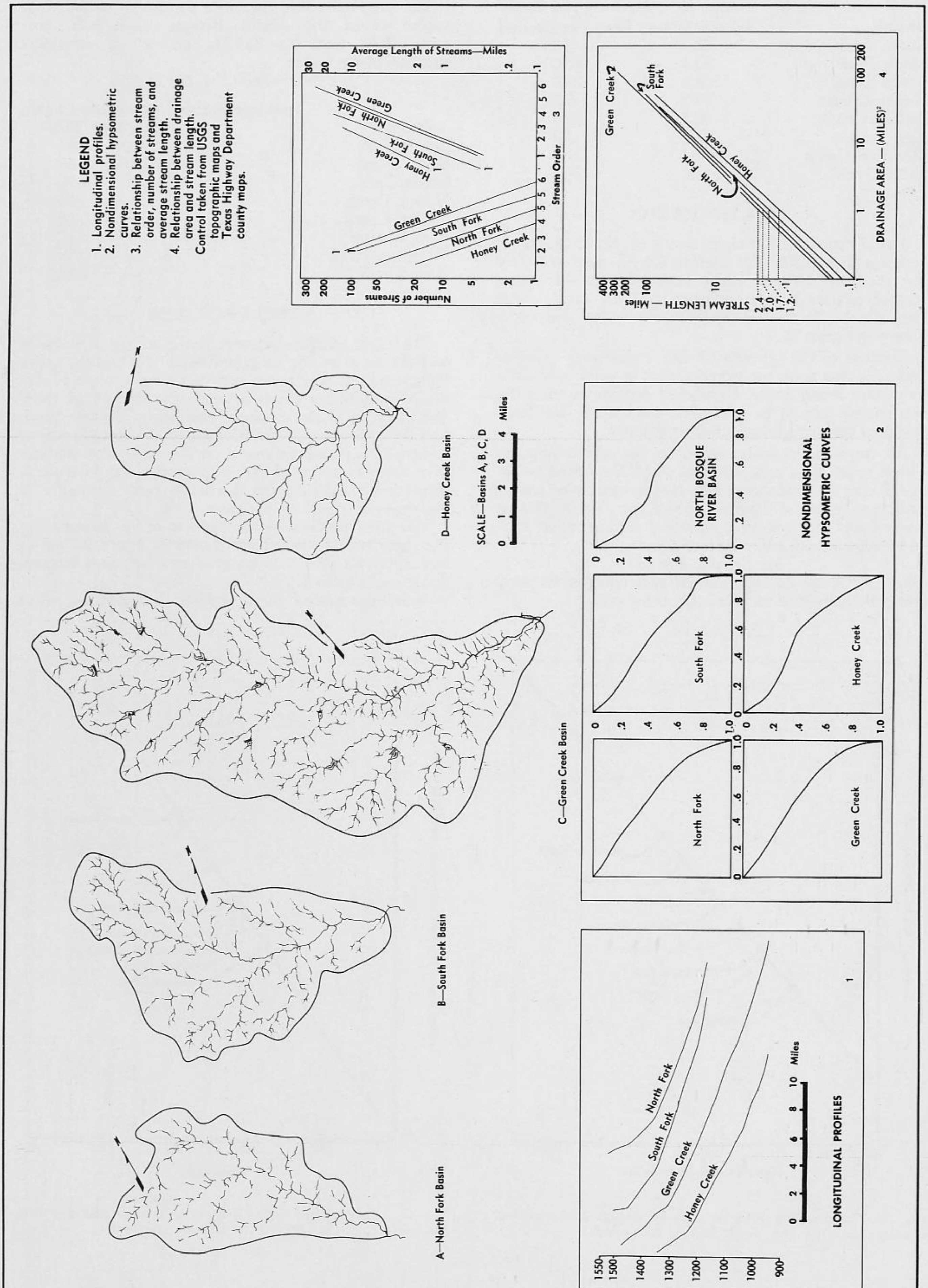


Fig. 22. Sub-basins of the North Bosque watershed.

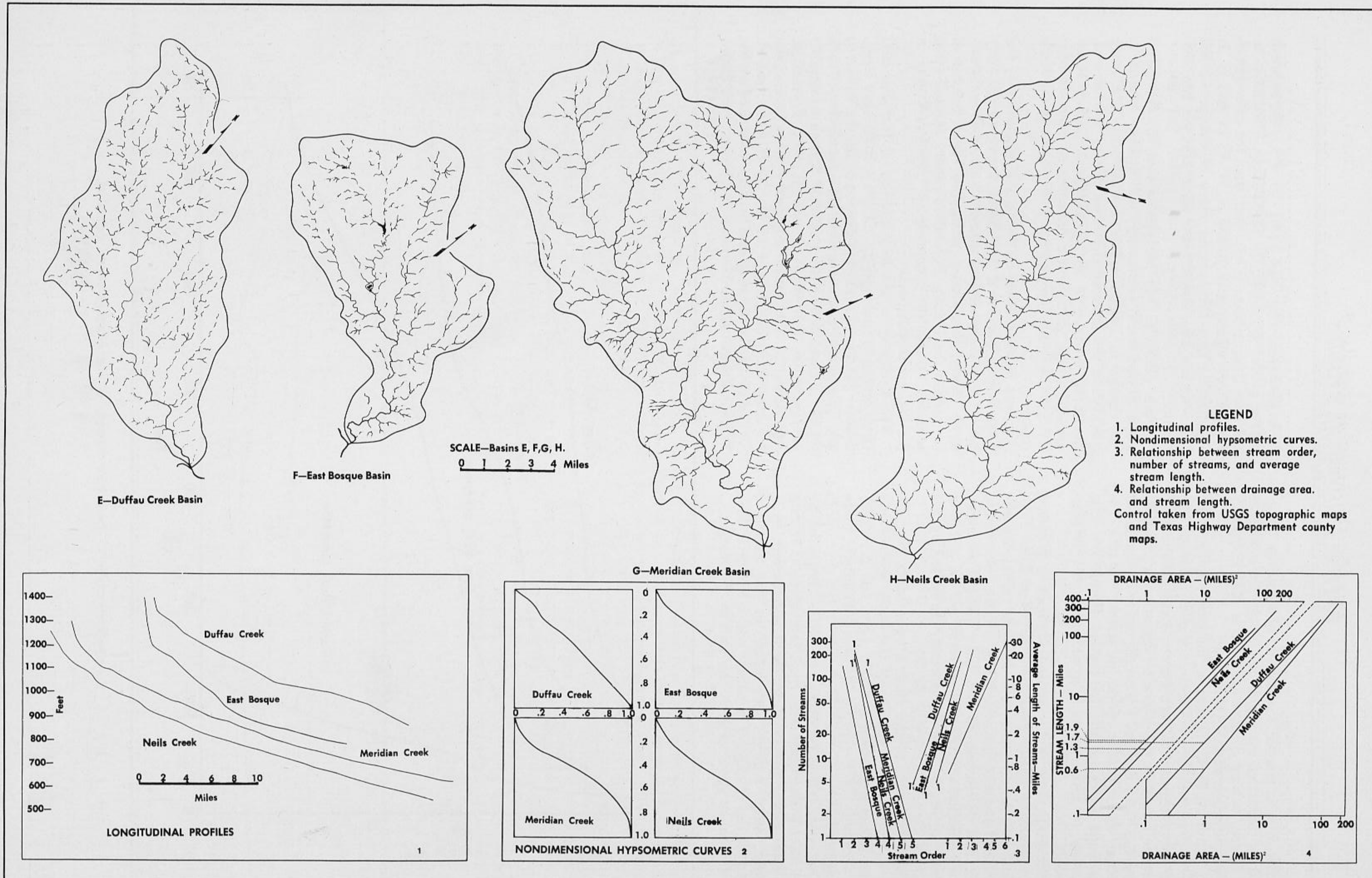


Fig. 23. Sub-basins of the North Bosque watershed.

channel, it is in essence a composite of segments dominated by distinctive lithologies. Each segment is a separate curve, having a particular slope and convexity or concavity determined by rock type.

In basins A, B, C, D, and E the outcropping rocks (fig. 2) dominate the profiles in a similar manner. The steep upper segment of each curve represents the hard limestone ledges of the Walnut Formation which constitute the basin divides. Following the first significant inflection in the profile curve, the second segment is a steep slope developed on the Paluxy Formation. The concavity of the first and second segments is pronounced.

The steep slope of the second segment is followed successively by flatter slopes on the Glen Rose Formation. The inflections in this segment reflect the differential resistance to weathering of the alternating marls and limestones of the Glen Rose Formation. These inflections give this segment of the curve a distinct convexity. This is especially exhibited by the profile of Duffau Creek (fig. 23, #1).

The long profile of the East Bosque basin (fig. 23, #1) varies from the profiles of the other seven study basins. Channel-gradient is higher (30.9 feet per mile) and concavity of the profile is correspondingly more pronounced.

The upper, steep concave segment is controlled by the Edwards and Comanche Peak formations. The first inflection in the profile is followed successively by a straight, steep segment developed on the limestone ledges in the Walnut Formation and a concave, flattened segment developed on the Paluxy Formation.

As illustrated (fig. 22,# 1; fig. 23, # 1), the segment of the profile developed on the Paluxy Formation in the East Bosque basin is less steep than the corresponding Paluxy segments of basins A, B, C, D, and E. It is probable that the varying rates of change in bed load particle size downstream have affected this difference.

Hack (1957, p. 74) has shown that the change of slope downstream (concavity) is directly related to the change in size of debris downstream. The more quickly the bed material decreases in size downstream, the more concave is the longitudinal profile. Conversely, where particle size increases or remains relatively fixed in size downstream, the profile has a small concavity.

In the upper reaches of the basin, tributaries of the East Bosque provide a continuous source of relatively large (¼ to 3 inches in diameter) fossil shell and limestone debris. In contrast, along the lower reaches of the stream the Paluxy Formation erodes as sand-sized particles, therefore producing a rapid decrease in particle size downstream.

The similarity of the long profiles of Meridian and Neils creeks is striking (fig. 23, #1). Both have steep, concave headward segments developed on the Edwards and Comanche Peak formations. The remainder of each profile is characterized by relatively flattened segments developed on the marls of the Walnut Formation. Inflections in the latter segment reflect occasional resistant limestone ledges in the Walnut Formation.

The similarity of the gentle profiles developed on the Walnut Formation in Meridian and Neils Creek basins

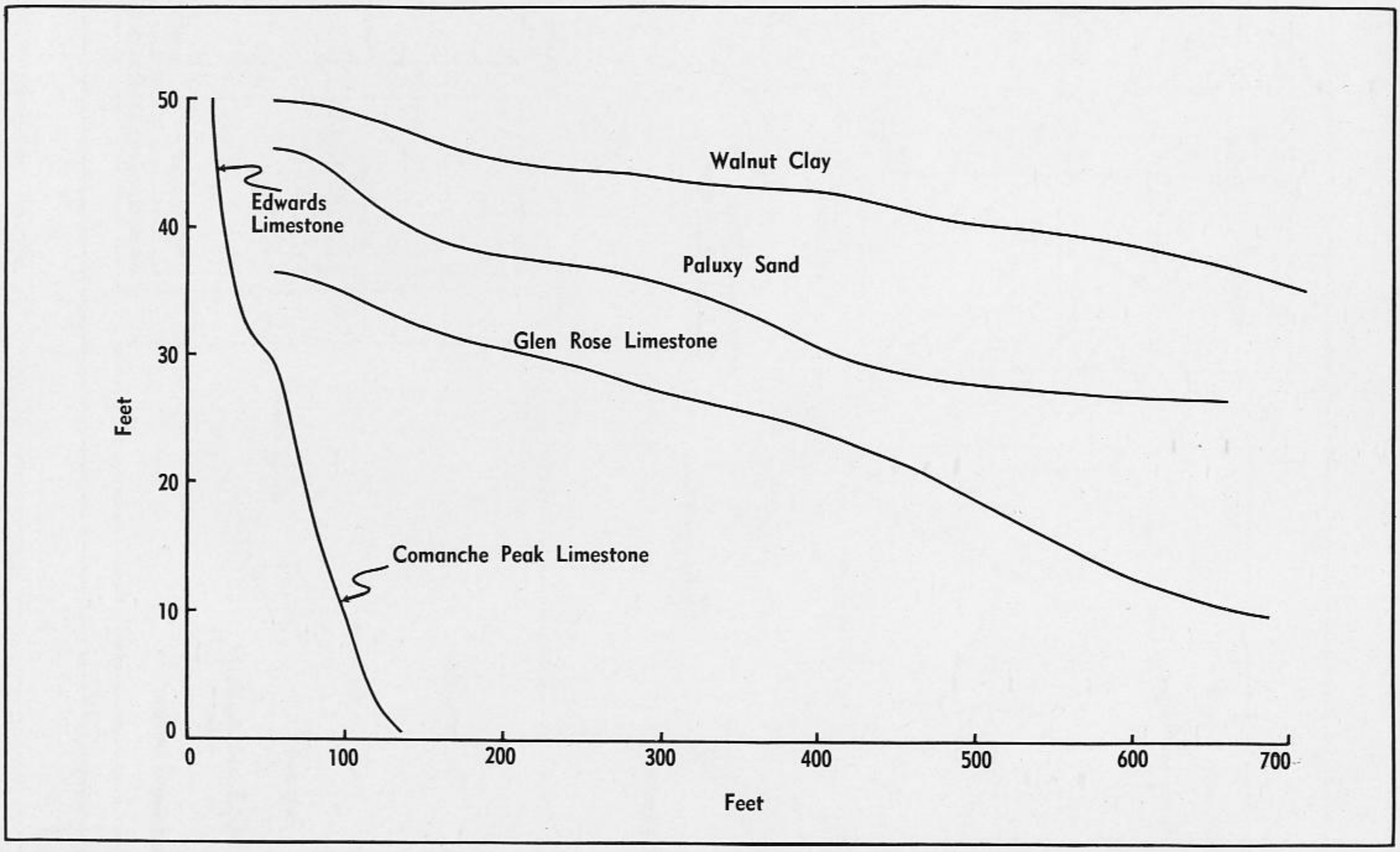


Fig. 24. Longitudinal profile of first-order streams of the North Bosque watershed.

indicates that this formation contributes a homogeneous sediment size throughout the lower segments of these basins.

In summary, the profiles of the highest order streams in basins A, B, C, D, and E show that steep, concave segments are developed on the Paluxy Formation and flatter, convex segments on the Glen Rose Formation. In the East Bosque basin the relative flatness of the long profile developed on the Paluxy Formation is directly related to the decrease in bedload particle size downstream. The relatively flat, straight profiles developed in the lower reaches of Meridian and Neils creeks is a function of the uniform sedment size eroded throughout the Walnut Formation.

The long profiles of first-order streams (fig. 24) developed on the various rock types outcropping in the North Bosque watershed exhibit the same relative shape and declivity as long profiles of the higher order streams previously discussed.

The profile of channels developed on the Edwards and Comanche Peak formations is extremely steep and displays a slight concavity. These first-order channels have a gradient of approximately 31 feet per 100 feet. First-order stream channels developed on the Walnut Formation have relatively straight, flat profiles and gradients of approximately 2 feet per 100 feet. Channel profiles of the Paluxy Formation exhibit a slight steepening—with channel gradients of approximately 3 feet per 100 feet—and show a marked concavity. Glen Rose first-order channel profiles show a marked convexity and have gradients of approximately 3.6 feet per 100 feet.

The long profile of the North Bosque River (fig. 25) is adjusted to carry away the products of erosion at a rate determined by the geology of the North Bosque watershed. The mean gradient of the North Bosque River is 9.3 feet per mile, and its long profile is generally concave. However, changes of rock type along the course of the North Bosque River are indicated by significant inflections in the profile curve (fig. 25).

Segments A and B of the profile (fig. 25) are developed on the dip slope of the Glen Rose Formation. A steepening of the gradients for these segments (12 feet per mile for A and 14 feet per mile for B) represents the southeastward increase in dip angle of the Glen Rose Formation.

As the North Bosque River erodes its channel through the Paluxy Formation, the profile is straight and relatively flattened. Segment C, with a gradient of 14 feet per mile, is developed on the dip slope of the Paluxy Formation. The portion of the channel between segment C and D is developed on the Walnut and Comanche Peak formations. Segment D, with a gradient of 27 feet per mile, represents the portion of the channel profile developed on the steep dip slope of the Edwards Formation. As the North Bosque River flows onto the Georgetown Formation the profile again flattens.

The profile of the North Bosque River (fig. 25) suggests that as the stream channel is developed on successively less resistant rock types, the gradient steepens and is coincident with the dip slopes of these formations (as illustrated by segments B, C, and D, fig. 25). Conversely, when the channel of the North Bosque River flows from a less to a more resistant rock type (as shown between the segments C and D where the stream channel flows from the Walnut Formation onto the Comanche Peak Formation) the profile remains constant and exhibits no perceptible change in gradient.

Cross sectional profiles of the North Bosque River (fig. 26) also show the effect of relative resistance of bed and bank material. In profile A—A' (fig. 26) the North Bosque River is flowing on the Glen Rose Formation and the valley sides are composed of the Paluxy Formation. The channel cross section is trapezoidal in shape, and the valley walls slope down to the channel at a gentle angle. This is approximately the "natural" channel and valley configuration expected of a river this size.

In profile B—B' (fig. 26), however, the cross section of the channel takes on an entirely different shape. At this point on the North Bosque River the channel is developed in the Edwards Formation, and the valley slopes are maintained by the Georgetown Formation. The resultant cross section (B—B', fig. 26) has a shape approaching a square, and the valley slopes are more abrupt than in profile A—A', (fig. 26).

For most river channels in cross section the appearance of rectangularity increases somewhat as the river increases in size downstream, since width increases downstream faster than depth (Leopold *et al.*, 1964, p. 202).

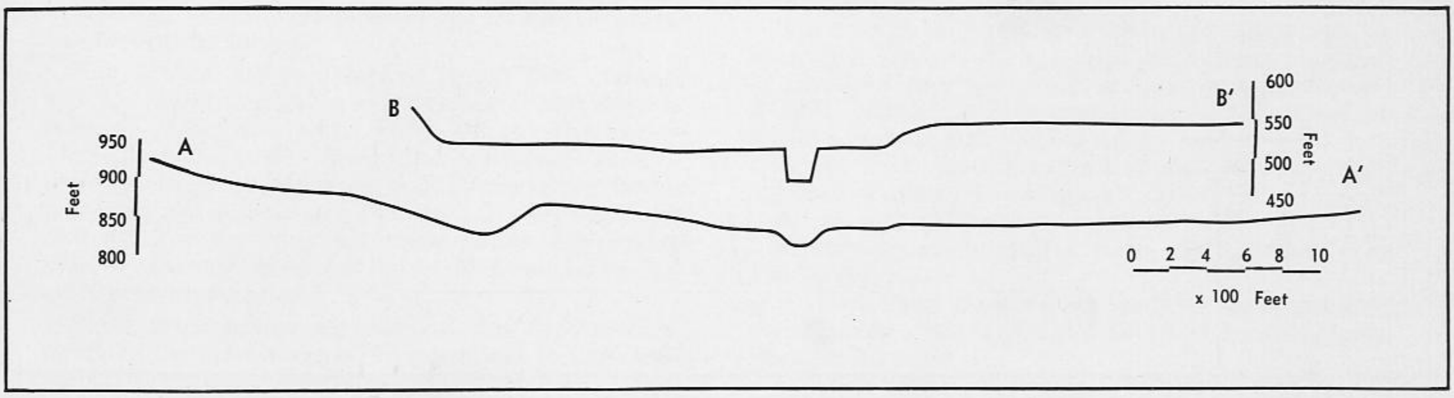


Fig. 25. Cross-valley profiles of the North Bosque River.

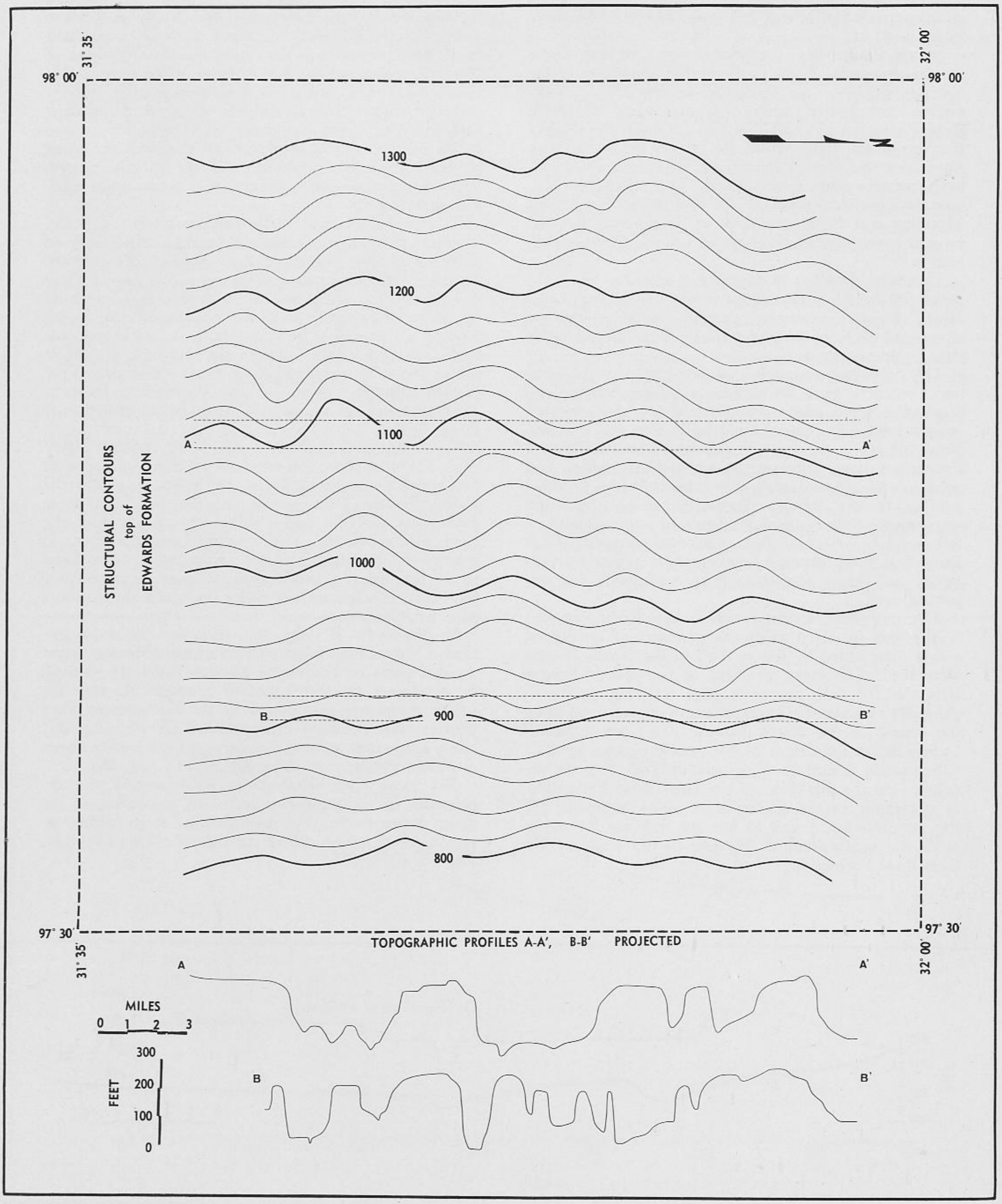


Fig. 26. Hillslope angles of the North Bosque watershed.

However, since the North Bosque River channel exhibits a relatively large increase in ratio of depth-to-width downstream, it is concluded that lithology is the dominant factor controlling channel configuration of the North Bosque River.

BASIN MORPHOMETRY

Morphometric properties of basins A through H were analyzed for conformity of these watersheds to the laws of drainage composition. (Unless otherwise indicated, all data discussed in this section are listed in table 3.) With the exception of Meridian Creek and Honey Creek basins, the excellent fit of straight lines to the data (figs. 22 and 23, #3 and #4) indicates that the laws of stream numbers, lengths, and areas apply closely to basins of the North Bosque watershed.

Horton (1945, p. 286) stated that the number of streams of each order in a given basin forms an inverse geometric series in which the first term is unity and the ratio of the number of streams of any order to the next lower order is the bifurcation ratio. The bifurcation ratio for basins A, B, C, D, E, and G ranges from 3.2 to 4.3, values consistent for well dissected basins throughout the United States. However, Neils Creek and East Bosque basins, as shown by the steepening of the curves (fig. 23, #3), have a bifurcation ratio of 5.3 and 5.0, respectively. This indicates that these basins are highly dissected.

The average stream length for each of the different orders in the eight study basins (figs. 22 and 23, #3) tends to closely approximate a direct geometric series in which the first term is the average length of streams of the first order. However, the curves for Honey Creek and Meridian Creek basins (figs. 22 and 23, #3) exhibit distinctly different slopes from the other six basins. Honey Creek and Meridian Creek basins have relatively long average first order stream lengths and a lower rate of length increase for the higher order streams than any of the other six basins.

It is suggested that this deviation for Meridian and Honey creek basins is caused by loss of headwaters (dominantly first order streams) to other basins. What we are now designating long first order streams in these basins are in reality remnant second or third order channels.

Meridian and Honey creek basins also have abnormally low stream frequency values, 1.5 and 0.7, respectively. Using the same line of reasoning as in the preceding section, a loss of first order channels in the headwaters would greately lower the stream frequency values for these basins.

The relation between stream length and drainage area for Meridian and Honey creek basins also deviates markedly from the other study basins. The curves (figs. 22 and 23, #4) show that one square mile of drainage basin of Meridian and Honey creek basins will maintain, respectively, 0.6 and 1.2 miles of stream channel. For the other six study basins, one square mile of drainage area will maintain from 1.3 to 2.4 miles of stream channel.

Basin shape factors also support this hypothesis of piracy of the headwaters of Meridian and Honey creek basins. With elongation ratios of 0.65 and 0.73, these basins are more nearly circular than any of the other basins studied. The geometric growth characteristic of any basin is to increase in length at a faster rate than in width. Meridian and Honey creek basins are obviously not increasing in length at a rate comparable to the other basins of the North Bosque watershed. The most obvious conclusion to be drawn from this data is that as Meridian and Honey creek basins ramify in width they are concurrently losing area in their headwaters by divide migration.

In conclusion, almost all the basins of the North Bosque watershed are moderately dissected. Neils Creek and East Bosque basins are intensely dissected. The relationship between stream numbers, length, and areas and the geomorphic factors of stream frequency, channel maintenance, and basin shape strongly suggests that the headwaters of Meridian and Honey creek basins are at the present (and have been in the geologic past) lost through divide migration to the Leon River.

Hypsometric analyses of the North Bosque watershed show that the eight study basins range in stage of erosional development from late inequilibrium to equilibrium (figs. 22 and 23, #2). Green Creek basin, with a hypsometric integral of 0.67, is in the most youthful erosional stage, and Duffau Creek basin, with an integral of 0.52 is the most maturely developed of the eight study basins.

The curves for the North Fork, South Fork, Green Creek and Duffau Creek basins are relatively straight and exhibit no significant inflections. It can be inferred that there is little break in slope between the uplands, valley slopes, and valley bottoms for those basins.

The curves for Honey Creek, East Bosque, Meridian Creek and Neils Creek basins show that they have very little mass remaining in their uplands. Most of the mass of these basins is concentrated in valley slopes and valley bottoms.

Honey Creek basin (fig. 22, #2) has a greater proportion of mass concentrated in the upper and mid-slopes of the basin than the other seven study basins. This correlates well with the high average annual sediment loss previously derived for Honey Creek basin.

The curve for the East Bosque basin (fig. 23, #2) also shows a large mass concentration in the upper- and mid-slopes. Again, this correlates well with the average sediment loss calculated for the East Bosque basin.

Significant correlations for the other study basins with discharge or average sediment loss are not apparent.

INTRAVALLEY VARIATION IN SLOPE ANGLES

The orientation of valley sides in the North Bosque watershed, through the agency of microclimate, appears to affect the processes of erosion and mass transport. Readily perceptible differences exist in the slopes of north- and south-facing valley walls.

In the North Bosque watershed east- or west-trending stream valleys have erosional slopes that are asymmetrical, with the north-facing slopes steeper (fig. 26). The variance in intravalley slope angle ranges from 2 to 18 degrees.

At least three plausible explanations for intravalley variations in slope angles can be given for the North Bosque watershed:

1. North-facing slopes tend to be steeper than south-facing slopes in the drier portions of the North Temperate Zone because the susceptibility to erosion is greater

on the south-facing slopes, as a greater quantity of material is eroded into the subjacent channels from the north. The toe of the south-facing slope is buried and built up to some extent, thereby shifting the stream channel against the north-facing slope (Melton, 1960, p. 134).

2. Runoff and erosion rates on north-facing slopes are less than on corresponding south-facing slopes because of greater vegetation density and soil development and therefore higher infiltration rate and surface resistance. South-facing slopes tend to be eroded more rapidly, with resulting lowered slope angle (Emery, 1947, p. 67-68).

3. Subtle structure of the underlying strata upon which valleys are developed tends to influence the lateral migration direction of stream channels. The resultant intravalley slopes would be similar to those described in one above. If a stream channel is initially shifted toward one valley wall by structure, the subsequent build up of the toe of the opposite slope would further shift the channel and accentuate the variance in valley slope angles.

In the area of study in the North Bosque watershed (fig. 25), the evidence strongly favors the conclusion that the asymmetrical erosional slopes, with north-facing slopes steeper, which result from a variety of basic causes can be attributed to a single mechanism —asymmetrical lateral corrasion by streams.

Topographic profiles (fig. 26) show that the major valleys are developed on the flanks of gently nosing structure of the underlying strata. This could exert the initial "impetus" to shift the stream channel toward the north-facing slopes.

Removal of debris from the south-facing slopes is less pronounced than on north-facing slopes because the vegetation density on the south-facing slopes is greater. This tends to stabilize and build up the toe of the south-facing slope, thereby further shifting the stream channel against the north-facing slope. The north-facing slopes are continually being undercut by lateral corrasion while the south-facing slopes are being built up and stabilized by vegetation.

In summary, intravalley asymmetry in the North Bosque watershed can be attributed directly to asymmetric basal corrasion, which results from vegetational density and structural controls within the valley.

CONCLUSIONS

1. The North Bosque watershed is located in a region frequented by more flood-producing storms than any other area in the United States. Peak flood discharges in the magnitude of 250,000 to 500,000 second feet are not only possible for the North Bosque watershed but should be expected over a long period of record.

2. The topography of the four physiographic regions of this study—Washita Prairie, Lampasas Cut Plain, Paluxy Cross-Timbers, Glen Rose Prairie—is a direct function of the physical, chemical, and hydrologic properties of the rocks outcropping within those regions.

   In the Washita Prairie the differential weathering of the limestones and clays of the Georgetown Formation gives this area a topography characterized by rounded benches and hillslopes and valley walls which have a distinct convexity. The characteristic hillslopes of the Lampasas Cut Plain are a result of the physical and hydraulic properties of the Edwards Formation. The Edwards Formation is the major perennial aquifer of the North Bosque watershed. The position of spring lines at the base of the Edwards crest-slopes insures that weathering and erosion are constantly active on the Comanche Peak mid-slopes and Walnut foot-slopes, but only active on the Edwards crest-slopes during periods of precipitation and overland flow.

   The friable sands of the Paluxy Formation easily disaggregate and drown the stream valleys of the Paluxy Cross-Timbers. This "drowning" effect results in a topography characterized by gentle slopes, rolling hills, and broad, indistinct stream valleys.

   The "benched" topography and steep convex hillslopes of the Glen Rose Prairie are a result of the differential resistance to weathering of the marls and limestones of the Glen Rose Formation.

3. Sheet erosion is the major sediment producer in the North Bosque watershed. Annual sedimentation rates range from 2.0 to 0.35 acre-feet per square mile of drainage basin area. This is equivalent to lowering the land surface by 0.095 to 0.034 cm per year, if distributed over the entire study area.

4. Solution is also an important agent in landscape modification of the North Bosque watershed. Surface water analyses show that approximately 83,000 tons of solids per year are removed in solution from the North Bosque watershed. This would result in a lowering of the landscape, by solvent action alone, by 0.0012 cm per year.

5. In the North Bosque watershed the relationship between channel length and drainage basin area is $\log L_l = a + b\log D_a$. The proportionality constants are $a = 0.1778$, $b = 0.5882$. Channel length-drainage area analyses in the North Bosque watershed show that for each square mile of drainage basin there will be from 0.6 to 2.4 miles of drainage channel.

6. A conservative relation exists in the North Bosque watershed between drainage area and discharge. An

empirical equation relating drainage area and discharge for this area is $\log Q = a + b\log D_a$. For the North Bosque watershed the proportionality constants have the values of $a = -0.7348$ and $b = 1.0159$.

7. Relief ratios show a conservative relationship to annual sediment yield for the North Bosque watershed. This relationship is $\log S_l = a + bR_r$. The proportionality constants are $a = -1.0372$ and $b = 231.54$.

8. The relationship between stream numbers, length, and area and the geomorphic factors of stream frequency, channel maintenance, and basin shape suggest that the headwaters of Meridian Creek and Honey Creek basins are in the process of losing drainage to the Leon River.

9. Hypsometric analyses of the North Bosque watershed show that the stage of erosional development ranges from late inequilibrium to equilibrium. The concentration of mass within the North Bosque watershed, as illustrated by the hypsometric curve, correlated well with the areas of maximum sediment yield.

10. Intravalley asymmetry of valley slopes in the North Bosque watershed, with the north-facing slopes steeper, can be attributed to asymmetrical basal corrasion, which results from vegetational density, and structural controls within the valley.

11. Within the North Bosque watershed erosional energy and topography are in equilibrium, and all elements of the topography are being downwasted at the same rate. Differences in relief and form must be explained in terms of spatial relationships rather than in terms of evolutionary development through time.

APPENDIX

FIELD ANALYSIS OF WATER

The following ions were determined using the Baroid Division National Lead Co., Water Analysis Test Kit: calcium, magnesium, iron, sulfate, bicarbonate, carbonate, chloride.

ALKALINITY DETERMINATION

Alkalinity is determined by titrating a sample of the water with standard sulfuric acid using a pH indicator to determine end points. With indicators, one changing at a pH of 8.3 and another at 4.5 to 5.1, it is possible to make two titrations and determine by calculations the amounts of hydroxyl, carbonate, and bicarbonate in the water.

pH Alkalinity Range	Color
5.1 Low alkalinities (1 emp or less)	Greenish blue gray
4.8 Medium alkalinities (3 epm)	Pink gray-bluish cast
4.5 High alkalinities (10 epm or more)	Light pink

Procedure

1. Measure 50 ml or more of fresh water sample into a titration dish.
2. Add 2 or 3 drops of phenolphthalein indicator solution. If a pink color develops, titrate with N/50 sulfuric acid until the pink color disappears, and record milliliters of acid used. If no pink color appears, no carbonate or hydroxyl is present.
3. Add 3 or 4 drops of brom cresol green-methyl red indicator solution. A greenish color will develop.
4. Titrate with N/50 sulfuric acid until each end point is reached, recording the amount of acid used to reach each end point as given above. Calculate the equivalents per million of total alkalinity for each end point as given below. Use the one that is nearest to the range of the indicated pH color shade.

Results

Calculate the hydroxide, carbonate, and bicarbonate from the following relations:

$$P = \frac{\text{ml of N/50 sulfuric acid required for phenolphthalein end point}}{\text{ml of sample used}}$$

$$M = \frac{\text{ml of N/50 sulfuric acid required to end point total alkalinity}}{\text{ml of sample used}}$$

When $P = O$, the alkalinity is due to bicarbonate alone.
$P = M$, the alkalinity is due to hydroxide alone.
$2P = M$, the alkalinity is due to carbonate alone.
$2P$ is greater than M, the alkalinity is due to a mixture of carbonate and hydroxide.
$2P$ is less than M, the alkalinity is due to a mixture of carbonate and bicarbonate.

Expression of Results

1. Total alkalinity
   $20M$ = epm of total alkalinity
2. Carbonate alkalinity
   (a) If hydroxide is present
   $40(M-P)$ = epm of CO_3, $1200(M-P)$ = ppm of CO_3
   (b) If hydroxide is absent
   $40P$ = epm CO_3, $1200P$ = ppm of CO_3
3. Hydroxide alkalinity
   $20(2P-M)$ = epm OH, $340(2P-M)$ = ppm OH
4. Bicarbonate alkalinity
   $20(M-2P)$ = epm HCO_3, $1220(M-2P)$ = ppm HCO_3

CHLORIDE DETERMINATION

Chloride content is determined by titrating a water sample with a standard silver nitrate solution, using potassium chromate as an indicator. The silver nitrate precipitates the chloride ion first. When the chloride is nearly all gone, silver chromate begins to precipitate which produces a red color taken as the end point.

Procedure

1. Pipette 1.0 ml or more of a water sample into the titration dish and dilute to 50 ml with distilled water. It may be preferable when using 'fresh' water samples to use 50 ml of the sample and not dilute with distilled water.
2. Add four or five drops of potassium chromate indicator solution.
3. Add standard silver nitrate solution from an automatic burette dropwise (very slowly), stirring continuously. Continue until the sample turns from yellow to orange or brick red.
4. The number of milliliters of standard silver nitrate used to obtain this end point is multiplied by 10,000, when the 0.01 g silver nitrate solution is used, to obtain parts per million of the chloride ion.

Results

The chloride content is expressed as parts per million chloride. To obtain equivalents per million of chloride ion, divide parts per million by 35.5 as follows:

$$\text{epm} = \frac{\text{ppm Cl}}{35.5}$$

VERSENATE TEST FOR IRON (FERRIC)

Procedure

1. To 100 ml clear, 'fresh' water sample add 3 drops concentrated hydrochloric acid. pH should be 1 to 2.
2. Add 0.5 ml (10 drops) hydrogen peroxide solution. The color that develops, usually pale yellow, will be the end point color.
3. Add 1.0 ml iron indicator solution. A purple color develops if iron is present.
4. Add 0.5 ml iron buffer solution. The pH should be between 2 and 3. If too much buffer is added a brownish-red precipitate will develop. Add one or more drops of concentrated hydrochloric acid until precipitate disappears.
5. Adjust the pH again with less buffer.
6. Titrate with hardness titrating solution back to color developed in Step #2.

Results

For 100 ml sample multiply milliliters of titrating solution used by 5.6 to obtain parts per million Fe^{+++} for 20 epm hardness titrating solution. Multiply milliliters of titrating solution used by 0.56 to obtain parts per million Fe^{+++} for 2 epm hardness titrating solution. To obtain equivalents per million of Fe^{+++}, divide parts per million by 18.6.

$$\text{epm } Fe^{+++} = \frac{\text{ppm } Fe^{+++}}{18.6}$$

VERSENATE TEST FOR TOTAL HARDNESS

The versenate test for total hardness is used to determine the calcium and magnesium ion concentration in a water sample.

Procedure

1. To 50 ml of 'fresh' water sample add about 2 ml of buffer solution, the pH should be about 10 to 10.5. Add 5 to 10 drops of hardness indicator solution. If a red or wine color develops indicating hardness in the sample, calcium and magnesium are present.
2. Add hardness titrating solution, stirring continuously until the sample first turns to blue or gray.
3. The total hardness is calculated as follows:
   20(ml of titrating solution)=epm Ca+Mg (if hardness titration solution 1 ml=20 epm is used)
   2(ml of titrating solution)=epm Ca+Mg (if hardness titration solution 1 ml=2 epm is used)

Both magnesium and calcium are tested. If magnesium is totally absent, no clear end point will be obtained. If this is the case, use the versenate test for calcium and report no magnesium.

VERSENATE TEST FOR CALCIUM

Procedure

1. To approximately 50 ml of 'fresh' water sample in a titrating dish, add 1 ml of calver buffer solution, the pH should be between 12.0 and 12.5. Add a big pinch of Calver I or Calver II indicator powder.
2. A wine or pink color will appear if calcium is present.
3. Add hardness titrating solution until the sample turns blue or deep purple.
4. The calcium is determined as follows:
   20 (ml of titrating solution)=epm Ca (if hardness titration solution 1 ml=20 epm is used)
   2(ml of titrating solution)=epm Ca (if hardness titration solution 1 ml=2 epm is used)
5. To determine Mg present subtract equivalents per million Ca obtained from equivalents per million total hardness (Ca+Mg) which was determined by the Versenate test for hardness above.

Results

ppm Ca^{++}=20 (epm Ca^{++})

ppm Mg^{++}=12 (epm Mg^{++})

SULFATE ION DETERMINATION

Procedure

1. Measure 2 ml of water sample into a clear test tube and add a few drops of Baroid sulfate indicator. Shake well and let stand about 2 minutes.
2. Judge the quantity of precipitate formed and estimate the sulfate ion according to the following table:
   Translucent white suspension—up to 10 epm $SO_4^=$
   Milk-white suspension—10 to 20 epm $SO_4^=$
   Heavy-white suspension—above 20 epm $SO_4^=$

   Report zero sulfate if no precipitate is formed.

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Page 33:

Column 1
Paragraph:

5 - Line 1, (Fig. 25) should be (Fig. 3)
Line 8, (Fig. 25) should be (Fig. 3)

6 - Line 1, (Fig. 25) should be (Fig. 3)

Column 2
Paragraph:

2 - Line 1, (Fig. 25) should be (Fig. 3)
Line 6, (Fig. 25) should be (Fig. 3)

3 - Line 2, (Fig. 26) should be (Fig. 25)
Line 3, A-A' (Fig. 26 should be:
B-B' (Fig. 25)

4 - Line 1, B-B' (Fig. 26) should be:
A-A' (Fig. 25)

Line 6, (B-B', Fig. 26) should be:
(A-A', Fig. 25)

Line 8, A-A', (Fig. 26) should be:
B-B', (Fig. 25)

Fig. 25 Profile designations B-B' and A-A' should be A-A' and B-B' respectively.

Page 36:

Column 2
Paragraph:

1 - Line 1, (Fig. 25) should be (Fig. 26).

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