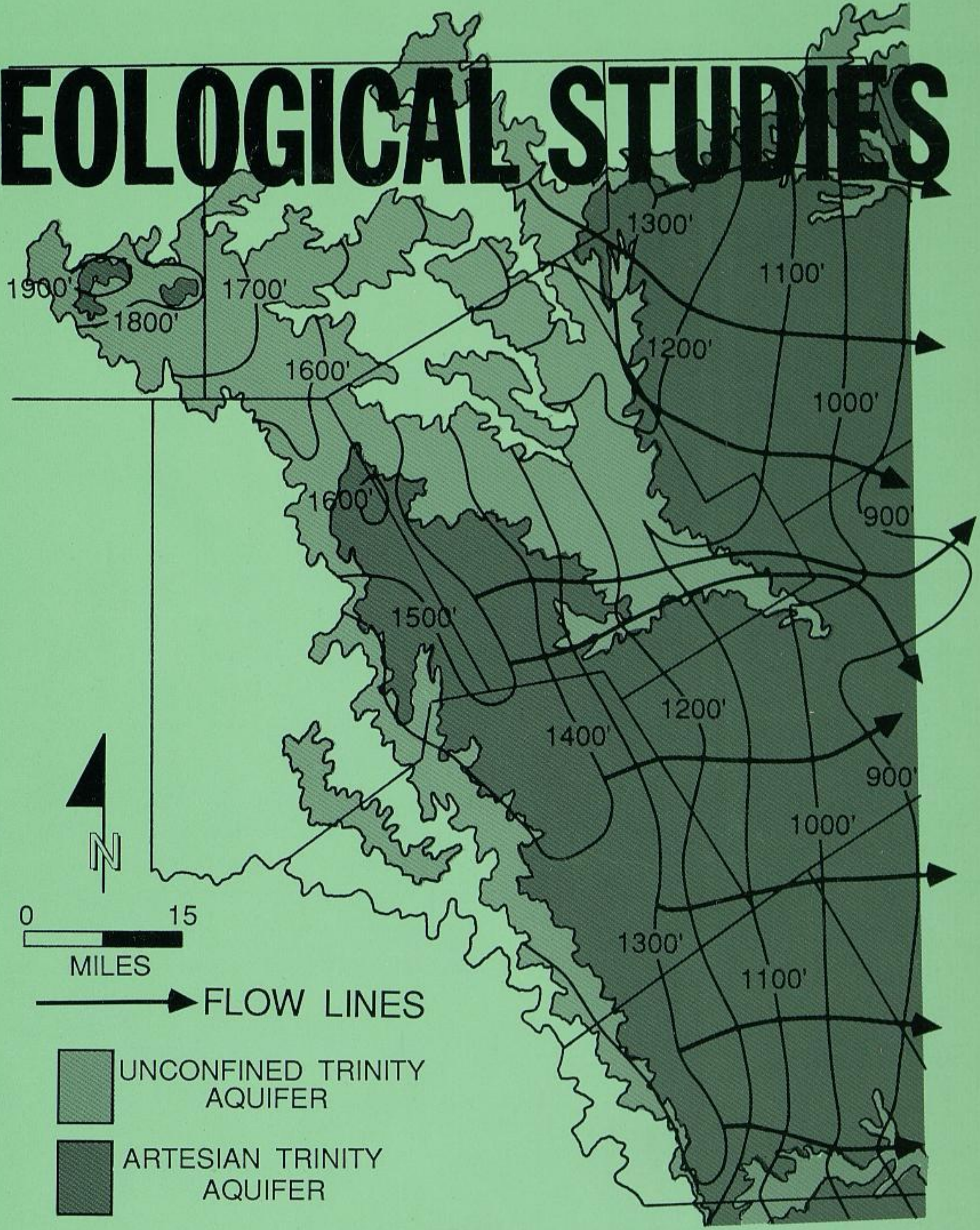
BAYLOR GEOLOGICAL STUDIES



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Bulletin No. 46

BAYLOR UNIVERSITY - WACO, TEXAS

Groundwater Recharge in the Trinity Aquifer, Central Texas

KEITH BURLEIGH RAPP

"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.

Cover: Groundwater flowpaths and flow net for a portion
of the Trinity aquifer, central Texas.

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BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Spring 1988

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published 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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Groundwater Recharge in the Trinity Aquifer, Central Texas

Keith Burleigh Rapp

ABSTRACT

The Lower Cretaceous Trinity aquifer, the primary groundwater resource in central Texas, comprises a gently southeast dipping unconfined aquifer in the outcrop belt and an artesian aquifer below the overlying Glen Rose Limestone. Sands of the Trinity aquifer in central Texas represent initial clastic deposition by earliest Cretaceous fluvial systems upon the irregular topography of the Wichita Paleoplain, followed by the deposition of marginal marine deposits by the transgressive Comanchean seas. The Trinity sands are represented by two systems in outcrop: 1) fluvial basal conglomerate, sandstones, and flood-basin muds, which unconformably overlie Paleozoic rocks; and 2) sandstones, siltstones, and mudstones, which lie below and interfinger with the Glen Rose Limestone.

Previous investigations in the Trinity aquifer system considered groundwater recharge from an aquifer concept, rather than from the concept of a regional flow system. When considered as a flow system, there are two points of critical importance: 1) large areas of the Trinity sands outcrop contribute no groundwater to the Trinity aquifer recharge area; and 2) recharge is not solely confined to the outcrop belt of Trinity sands.

The Trinity aquifer recharge area is in the southeastward draining Leon, Paluxy, and Lampasas River basins, where recharge occurs by precipitation on the outcrop belt of Trinity sands. Where the aquifer is covered recharge occurs by leakage through the overlying Glen Rose Limestone. Westward draining slopes in the Colorado River basin and northward draining slopes in the Brazos River basin carry groundwater away from the regional southeast flow system and the recharge area. Therefore, these areas of the Trinity sands outcrop belt and covered Trinity aquifer do not contribute recharge to the artesian aquifer system.

Offsetting the loss of recharge in the outcrop belt is leakage through the overlying Glen Rose Limestone and Fredericksburg Group, as indicated by geochemical and head data. Leakage through the Glen Rose Limestone substantially increases recharge to the Trinity aquifer and results in chemical variations within the artesian Trinity aquifer.

Recharge assessments suggest that approximately 20 percent of the effective recharge to the artesian aquifer is derived from the Trinity sands outcrop belt, which constitutes 25 percent of the total Trinity aquifer recharge area. Eighty percent of the effective recharge is derived from leakage through the overlying Glen Rose Limestone and Fredericksburg Group over 75 percent of the total recharge area. While recharge on the outcrop belt is seasonal, recharge through leakage continues throughout the year, making it important to the maintenance of the artesian aquifer system.

INTRODUCTION*

The principal aquifers in central Texas are eastward dipping Cretaceous age sandstones of the Trinity Group which unconformably overlie a westward dipping complex of Paleozoic rocks. Within this region basal Cretaceous sandstones have been divided into several formations. In an attempt to apply a consistent nomenclature to this stratigraphic and hydrologic interval, this study considers the Trinity sands as the

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*A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1986.

stratigraphic unit of contiguous basal Cretaceous sandstones, normally included in the Twin Mountains (Trinity Group sands) and Antlers (Trinity and Fredericksburg Group sands) Formations, and the Hensel and Hosston Formations in the subsurface.

The Trinity aquifer is therefore defined as the saturated section of Trinity sands. This aquifer designation deviates from the "Trinity Group aquifer" defined by the Texas Department of Water Resources (Muller and Price, 1983, p. 24), which includes the Paluxy and Glen Rose Formations. Although the Trinity sands, Glen Rose Limestone, and Paluxy Sand are in hydrologic communication, the Trinity sands are the most productive, and the Glen Rose Limestone is considered a confining unit throughout the study area even though wells producing high-sulfate water have been completed in the Glen Rose Limestone. The overlying Paluxy Formation, a sandstone aquifer in the Fredericksburg Group, is laterally equivalent to the upper Antlers sands.

PURPOSE

The Trinity aquifer, one of seven major aquifers in Texas, provides central Texas with an abundant, high-quality water resource. The value of the aquifer lies in the quality and quantity of water, its shallow depth, the ease with which groundwater can be extracted, and the vast regional extent and reliability of wells producing from it.

In the early 1870s, the first wells in the Waco region were drilled into the artesian Trinity aquifer, and water flowed at the surface. Increased water demands have reduced the head in the regional Trinity aquifer far below the surface, suggesting that pumpage may have greatly exceeded recharge. Projected increases in water use will further tax the aquifer. Thus, knowledge of recharge becomes critical to future decisions regarding groundwater management in central Texas.

Recharge generally has been attributed to infiltration on the outcrop belt of Trinity sands, an area of approximately 1700 square miles lying about 100 miles northwest of Waco. However, a significant portion of the outcrop area is in remnant outliers or within basins with surface streams that drain away from the artesian Trinity aquifer system. Annual recharge is largely unknown, as are the groundwater contributions from overlying formations. Therefore, the purpose of this study is to assess the nature and magnitude of groundwater recharge contributions to the Trinity unconfined and artesian aquifer, as an aid to future decisions regarding water management in the Trinity aquifer of central Texas.

LOCATION

The outcrop belt of Trinity sands forms the physiographic province of the Western Cross Timbers, an area of gentle topography and sandy soils that lies west of the Glen Rose Prairie, north of the Llano Uplift, and east of the Callahan Divide.

The outcrop of Trinity sands extends from the Brazos River on the north, south to the Colorado River, and includes all or parts of Brown, Callahan, Comanche, Eastland, Erath, Hamilton, Lampasas, and Mills Counties.

Structurally, the outcrop belt of Trinity sands lies near the eastern margin of the Texas Craton, and west of the East Texas basin (Fig. 1). The basal Cretaceous Trinity sands unconformably overlie Paleozoic rocks of the Wichita Paleoplain.

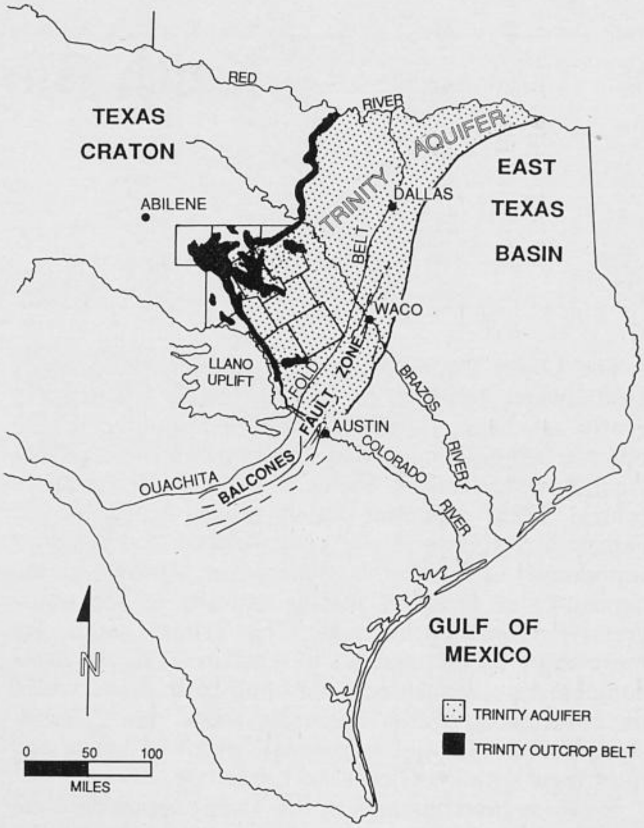

Fig. 1. Regional map of structural features affecting the Trinity aquifer. The Trinity aquifer is one of seven major aquifers in Texas. The aquifer is composed of the saturated section of Trinity sands exposed in the west, and the artesian Trinity aquifer system which extends eastward from the outcrop belt. The Trinity aquifer system transects the eastern margin of the stable Texas Craton, and the western margin of the East Texas basin, where Trinity sediments increase in thickness eastward into the East Texas basin. (Modified from Rupp, 1976)

METHODS

This study is based on data obtained from field reconnaissance, use of published water level and chemical analyses performed by the Texas Department of Water Resources (Klemt et al., 1975), water level data collected from mini-piezometers installed in the bed of the Leon River, and a review of topographic, soil, and geologic maps.

Because of the size of the study area the geology was determined from existing maps (Barnes, 1972, 1976), with field confirmation. Stratigraphic reconnaissance provided an understanding of depositional systems in the Trinity sands outcrop area, and thin sections provided information on aquifer lithologies.

A water level contour map was constructed from published water level data (Klemt et al., 1975), and refined by the preparation of a unit well hydrograph for the month of March 1969. The refinement process provides a "static" water level measurement at the yearly high level. The water level contour map was used to define groundwater divides, recharge and discharge areas, and flow directions. Effective recharge to the artesian Trinity was calculated from the transmission capacity of the Trinity aquifer between the Paluxy and Lampasas Rivers. Effective recharge was determined from the water level contour map along the 900-foot equipotential head level in the artesian Trinity aquifer, and represents the total amount of groundwater derived from the Trinity aquifer recharge area.

Published water analyses (Klemt et al., 1975) from selected wells were utilized to determine the nature and abundance of common ions in solution. The selection of wells was based on well position in the Trinity aquifer recharge area both stratigraphically and areally. Data obtained from water analyses was plotted on trilinear diagrams used to establish the geochemical signatures of formations contributing recharge.

PREVIOUS WORKS

The growth of knowledge of Lower Cretaceous rocks in central Texas was described in some detail by Boone (1968), and this study utilizes facies designations and time divisions based on his contribution. Studies of the Trinity Group since that time have been summarized by Atchley (1986), and, although interesting, are not directly significant to the present study.

The hydrogeology of the Trinity aquifer was first discussed by Hill (1901), who noted its importance as a water supply when wells flowed at the surface and Waco was known as the "geyser city."

The next study of importance was by Holloway (1961), who described the development of the artesian Trinity aquifer and its hydrologic properties in McLennan County.

Henningsen (1962) discussed the diagenesis of water in the Trinity aquifer of central Texas from outcrop to the Balcones fault zone and delineated two recharge provinces based on water chemistry. More recent work has questioned the Stephenville and Llano recharge source areas, and the present study attempts a more precise delineation of recharge areas.

Thompson (1967), in a hydrogeologic survey of Brown County, assessed the occurrence and quality of groundwater in Paleozoic and Cretaceous aquifers, and concluded that the Trinity aquifer is the most productive aquifer within the county.

Klemt et al. (1975) assessed hydrologic properties and groundwater resources in a regional study of Cretaceous aquifers in central Texas. They were primarily concerned with the artesian portion of the Trinity aquifer. This study based recharge estimates on Trinity sands outcrop area, assuming all of the outcrop area to be equally effective in recharge, and recognizing no other contributions.

In a regional study of depositional facies in sands of the Trinity Group, Hall (1976) demonstrated a correlation between depositional systems and hydrochemistry. His descriptions of depositional facies provided a stratigraphic framework for the present study.

Rupp (1976) was primarily concerned with the geology, hydrology, and water chemistry of the artesian Trinity aquifer in the Waco region, providing a history of early development of the aquifer and of water level decline in Trinity wells.

In a study which briefly considered groundwater recharge Price, Walker, and Sieh (1983) assessed the occurrence, quality, and availability of groundwater in Paleozoic and Cretaceous aquifers in Callahan County. They estimated recharge based on the investigation of Klemt et al. (1975).

Muller and Price (1983) discussed the "trough method" of calculating effective recharge to the artesian Trinity aquifer, suggesting that approximately 1.5 to 3.0 percent of the average annual precipitation in the outcrop area becomes effective recharge. The "trough method" is a calculation of the transmission capacity along an equipotential head level in an aquifer.

ACKNOWLEDGMENTS

I am indebted to numerous individuals for material, physical, and financial support. Special thanks are due to landowners who freely allowed access to property. Expenses were partially defrayed by funds from the Baylor University groundwater studies program. Field assistance was rendered by many individuals; particular thanks go to Daniel P. Barrett. Grateful appreciation is extended to Daniel A. Muller, Texas Water Commission, for discussion of the "trough method" of calculating recharge.

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I am particularly indebted to Joe C. Yelderman, Jr., my thesis advisor, for his helpful discussion and insight, field acumen, and attention to methodology and interpretation, without which this study would have been impossible. Finally, and most importantly, I thank my parents, Burleigh and Arlene Rapp, for their continued inspiration, moral, and financial support throughout my education.

REGIONAL SETTING

GEOLOGY

INTRODUCTION

The hydrogeologic setting for an aquifer is a complex of geologic, topographic, hydrologic, and climatic factors, all of which directly affect recharge potential. The lithology of rocks, stratification, and degree of cementation affect transmissivity, storage, and infiltration. The dip of the Trinity aquifer, and the influence of initial sedimentation of the irregular Wichita Paleoplain, has created aquifer conditions that affect groundwater flow. Surface topography exerts a direct control on recharge and discharge areas, surface drainage, and flow directions. The most obvious climatic factor affecting groundwater recharge is precipitation. High-intensity, short-duration precipitation events are less effective in infiltration and recharge than steady, long-duration rainfall events. Climatic factors such as evapotranspiration are less obvious and more difficult to assess in terms of groundwater loss to the aquifer.

Therefore, a knowledge of the regional setting is critical to understanding the potential for recharge in the Trinity aquifer of central Texas. Regional structure, topography, soils, and climate are described, and the critical stratigraphy is summarized.

North and West Texas	Central Texas	Sub surface	**Present Study**
Antler's sands	Twin Mountains	Hensel and Hosston	**" Trinity sands "**

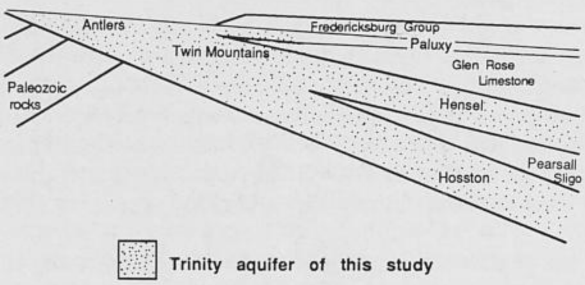

Fig. 2. Nomenclature of the basal Cretaceous Trinity aquifer in various areas of central Texas. In west-central Texas the Trinity aquifer is represented by the Antlers sands of Trinity through Fredericksburg Age. In central Texas sands of the Twin Mountains Formation of Trinity Age comprise the Trinity aquifer. In the subsurface, sands of the Trinity Group are the Hosston and Hensel Formations, separated by the Pearsall and Sligo Formations east of the study area. The present study considers all sands in this stratigraphic interval as "Trinity sands," whether in outcrop or in the subsurface. (Modified from Atchley, 1983, p. 12)

STRATIGRAPHY

The basal Cretaceous sands in central Texas have been divided into the Twin Mountains sands where they underlie Glen Rose Limestone (Trinity Group sands), and Antlers sands where the Glen Rose Limestone is missing (Trinity and Fredericksburg Group sands) (Fig. 2). In outcrop and in the subsurface these form interfingering blankets, combined here as "Trinity sands," products of initial Cretaceous fluvial and marine clastic deposition on the Wichita Paleoplain. As Comanchean seas transgressed northeastward across central Texas, the fluvial phase of the Trinity sands graded upward into marginal marine sand and mud deposits, and eventually into Glen Rose Limestone (Fig. 3).

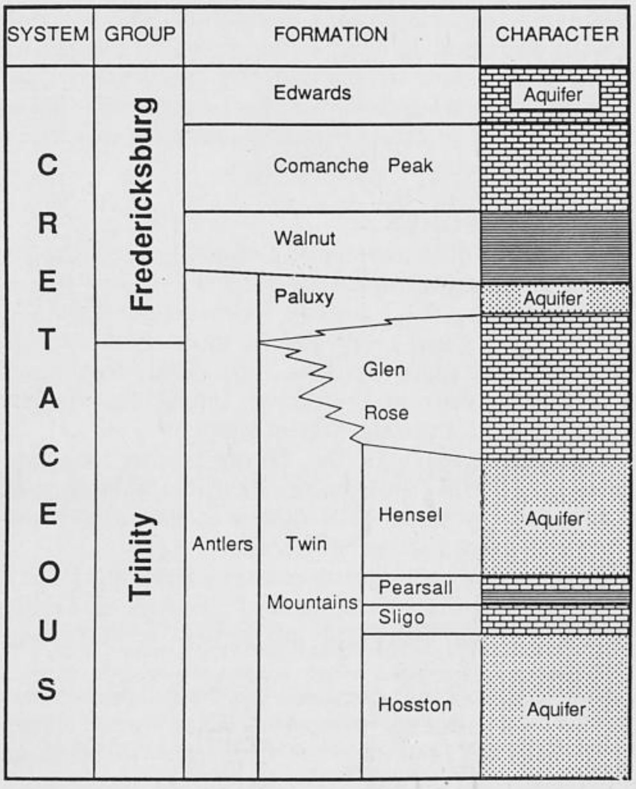

Fig. 3. Stratigraphic column of Trinity and Fredericksburg rocks in central Texas. The Trinity aquifer is composed of basal Cretaceous sandstones and constitutes the regional aquifer in central Texas. The Glen Rose Limestone is the upper member of the Trinity Group, consisting primarily of marginal marine limestones, shales, and marls. The Fredericksburg Group consists of marine sands, muds, and limestones, which overlie the Trinity Group. The lithology of formations overlying the Trinity aquifer is of direct importance since the chemical composition of water in these formations affects water chemistry in the Trinity aquifer. (Modified from Fisher and Rodda, 1966)

The stratigraphic interval important to this study consists of the Trinity sands below the base of the Glen Rose Limestone and above the Paleozoic rocks of the

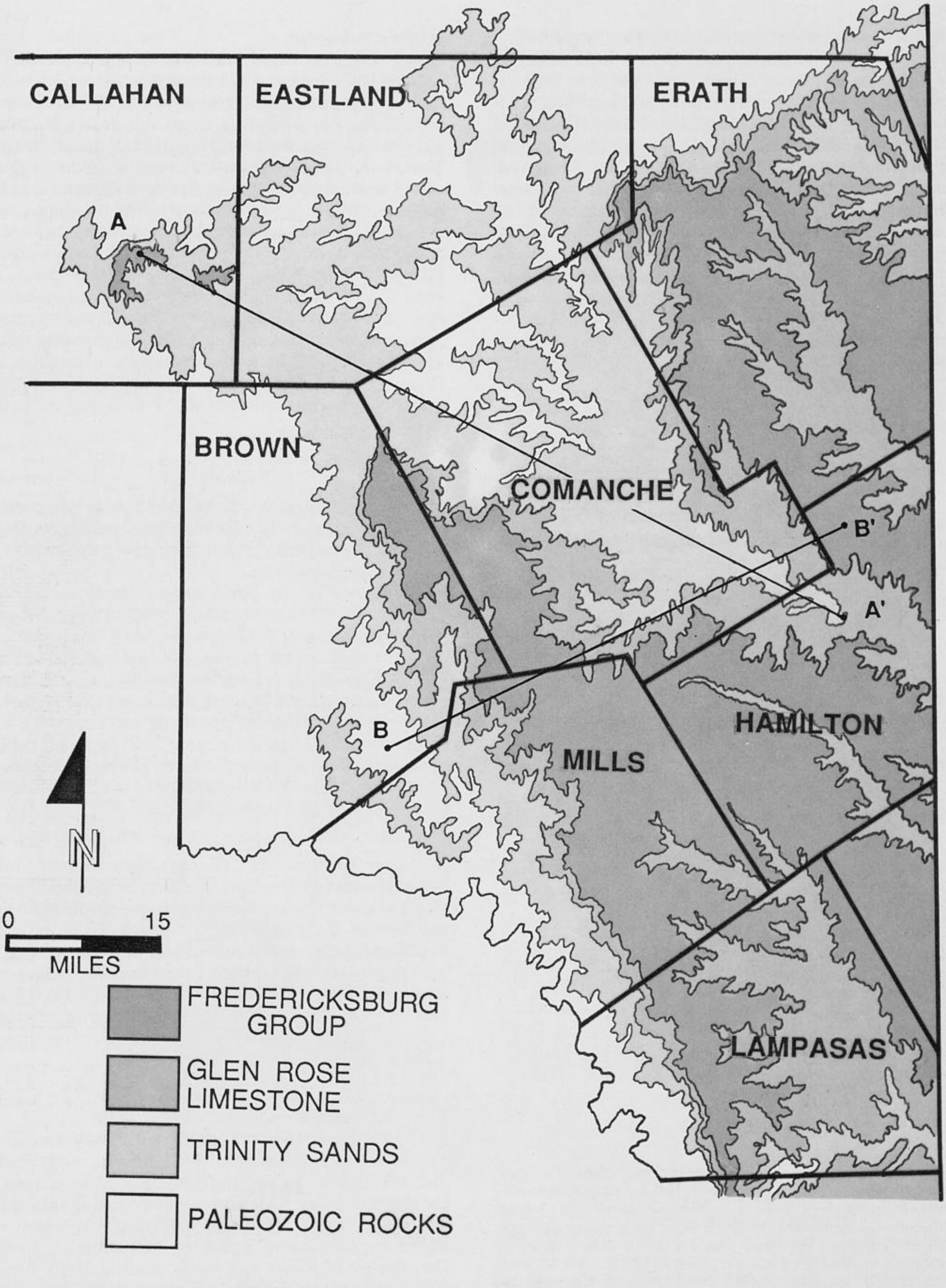

Fig. 4. Outcrop belt of Trinity sands, Glen Rose Limestone, and Fredericksburg rocks in central Texas. The southeast dipping Cretaceous section rests unconformably upon Paleozoic rocks. The Trinity sands are the lowest Cretaceous stratigraphic unit, and occupy the lowest topographic elevations of Cretaceous rocks in the study area. (Modified from Barnes, 1972, 1976)

Wichita Paleoplain. However, because the Trinity aquifer is in hydrologic communication with both the overlying Glen Rose Limestone and yet higher Fredericksburg Group, the lithologic composition of these formations is also of direct importance (Fig. 4).

The stratigraphic description followed here is based on work by Boone (1968), who recognized lithofacies in basal Cretaceous sands over a broad outcrop area in central Texas. Three stratigraphic elements are critical to the hydrogeology in the present study: 1) the Wichita Paleoplain, which controlled initial Cretaceous sedimentation; 2) basal conglomerate and sandstone deposits, which fill the low areas of the Wichita Paleoplain; and 3) the overlying "upper Trinity sands" consisting of sheet-like sandstones, sandy siltstones, siltstones, and mudstones (Fig. 5).

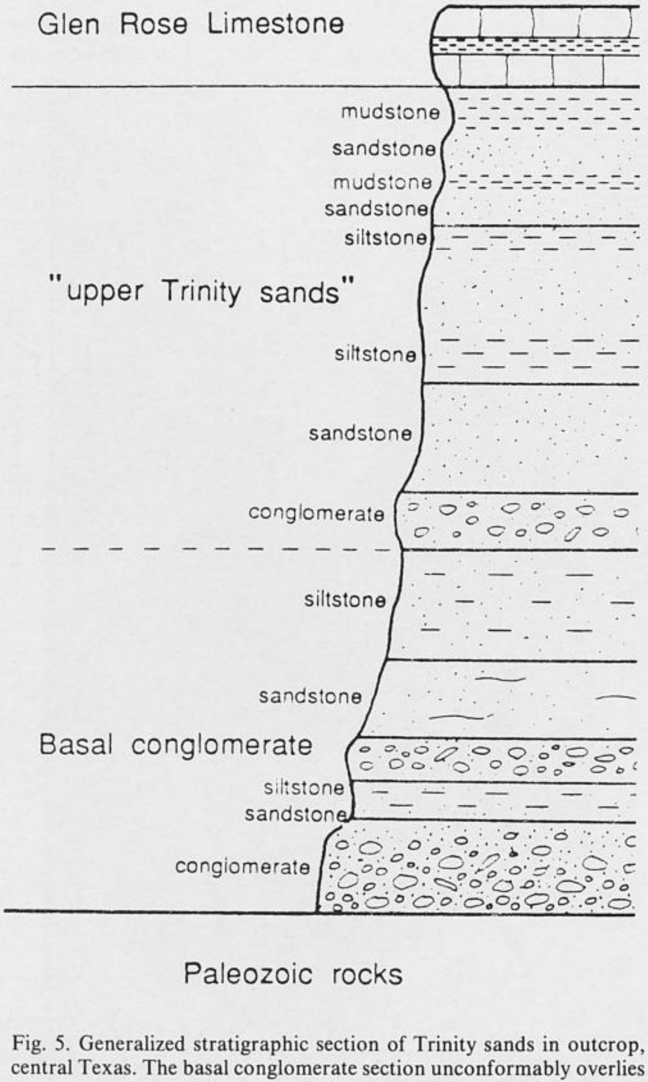

Fig. 5. Generalized stratigraphic section of Trinity sands in outcrop, central Texas. The basal conglomerate section unconformably overlies westward dipping rocks of the Wichita Paleoplain, and the irregular topography on the unconformity allows for the great variability in sediment thickness. The basal conglomerate section consists of sandstones, conglomerates, and siltstones which filled in the low areas of the Wichita Paleoplain. Overlying the basal conglomerate section sandstones, siltstones, and mudstones constitute the major sand interval of Trinity aquifer sediments. These sands lie directly below the Glen Rose Limestone. (Modified from Marchand, 1978, p. 17)

Wichita Paleoplain

The Wichita Paleoplain was a mature erosional topography of north-south trending valleys and divides shaped by subaerial erosion prior to Cretaceous deposition. Superimposed upon this trellis landscape were major east-west valleys of consequent streams. These latter paleo-valleys were channels for the eastward transportation of Cretaceous fluvial sediments (Atchley, 1983, p. 40). A major southeastward trending paleo-valley, the Hamilton Valley, transects the paleoplain from northwestern Comanche County through central Hamilton County (Atchley, 1986). Sedimentation in the 10 to 15 mile-wide Hamilton Valley produced maximum sand thickness oriented along the paleo-valley, and minimum sand thickness coinciding with paleo-ridges. The Wichita Paleoplain is formed on Pennsylvanian and Permian shales, limestones, siltstones, and sandstones that strike north-south and dip 1 to 3 degrees to the west.

Trinity Sands

Basal conglomerate. The basal conglomerate consists of interfingering sandstones, variegated pebble conglomerates, and siltstones, which filled the paleo-valleys of the Wichita Paleoplain.

Sandstones in the basal conglomerate section are typically crossbedded, coarse-grained, subrounded, and moderately mature. Siltstones are finely laminated and discontinuous within the basal conglomerate section. The conglomerates are crossbedded to massive, poorly sorted, fine to coarse-grained, with clasts that are round to subrounded. They are poorly to well cemented with cryptocrystalline opaline cement and, less commonly, by calcite. Clast size ranges from pebble to cobble in a sand matrix, commonly cemented in outcrop, although this appears to be a surface phenomenon.

"Upper Trinity sands." The term "upper Trinity sands" is an informal designation for the stratigraphic interval that lies above the basal conglomerate section and below the base of the Glen Rose Limestone. In outcrop the sandstone facies are crossbedded to massive, fine to coarse-grained, subrounded to subangular, moderately mature to very mature quartz sandstones. They grade laterally and vertically into finely-laminated siltstones creating a complex heterogeneous and anisotropic aquifer system.

Glen Rose Limestone

The marginal marine Glen Rose Limestone consists primarily of interbedded limestones, shales, sandy shales, and silty marls. In outcrop the Glen Rose section at the margin of Glen Rose deposition consists of thin sandy limestones, limey siltstones, and shales in which the clastic units dominate. Eastward, limestones increase at the expense of shales and sands, until near the Brazos River the section is dominated by fossiliferous limestone and finely-crystalline limestone, interbedded with thin marls, dolomitic beds, and chalky nodular limestones.

Fredericksburg Group

The mid-Comanchean Age Fredericksburg Group consists of marginal marine sands, clays, and limestones that are thought to conformably overlie the Trinity Group (Fig. 3).

The Paluxy Sand is the basal member of the Fredericksburg Group. In outcrop the Paluxy is thin bedded to massive, very fine to medium-grained, subangular to subrounded, mature, porous, friable quartz sandstone, with thin discontinuous clay beds.

The Walnut Clay overlies and downdip interfingers with the Paluxy Sand. It consists of calcareous clay and silt, with thin, dense, fossiliferous limestone beds, and discontinuous coquinoid beds consisting almost entirely of *Texigraphea.*

The Comanche Peak Limestone which overlies the Walnut Clay is a fossiliferous, nodular limestone, with thin marl and shale beds.

The Edwards Limestone, the upper member of the Fredericksburg Group, is a dense, fossiliferous, massive limestone, with abundant fragmented and whole shells in conspicuous circular rudistid reefs, and nodular continuous chert beds in some facies. Edwards Limestone caps the highest elevations throughout the principal interest area of the present investigation.

STRUCTURE

The basal Cretaceous Trinity sands of central Texas were deposited in two major structural regions, the Texas Craton and East Texas basin (Fig. 1). The Texas Craton

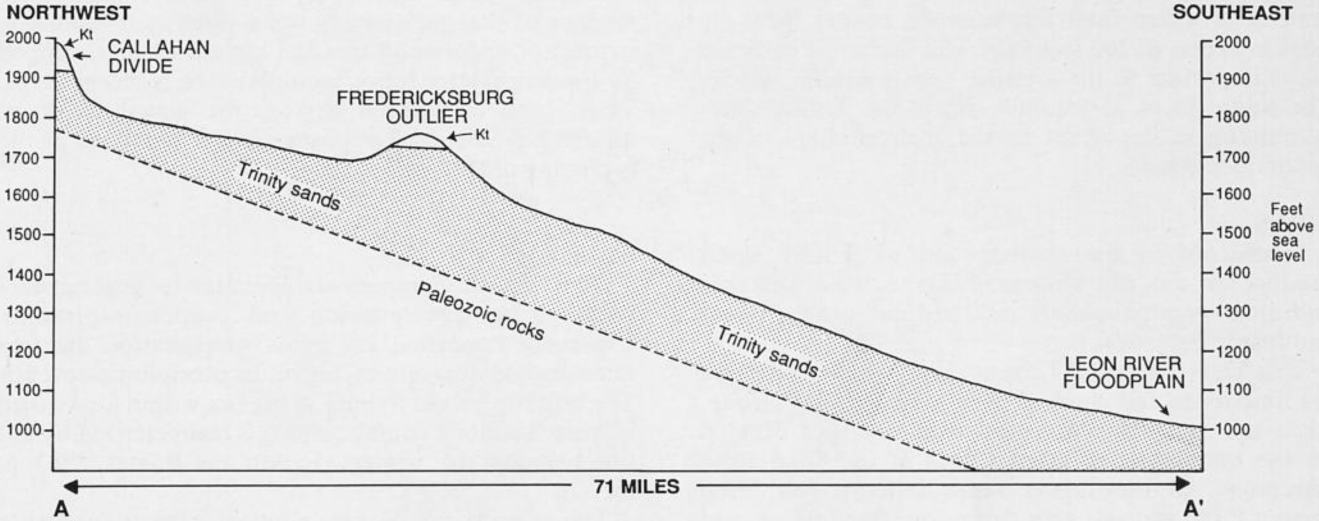

Fig. 6. West to east topographic profile from the Callahan Divide in Callahan County, to the Leon River floodplain in Hamilton County, Texas. Slopes in the Trinity sands section dip 15 to 25 feet/mile to the southeast. The Callahan Divide occupies the highest elevation in the study area and marks the drainage divide between Brazos and Colorado River drainage. The gentle bump is created by an outlier of Fredericksburg rocks, more resistant than the Trinity sands. Topography slopes southeast, in the same direction and slightly less than the rate of the structural dip of the Cretaceous section. (For location of section line see Fig. 4.)

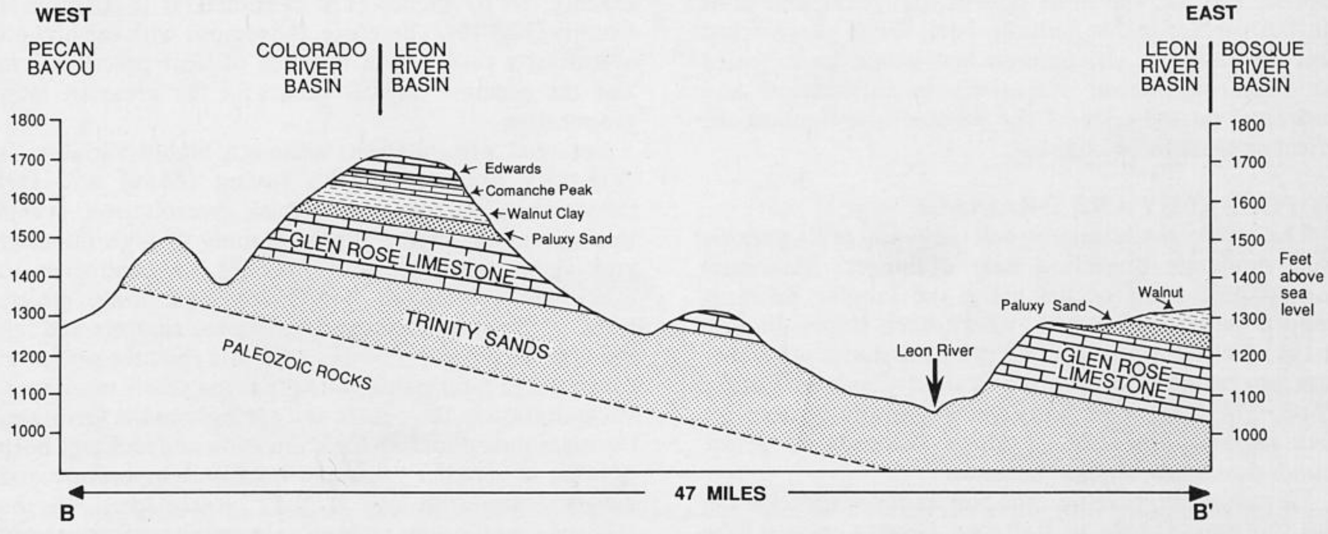

Fig. 7. Topographic profile and stratigraphic section from Pecan Bayou to the Bosque River divide, central Texas. The topographic expression along the cross section is dependent upon the erosional resistance of the various formations. The steepest slopes are developed on limestones of the Edwards and Glen Rose Formations. Gentle slopes develop on the Walnut Clay and Paluxy Sand of the Fredericksburg Group, and in the Trinity sands outcrop belt. (For location of section line see Fig. 4.)

remained a relatively stable structural platform as the Comanchean seas transgressed northeast depositing the Cretaceous section. In contrast, the East Texas basin was an area of active subsidence throughout Trinity time, and Trinity Group sediments increase in thickness east toward the basin.

The primary structural feature affecting the Trinity aquifer is the regional southeast dip of the Cretaceous rocks on the basal Cretaceous unconformity. The irregular topography of valleys and divides on the Wichita Paleoplain produced topographic variations that initially controlled Cretaceous sedimentation.

In the outcrop belt Trinity sands dip southeast at 15 to 25 feet/mile, gradually increasing in dip eastward to 40 feet/mile in Bosque and Coryell Counties, and radically increasing to 100 feet/mile near the Balcones fault zone where fault displacement creates local dip rates in excess of 200 feet/mile. This increased eastward dip is important to the artesian Trinity aquifer system. The subtle 15 to 25 feet/mile dip of the Trinity sands in outcrop is important to the hydrogeology of the unconfined aquifer.

SOILS

Sandstones in the outcrop belt of Trinity sands produce tan, red, and white sandy loams, while siltstones and mudstones commonly yield red and orange loams and loamy clay soils.

Thin Denton-Purves-Tarrant clayey soils develop on the limestones and clays of the Fredericksburg Group, while thin, angular Purves-Bolar clayey soils develop on the undulating to steep slopes of the Glen Rose Limestone. In the Trinity sands outcrop belt, deep Energy-Frio alluvial soils form on floodplains and constitute narrow zones of moderately permeable soils. Thick, tension-cracked Chaney-Deleon loam soils form on the flat to gently sloping siltstones and mudstones of the Trinity sands outcrop belt. Abilene-Cisco-Demona-Nimrod loamy sands form on Trinity sandstones, and are the most porous and permeable soils on the surface in the outcrop belt. While the marked soil variability in the outcrop belt would be expected to cause significant variations in infiltration and recharge, on the scale of the present investigation the effect appears to be minimal.

TOPOGRAPHY AND DRAINAGE

The Trinity sands outcrop belt is a gently rolling prairie with moderate dissection near drainages. Maximum topographic relief occurs along the tabular Edwards capped mesas and divides, where steep slopes develop in the underlying Comanche Peak Limestone, and slopes taper to broad valleys in the Walnut Clay and Paluxy Sand. The Glen Rose Limestone typically produces a stair-stepped topography, which descends to gentle slopes developed on Trinity sands.

Elevation ranges from 2100 feet above sea level along the Callahan Divide in Callahan County to less than 1000 feet in the Leon River floodplain in Hamilton County, producing an average land surface gradient of 15 to 25 feet/mile (Fig. 6). Topography slopes southeast as does the dip of Cretaceous rocks. Local variations in topography are caused by differing rock resistance to erosion (Fig. 7).

In central Texas the two major drainage systems are the Brazos and Colorado Rivers (Fig. 8). The Trinity sands are exposed in the basins of both rivers. Westward drainage in the Colorado River is provided by tributaries of Pecan Bayou which drain across the Trinity sands outcrop belt. Northeastward drainage across the Trinity sands outcrop belt is by tributaries of the Palo Pinto River, a tributary of the Brazos River. The westward and northward drainage of these systems is opposite to the major southeast drainage of the Leon, Paluxy, and Lampasas Rivers, which drain the entire Trinity aquifer recharge area (Fig. 8). While it was early recognized that topography has a significant influence, it was not understood that the highest divides, capped by Fredericksburg rocks, would also be recharge areas. Thus, to a substantial degree, the actual effect of topography is almost opposite to that predicted at the beginning of the investigation.

CLIMATE

The climatic components essential to groundwater recharge are precipitation and evapotranspiration. Especially important are gross precipitation and the intensity and duration of individual precipitation events. The outcrop belt of Trinity sands lies within a modified marine subhumid climate, which is characterized by hot summers and dry winters (Larkin and Bomar, 1983, p. 2).

The average annual precipitation increases eastward from 24 inches (61 centimeters) in Callahan County, to 28.2 inches (71.5 centimeters) in Comanche County, and 29.3 inches (74.3 centimeters) in Erath County (Fig. 9). Evaporation trends also vary in an east-west direction, decreasing from 75 inches (190 centimeters) in Callahan County, to 67 inches (170 centimeters) in Lampasas County (Fig. 10). Therefore, the regions with the highest evaporative rates are in the area of least precipitation, and the greatest rainfall occurs in the areas of least evaporation.

Seasonal precipitation, although highly variable, is generally greatest in the spring (May) and fall (September) months. Individual precipitation events throughout the region are commonly of high intensity and short duration, and are not as conducive to maximum infiltration conditions as a long, steady rainfall. Precipitation events during the summer and fall months are generally of this sort, and thus the potential for recharge during this period is at the yearly minimum. Precipitation in the winter and spring months facilitates the maximum potential for infiltration and recharge both because of steadier rains and because temperature and evapotranspiration are at their yearly lows. In the average year the water budget is in deficit; average yearly potential evapotranspiration exceeds the average yearly precipitation (Fig. 11).

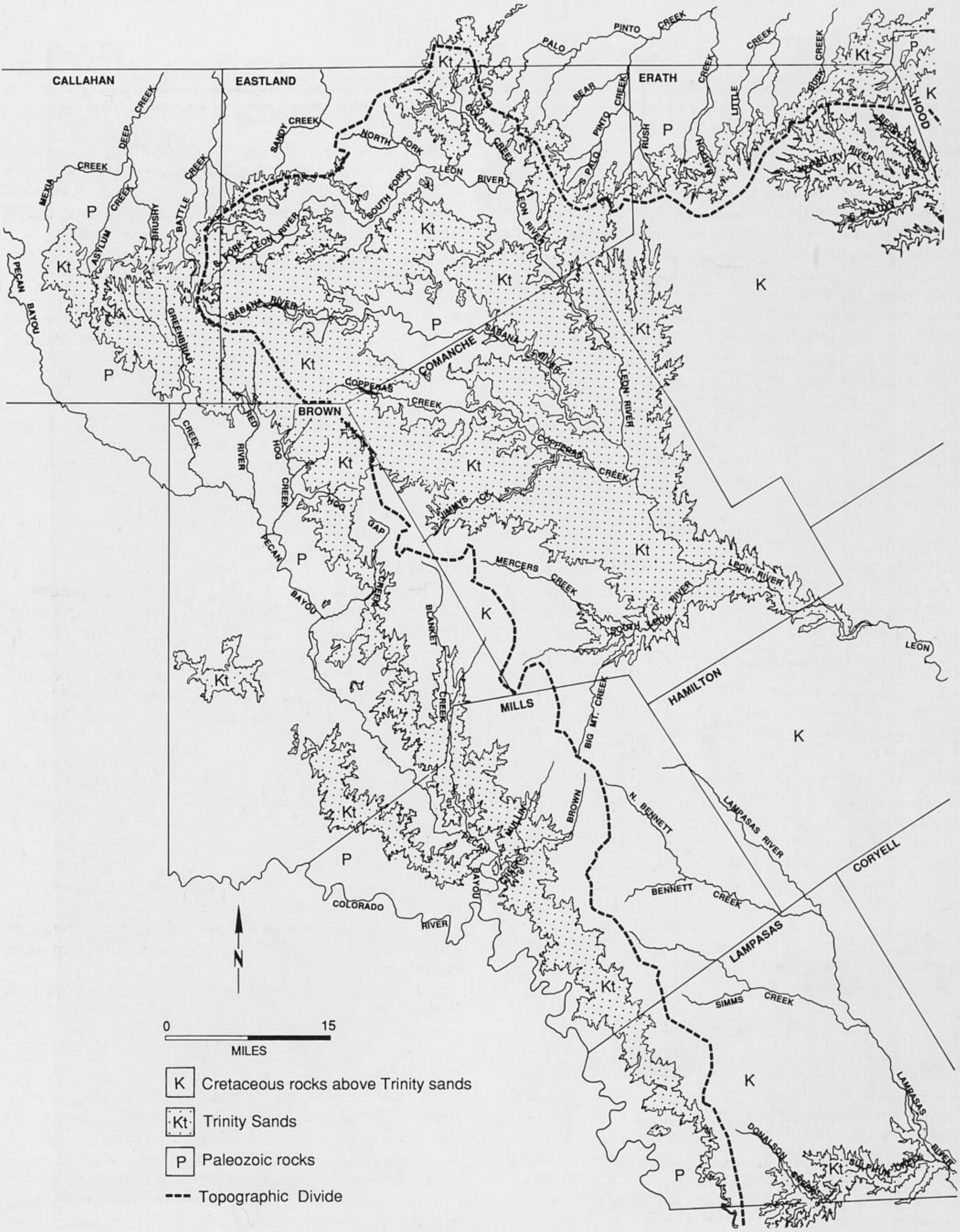

Fig. 8. Topographic divide separating the Leon, Paluxy, and Lampasas basins, from the Colorado and Brazos River basins in central Texas. The divide is developed on Fredericksburg and younger rocks in Lampasas, Mills, Brown, and Erath Counties, and on Trinity sands in Callahan, Comanche, and Eastland Counties. Westward draining tributaries of Pecan Bayou drain across the Trinity sands outcrop belt. Northward draining tributaries occur in the Palo Pinto basin. These westward and northward flowing streams are opposite in direction from the southeast flowing Leon, Paluxy, and Lampasas Rivers, which parallel the topographic and structural dip of Cretaceous rocks. (Modifed from Barnes, 1972, 1976)

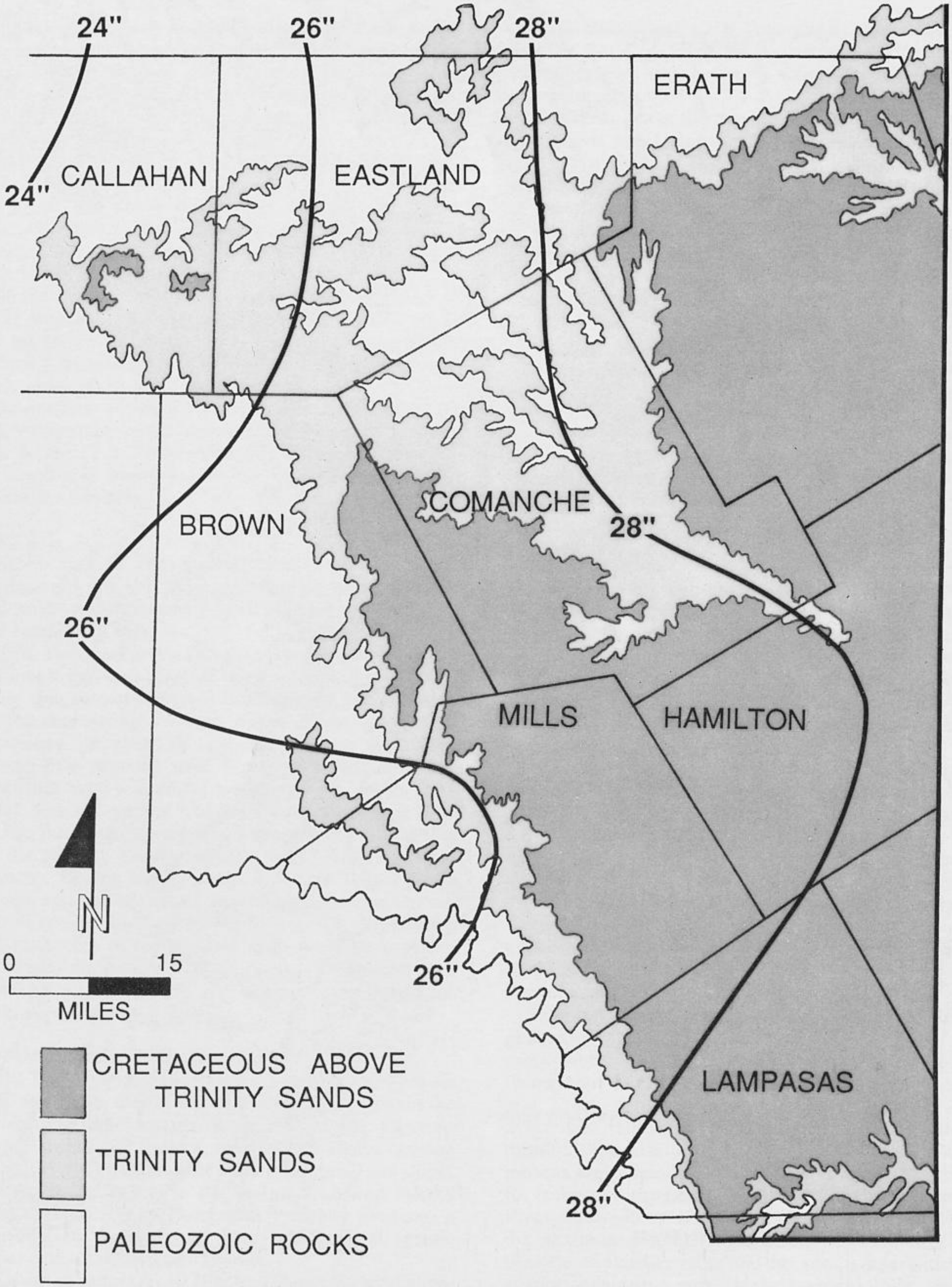

Fig. 9. Thirty year (1951 to 1981) average annual precipitation contour map of the Trinity sands outcrop belt, central Texas. Climatic trends vary in an east-west direction. Precipitation increases eastward from 24 inches in Callahan County to greater than 28 inches in Erath County. Comanche County, situated in the center of the study area, averages slightly greater than 28 inches of rainfall/year. The precipitation increases approximately 15 percent from west to east over the Trinity sands outcrop area. (Modified from Larkin and Bomar, 1983)

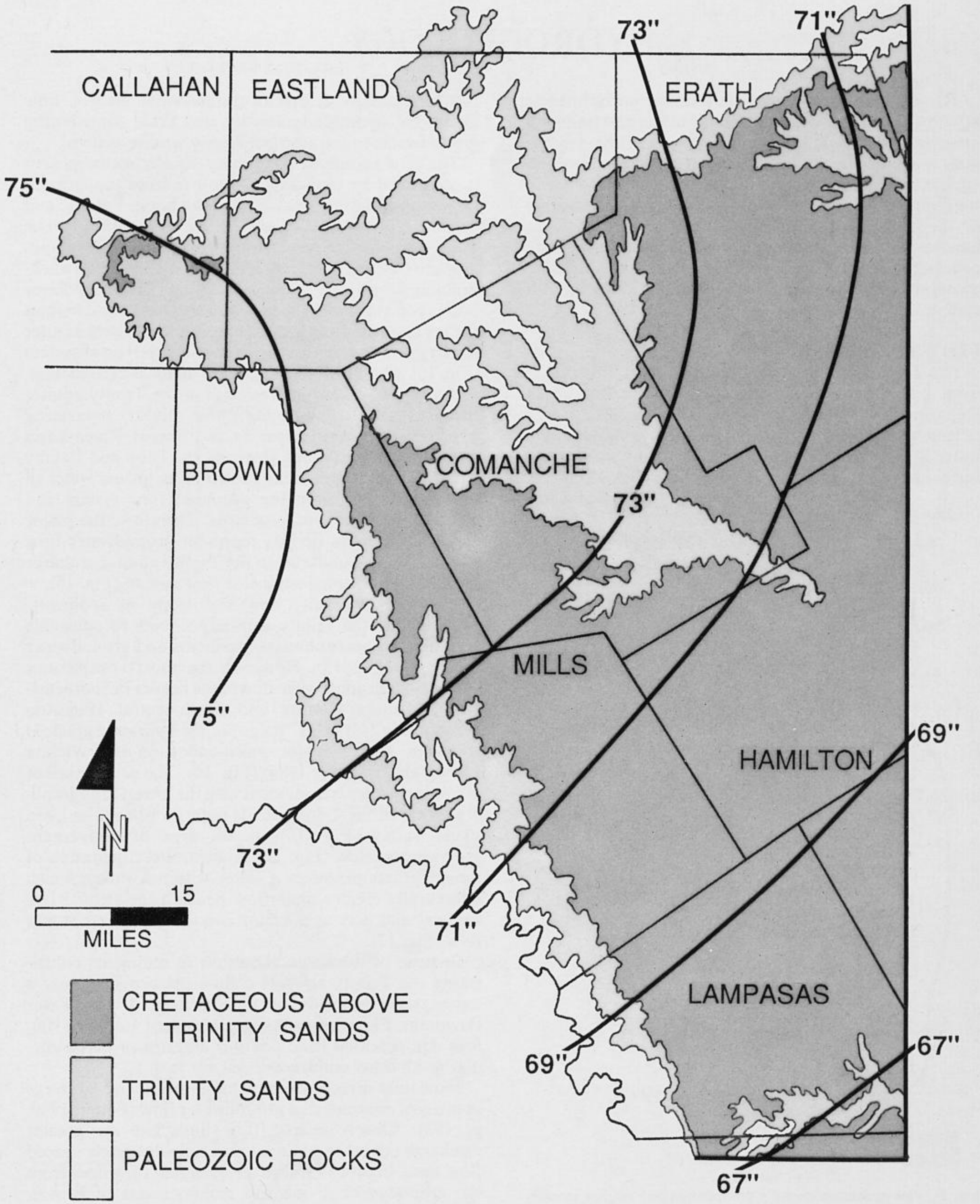

Fig. 10. Thirty year (1951 to 1981) average annual evaporation contour map of the Trinity sands outcrop belt, central Texas. The average annual evaporation is greatest in Callahan County with 75 inches of evaporation, and decreases eastward to 67 inches in Lampasas County. This west to east decrease in evaporation is opposite the rainfall trend, which increases eastward. Therefore the areas of greatest evaporation receive the least rainfall. These evaporative trends also imply that evapotranspiration decreases eastward throughout the Trinity sands outcrop belt. (Modified from Larkin and Bomar, 1983)

HYDROGEOLOGY

The Trinity aquifer resembles a classic unconfined to artesian aquifer flow system. Major urban and pumping areas are located in the artesian portion of the aquifer, and thus the groundwater resources of the artesian aquifer have been investigated in greater detail than in the unconfined aquifer, although it supplies recharge to the artesian aquifer. This introduces a significant handicap in management decisions. Therefore, this study concentrates on recharge, and especially the effective recharge that flows into the artesian Trinity aquifer system.

FLOW DIRECTIONS

The Trinity aquifer water level map was constructed from water level measurements made by the Texas Department of Water Resources over the study area (Klemt et al., 1975). Unconfined flow systems create water tables that are muted expressions of the general surface topography. The water level map (Fig. 12) shows this relationship. It defines groundwater divides, flow directions, hydraulic gradients, and areas contributing groundwater to the artesian Trinity aquifer system.

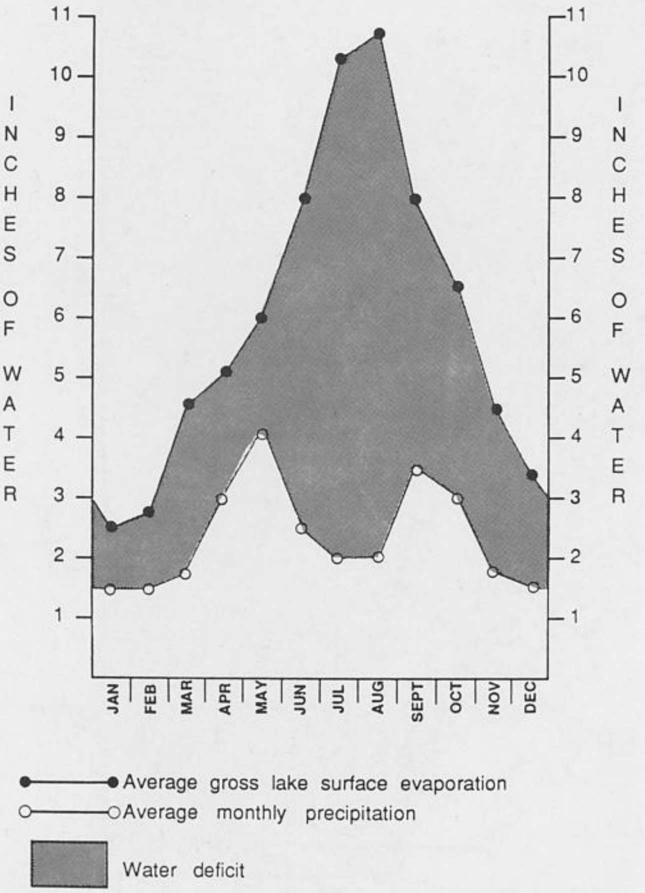

Fig. 11. Plot of average monthly precipitation and average monthly gross pan evaporation for Comanche, Comanche County, Texas. Pan evaporation rates are very close to actual evapotranspiration rates in sub-humid climates, suggesting that the monthly water budget between precipitation and evaporation, and indirectly evapotranspiration, is in deficit throughout the average year (Lomas and Levin, 1969, p. 223). (Modified from Larkin and Bomar, 1983)

The flow system of the Trinity aquifer recharge area is controlled by topography. Flow is from topographically high recharge areas toward the Leon, Paluxy, and Lampasas River valley discharge areas (Fig. 13, 14). The topographic divide separating westward-draining slopes in the Colorado River basin from southeastward-draining slopes in the Leon, Paluxy, and Lampasas River basins coincides with the groundwater divide and defines the area contributing groundwater to the Trinity aquifer recharge area and the regional southeast flow system (Fig. 15). Groundwater west of the divide is carried west, and does not contribute recharge in the Trinity aquifer recharge area. The topographic divide separating northward-draining slopes in the Brazos River basin from southeast-draining slopes in the Leon and Paluxy River basins defines areas contributing groundwater to the north, away from the southeast flow system and the Trinity aquifer recharge area. Therefore, the major topographic basin divides represent groundwater flow and recharge boundaries to the Trinity aquifer recharge area and the regional southeast flow system (Fig. 15).

Local heterogeneity and anisotropy of sediments comprised in the Trinity aquifer produces recognizable variations in potentiometric gradients and groundwater flowpaths (Fig. 13). However, the most conspicuous anomaly in groundwater flowpaths occurs in southeastern Comanche County and north-central Hamilton County (Fig. 13). This "bulge" in the hydraulic gradient coincides with a major paleo-valley on the Wichita Paleoplain (Atchley, 1986) (Fig. 16). The orientation of Hamilton Valley is coincident with the lowest topographic portion of the Trinity sands outcrop belt in the Leon River valley (Fig. 16), in an area of convergent groundwater flow (Fig. 12). The parallel orientation of these features produces a valley within a valley, which structurally creates underflow beneath the Leon River channel and acts as a major conduit for groundwater flow (Fig. 17).

Because of lithologic variations in sediments constituting the Trinity aquifer, a flow net provides only a qualitative method for determining groundwater flowpaths. Flow lines were equally spaced along the 900-foot equipotential head contour and drawn perpendicular to all other contours.

Flow lines diverge from recharge areas, and converge in areas of concentrated groundwater flow (Fetter, 1980, p. 153). Closely spaced flow lines indicate greater discharge per cross sectional area than do widely spaced flow lines. Figure 17 shows the divergent flow lines from the groundwater divide and recharge area in Brown, Comanche, Mills, and Lampasas Counties. The flow line convergence in southeastern Comanche County indicates that this is an area of concentrated groundwater flow coinciding with Hamilton Valley, and major groundwater flowpaths occur in major paleo-valleys on the

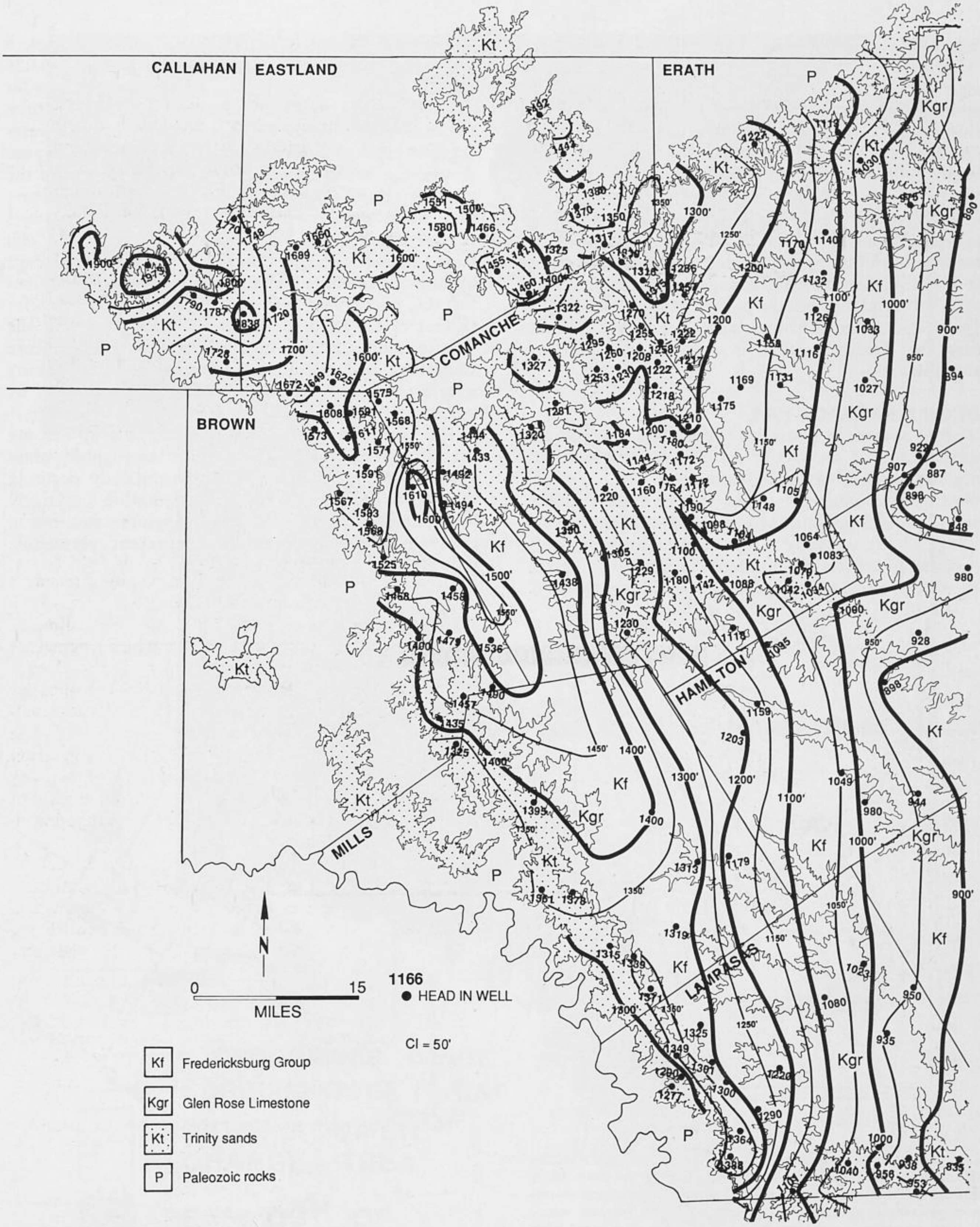

Fig. 12. Water level map (1969) for the Trinity aquifer, central Texas. The water level map includes the water table in the Trinity sands outcrop belt, the covered aquifer, and artesian Trinity aquifer. The highest head occurs where the Trinity aquifer is confined below the Glen Rose Limestone and Fredericksburg Group, creating groundwater divides. The regional groundwater gradient averages 10 to 25 feet/mile to the southeast. The flow direction is from the groundwater divides or recharge areas to the discharge areas of the Leon, Paluxy, and Lampasas Rivers. Where the Trinity aquifer is semi-confined below the Glen Rose Limestone, flow is to the southeast and recharge is derived through leakage. Groundwater flow in the Colorado River basin is to the west. In the Palo Pinto basin (Brazos River drainage) it is to the north.

Wichita Paleoplain (Atchley, 1986) (Figs. 16, 17).

The relative spacing of flow lines suggests that an exceptionally large amount of recharge originates in Comanche County both by normal recharge on the Trinity sands outcrop belt and through leakage contributions where the aquifer is covered by Glen Rose Limestone and Fredericksburg rocks. These observations closely parallel those of Hall (1976, p. 20), who concluded that the primary groundwater flowpath originated from the Trinity sands outcrop area in Comanche County. In the covered Trinity aquifer, flow line deviations are related to changes in aquifer thickness and facies variations, but the pattern of flow line spacing suggests that recharge from leakage is relatively uniform where the Trinity aquifer is covered by overlying formations.

AQUIFER PARAMETERS

Three parameters used to describe hydrologic characteristics of an aquifer are 1) hydraulic conductivity, 2) transmissivity, and 3) storage.

Hydraulic conductivity in the Trinity aquifer ranges from 17 to 235 gallons/day/square foot (Klemt et al., 1975, p. 12-13), attesting to the heterogeneity of sands comprised in the Trinity aquifer. Transmissivity values vary widely, ranging from 2700 to 42,000 gallons/day/square foot (Klemt et al., 1975, p. 12-13). Storage, a dimensionless value, ranges from 0.000028 to 0.026 (Klemt et al., 1975, p. 12-13). The unconfined aquifer exhibits higher values of storage (0.013 to 0.026) than the artesian aquifer (0.000028 to 0.000084) because water released in the unconfined aquifer represents pore space dewatering, while release of water from storage in the artesian Trinity aquifer results from aquifer compaction and water expansion. Predictably, in aquifer tests conducted where the Trinity aquifer is covered by Glen Rose Limestone and the Paluxy aquifer, values of storage lie midway (0.0011 to 0.00023) between the storage values for the unconfined and the artesian Trinity aquifer (Klemt et al., 1975, p. 12-13). This suggests that the Trinity aquifer is semi-confined below the Glen Rose Limestone and the Paluxy aquifer, and the Trinity aquifer becomes confined where it is covered by substantially thicker sediments.

The sandstones in the Trinity sands outcrop belt are the most permeable, and therefore the highest values of hydraulic conductivity and transmissivity occur in the sandstone facies. Secondary cementation has largely been restricted to the outcrop of conglomerates, but in the subsurface conglomerates represent permeable sediments.

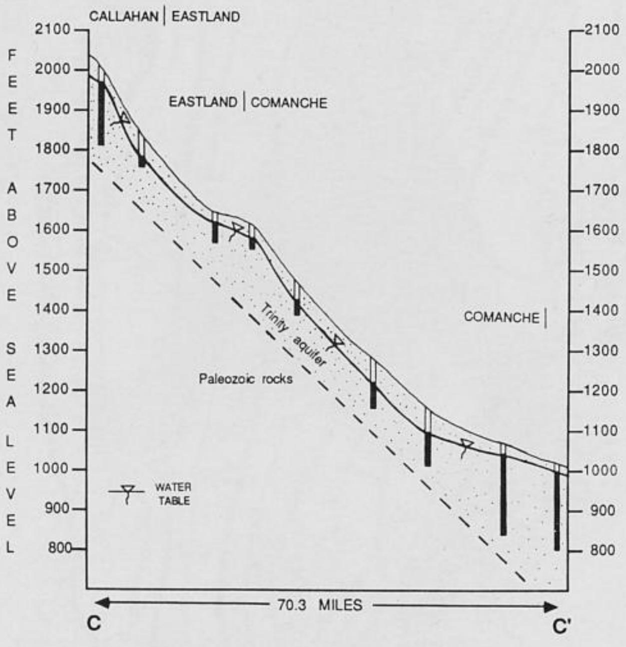

Fig. 13. Topographic profile with water levels in a line of section from the Callahan Divide in Callahan County, to the Leon River floodplain in Hamilton County, Texas. The water table gradient closely mimics surface topography. Water levels show an increase where surface elevation increases, and decreases in areas of reduced relief (the water table increase in northwestern Comanche County is affected by a third dimension of flow perpendicular to the page). The diagram clearly shows the topographic control of water levels along the Comanche-Hamilton County border where the structural dip and saturated thickness show no effect on water levels, but the water table level and gradients are affected by the surface topography. (For location of section line see Fig. 14.)

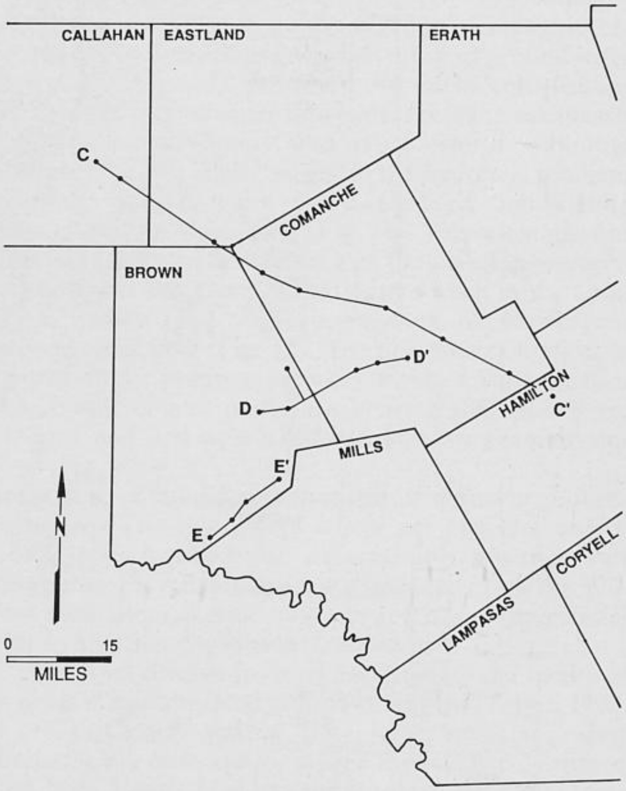

Fig. 14. Location of cross sections used to show water levels in relation to topography and lithology. Section C-C′ is from the Callahan Divide in Callahan County to the Leon River in Hamilton County (Figure 13). Section D-D′ includes water levels in different geologic units across the divide between the Colorado and Leon River basins (Figure 18). Section E-E′ contains water levels across an outlier of Trinity sands (Figure 19).

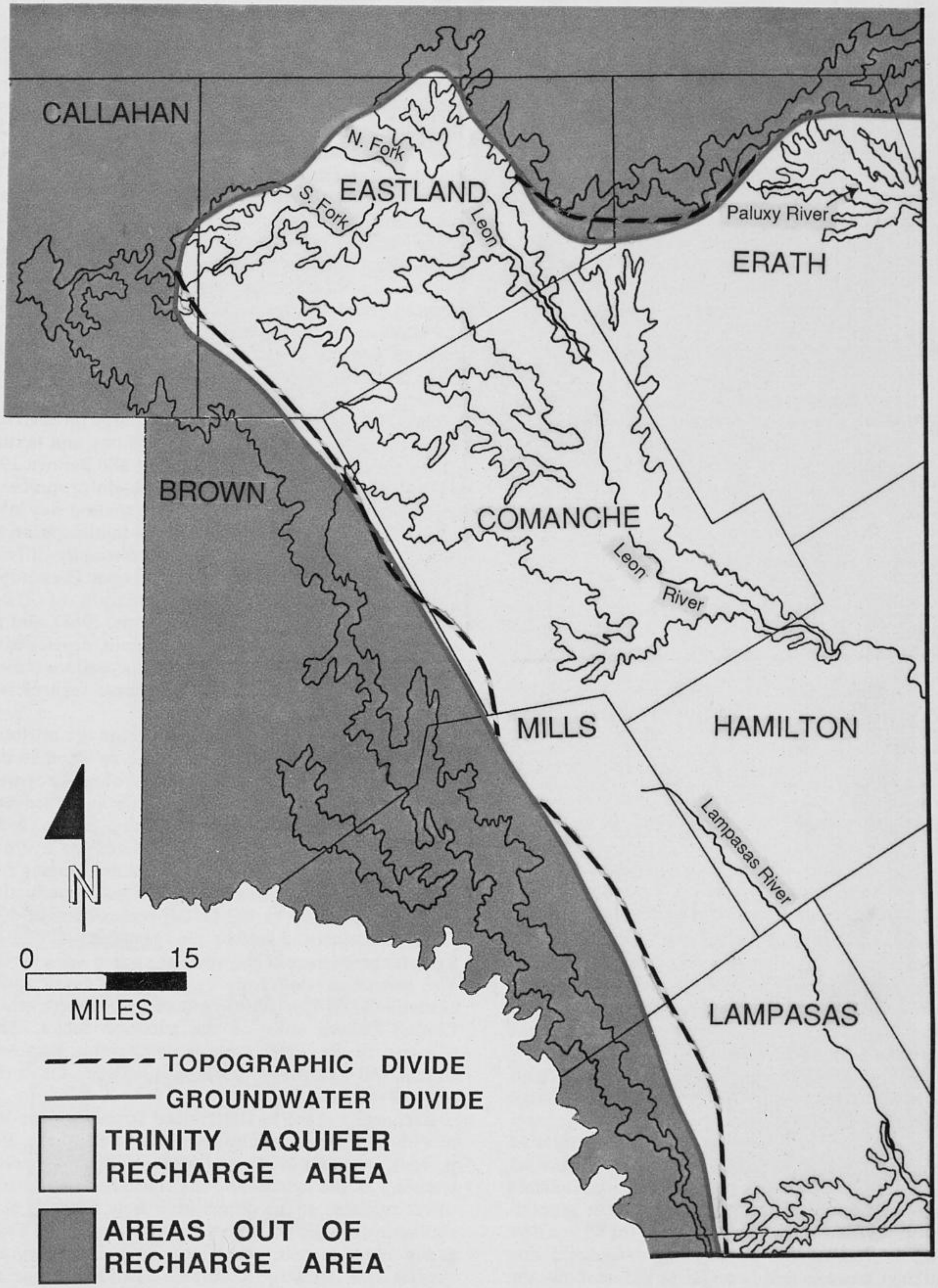

Fig. 15. Topographic and groundwater divides in the areas contributing groundwater in the Trinity aquifer recharge area. The groundwater divides and topographic divides closely correspond (based on 50 foot contour interval). The area contributing groundwater in the Trinity aquifer recharge area occurs in southeastward-draining Leon, Paluxy, and Lampasas River basins, an area of approximately 3100 square miles in central Texas. (Modified from Barnes, 1972, 1976)

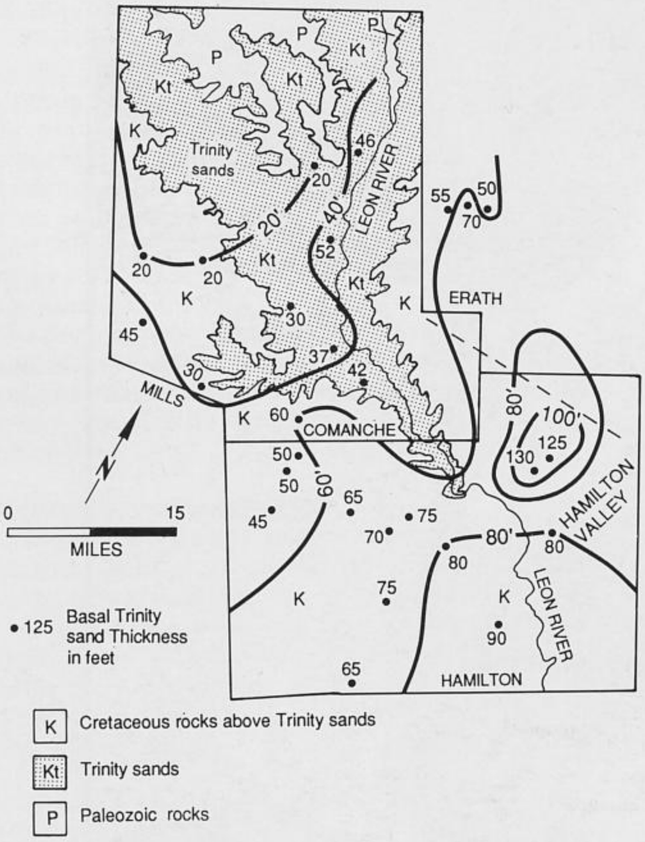

Fig. 16. Isopach thickness of basal Trinity sands, Comanche and Hamilton Counties, Texas. The isopach thickness of basal Trinity sands shows an increase in sediment thickness coinciding with a paleo-valley developed on the Wichita Paleoplain, approximately parallel to the present Leon River. The 10-15 mile-wide Hamilton Valley, with its increase in gravel and sand content, provides a significant increase in aquifer thickness through the paleo-valley, which dramatically affects groundwater flow. (Modified from Klemt et al., 1975)

AREAS AND SOURCES OF RECHARGE

Previous investigations concluded that 1.5 to 3.0 percent of the average annual precipitation falling on the entire 1700 square mile Trinity sands outcrop belt results in groundwater recharge (Klemt et al., 1975, p. 11). Although infiltration and recharge occur throughout the outcrop belt, effective recharge is determined by flow directions that follow the topographic expression, and large areas of the outcrop belt do not contribute recharge or groundwater to the artesian Trinity aquifer.

Determination of areas contributing groundwater to the artesian Trinity aquifer was based on the water level contour map (Fig. 12). Vertical head variations indicate leakage through confining beds and show the groundwater divide in the same general position for all aquifers (Fig. 18). A cross section through the drainage divide between the Colorado and Leon River basins shows the head distribution between east- and west-draining slopes. The water table is slightly asymmetric to the east, similar to the eastward asymmetry of topography (Fig. 18). Figure 15 shows the close correlation between topographic and groundwater divides. Groundwater flow in westward-draining slopes of the Colorado River basin is carried west, away from the regional southeast flow system in all Trinity, Glen Rose, and Paluxy layers (Fig. 18). Therefore, areas west of the groundwater divide lie outside the Trinity aquifer recharge area that contributes groundwater to the artesian Trinity aquifer system. Remnant outliers of Trinity sands in the Colorado River basin also lie west of the groundwater divide, and do not contribute groundwater to the artesian Trinity aquifer (Fig. 19).

Exclusion of areas north and west of the groundwater divides significantly reduces the total contributing outcrop recharge area from 1700 square miles to less than 760 square miles; this reduction means that more than 50 percent of the outcrop belt of Trinity sands does not contribute recharge to the artesian Trinity aquifer.

Calculations of infiltration and recharge through soils based on saturated hydraulic conductivity and textural classification may be incorrect (Freeze and Banner, 1970, p. 154). Subtle differences in hydrologic properties of soils caused by tension-cracks and restricting clay layers may account for significant variations in infiltration and recharge in the same soil, and two distinctly different soil types may act hydrologically the same. The complex lateral and vertical lithologic gradation of Trinity sandstones has been established (Boone, 1968), and this introduces significant variations in soils developed on Trinity rocks. However, water table fluctuations indicate that similar water level responses occur regardless of facies or soil development (Fig. 20).

Such similar responses to precipitation are attributed to three factors: 1) the shallow depth to water in each facies; 2) soil structure and similar hydrologic properties; and 3) lateral pressure migrations in the saturated zone. The Abilene-Cisco-Demona-Nimrod sandy loams developed on sandstone facies have saturated hydraulic conductivities in the upper 6 to 10 inches ranging from 2 to 6 inches/hour. The saturated hydraulic conductivity drops dramatically to 0.2 to 0.6 inches/hour at 10 to 73 inches below the surface, and this interval contains a greater percentage of clay than is exposed at the surface. The restricting clay zone in the sandy loam soils is equivalent to the blocky, tension-cracked, clayey Chaney-Deleon soils of the siltstone facies. Thus, recharge to the water table is comparable because of similar soil hydrologic properties between the surface and the saturated zone.

Recharge cannot be determined strictly on the basis of well hydrograph analysis (Freeze and Banner, 1970, p. 154). A water table rise may result from pressure transfers in the saturated zone that are not related to direct recharge at the observation well. Because of the similar hydrologic properties of soils covering the Trinity sands outcrop belt, variations in well hydrographs suggest that recharge occurs in both sandstone and siltstone facies (Fig. 20). However, the similar hydrograph responses may be the result of more recharge in some areas of the Trinity sands outcrop belt, thus increasing the head in the area of recharge; the increased

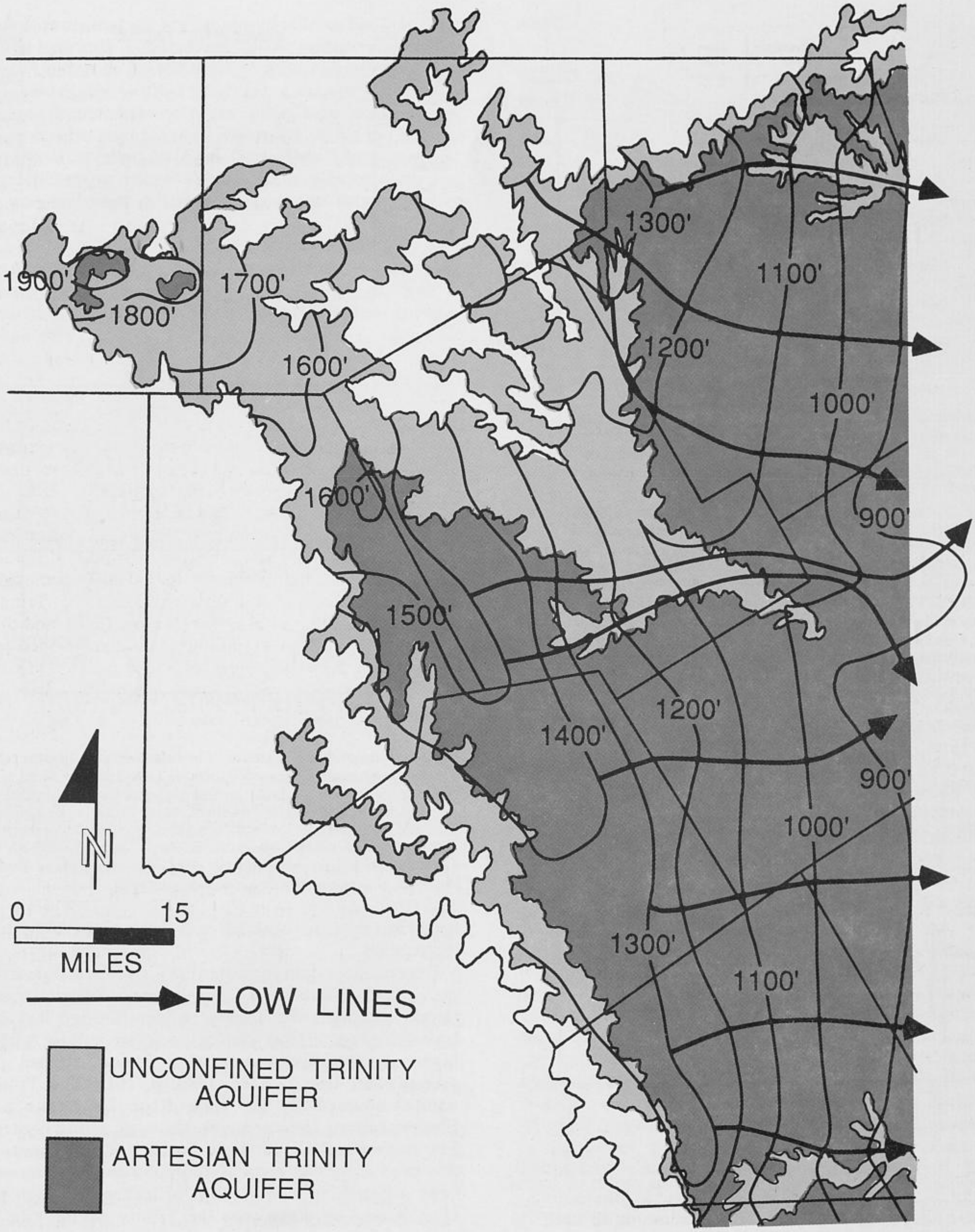

Fig. 17. Groundwater flowpaths and flow net for a portion of the Trinity aquifer, central Texas. The flow lines are equally spaced along the 900-foot equipotential contour, perpendicular to all other contours. Flow lines diverge from the recharge areas along the western divide in Brown, Mills, and Lampasas Counties, and the northern groundwater divide in Erath County, and converge east of the Trinity sands outcrop belt. The convergence in eastern Comanche County coincides with Hamilton Valley, developed on the Wichita Paleoplain. The flow net shows the paleo-topographic effect of the Hamilton Valley as a major groundwater flowpath.

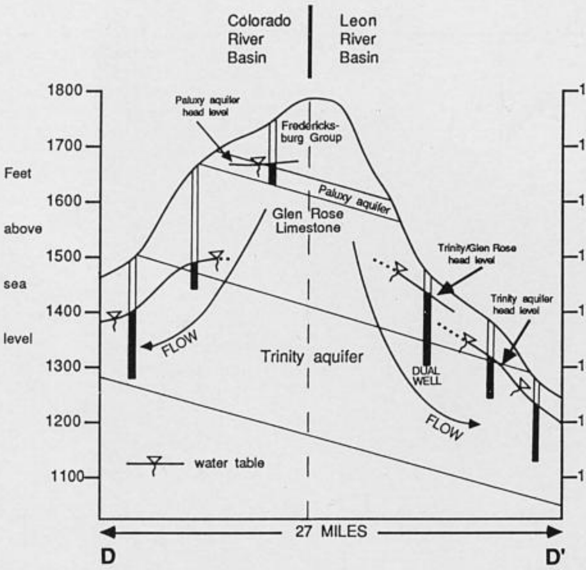

Fig. 18. Cross section showing geology, topography, and water levels across the divide separating the Leon and Colorado River basins, central Texas. The groundwater divide corresponds to the topographic divide between the Colorado and Leon River basins. Groundwater west of the divide does not contribute to the Trinity aquifer recharge area. The Paluxy water level is extrapolated from wells approximately 6 miles north of the line of section, and shows the higher head in the Paluxy aquifer throughout the region. A dual completed well in the Glen Rose Limestone and Trinity aquifer shows an intermediate water level, through the Glen Rose Limestone into the Trinity aquifer. (For location of section line see Fig. 14.)

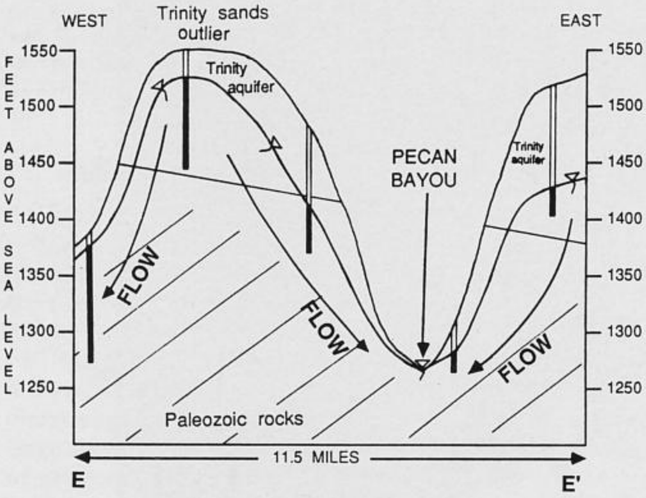

Fig. 19. Groundwater flow in isolated outliers of Trinity sands, Colorado River basin, central Texas. Local flow systems on outliers show recharge occurring on the topographically higher Trinity sands and flowing to discharge points in the Colorado River basin. The westward flowpath from the main Trinity sands outcrop area is also toward the discharge area in Pecan Bayou, which lies in the Colorado River basin west of the groundwater and topographic divide. Groundwater flow in the Paleozoic rocks also conforms to topographic control at shallow depths, and shows the strong control of topography on water levels and flow directions. (For location of section line see Fig. 14.)

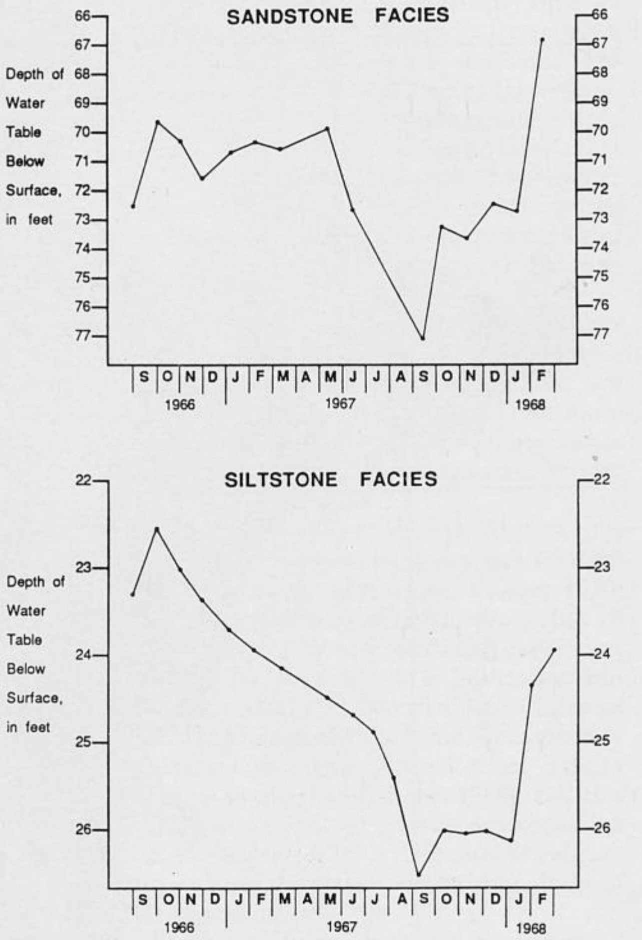

Fig. 20. Hydrographs of water wells in sandstone and siltstone facies in the Trinity sands outcrop belt, central Texas. Similar water table response is attributed to similar hydrologic properties of soils, shallow depth to water, and pressure transfers, which occur in the saturated zone and move laterally through the aquifer. Variations in water level response in both facies suggest that recharge occurs throughout the Trinity sands outcrop belt, but the coincident major peaks may be the result of head pressure transfers between wells.

head then migrates outward as a pressure wave through the aquifer.

Geochemical data indicate that significant flow from the overlying Glen Rose Limestone and Fredericksburg Group recharges the Trinity aquifer through leakage. In heterogeneous flow systems, a lower aquifer with a higher transmissivity acts as a major channel for groundwater flow (Fetter, 1980, p. 161). The Trinity aquifer covered by the Glen Rose Limestone and Fredericksburg Group represents such a flow system. The rate of leakage through the Glen Rose Limestone is a product of the vertical hydraulic conductivity and head differential. The amount of leakage through the Glen Rose Limestone into the Trinity aquifer can be assumed to be uniformly distributed along the aquifer/aquitard interface (Hantush, 1967, p. 583), and the head distribution in the aquifers supplying leakage can be assumed to be constant.

The Trinity and Paluxy sandstone aquifers generally exhibit hydraulic conductivities that result in flow components that are horizontal, parallel to bedding. The lower hydraulic conductivity of the semipervious Glen Rose Limestone is conducive to a flow component that is more nearly vertical (Fig. 21). Leakage also occurs where Fredericksburg rocks have been removed by erosion, although leakage is greatest where the Trinity aquifer is overlain by *both* Glen Rose Limestone and Fredericksburg rocks because of a greater saturated section and head differential above the Trinity aquifer (Fig. 22).

The Glen Rose Limestone acts as a confining bed between the overlying Paluxy aquifer and the underlying Trinity aquifer. Although the Trinity aquifer is semiconfined below the Glen Rose Limestone, groundwater head data indicate that the flow component is downward from the Paluxy aquifer, across the Glen Rose Limestone and into the Trinity aquifer (Fig. 23), further suggesting that leakage through the Glen Rose Limestone represents a significant recharge source to the Trinity aquifer. Recharge derived from a saturated source above the Trinity aquifer is not subject to the same meteorologic and climatic conditions as recharge derived from precipitation on the Trinity sands outcrop belt, which is seasonal. Drought conditions may result in little or no recharge for extended periods (Fig. 24), but leakage to the Trinity aquifer through the Glen Rose Limestone occurs throughout the year.

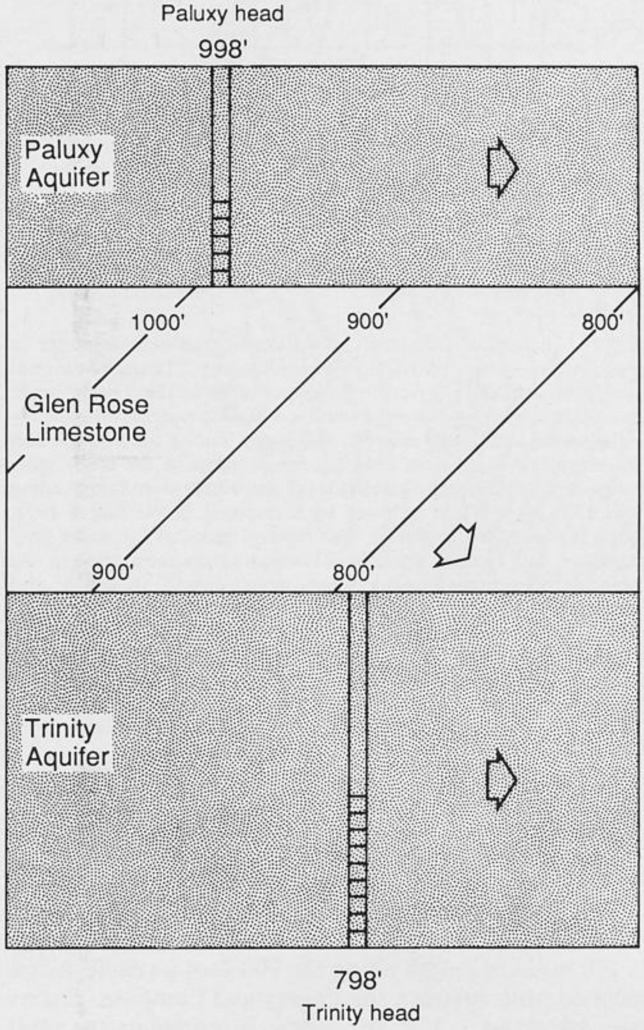

Fig. 21. Diagrammatic profile of head distribution and flow between the Paluxy aquifer, Glen Rose Limestone, and Trinity aquifer. The flow component in the Trinity and Paluxy aquifers is essentially horizontal, while flow in the Glen Rose Limestone with a lower hydraulic conductivity creates an increased gradient downward. The substantially higher head in the Paluxy aquifer creates a strong vertical flow component into the Trinity aquifer. The rate of leakage through the Glen Rose Limestone is a product of the vertical hydraulic conductivity and the head differential across it. The head drop is large, and the vertical hydraulic conductivity is relatively small, thus leakage per unit area of Glen Rose Limestone/Trinity aquifer interface is small, but the total area of this interface is large, and therefore the total leakage along the interface is large.

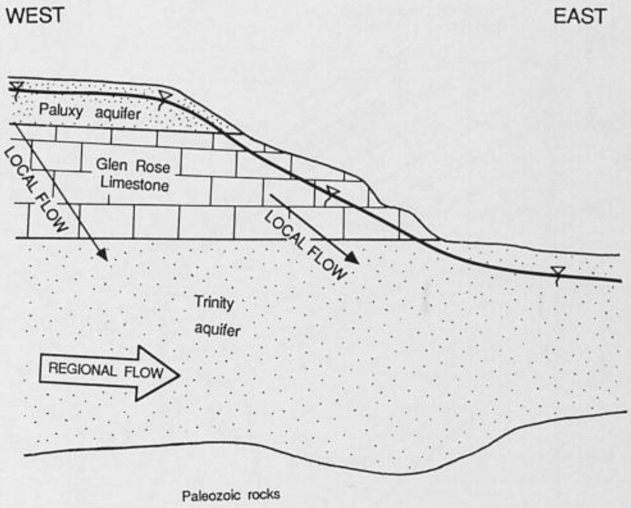

Fig. 22. Diagrammatic water table profile of the Trinity aquifer overlain by the Glen Rose Limestone and Paluxy aquifer in the Trinity sands outcrop belt, central Texas. The higher transmissivity of the Trinity aquifer allows it to carry all the leakage from the Glen Rose Limestone, as is evident by the absence of springs along the contact of the Trinity sand and Glen Rose Limestone. This suggests that the vertical hydraulic conductivity in the Trinity aquifer is greater than the horizontal hydraulic conductivity in the Glen Rose Limestone, and although the Trinity aquifer is semi-confined below the Glen Rose Limestone, the Glen Rose is a leaky confining bed. Note the greater head differential where the Paluxy aquifer is present, leading to maximum recharge beneath the Fredericksburg section.

In the Trinity aquifer recharge area, leakage is considered uniform where the Trinity aquifer is covered by the Glen Rose Limestone and rocks of the Fredericksburg Group, whereas recharge is variable in the outcrop area of Trinity sands. Rainfall is lowest in the upper portions of the Leon River basin where dissection of Trinity sands is greatest (Fig. 15). Therefore, recharge should be lowest in the northwestern portions of the Trinity sands outcrop belt. Rainfall is greatest in the lower portions of the Leon River basin in Comanche County, dissection is minimal, and thus recharge should be greatest in the eastern half of Comanche County. Also, because the southeastern portion of Comanche County coincides with the Hamilton Valley (Fig. 16) and a major groundwater flowpath (Fig. 17), this area is probably the major recharge area in the entire Trinity aquifer, and thus deserves more attention from a recharge management standpoint than any other portion of the aquifer.

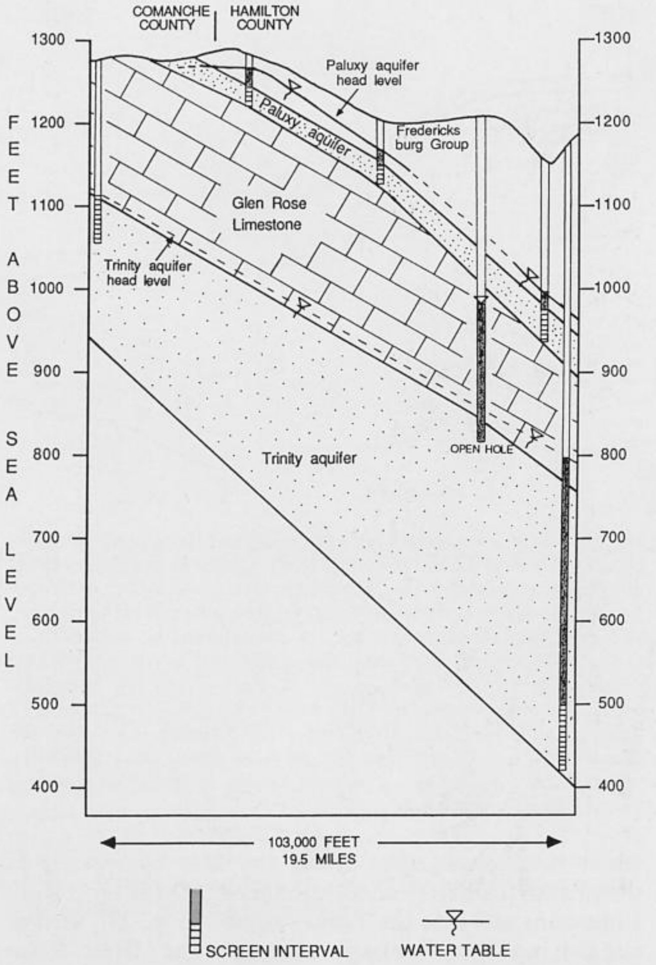

Fig. 23. Cross section and water levels in the Trinity aquifer, and overlying formations in Comanche and Hamilton Counties, Texas. Water levels in the Paluxy aquifer vary from 50 to 250 feet above the Trinity aquifer, which creates a strong downward gradient from the Paluxy aquifer to the Trinity aquifer. The "open hole" well in Hamilton County shows that the combined head is significantly lower than the Paluxy potentiometric level, and significantly higher than the Trinity potentiometric level. The water level in the open well is approximately midway between the levels in the Trinity aquifer and Paluxy aquifer, and indicates that the head and flow direction is downward from the Paluxy aquifer and Glen Rose Limestone and into the Trinity aquifer. The Glen Rose Limestone, although a confining bed to the Trinity aquifer, is a leaky confining bed that contributes recharge not only along groundwater divides, but throughout the area where Glen Rose Limestone covers Trinity sands.

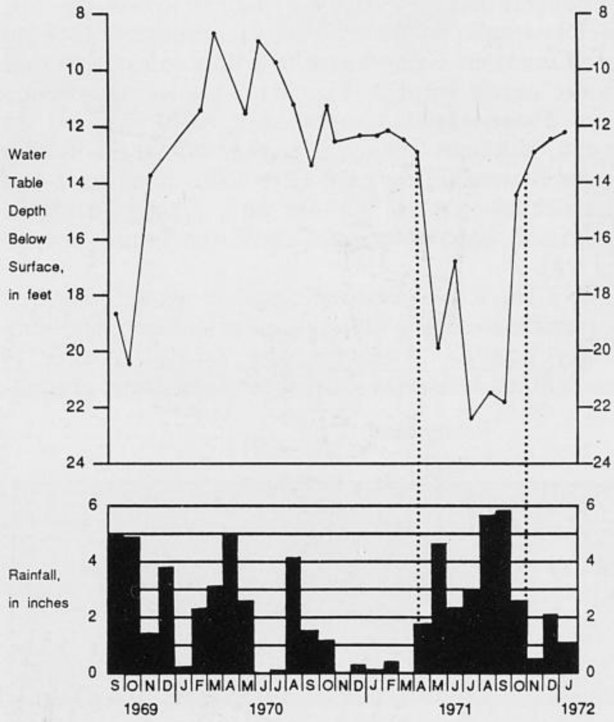

Fig. 24. Seasonal fluctuations in well hydrographs in response to precipitation near Baird, Callahan County, Texas. Seasonal fluctuations in water level show that recharge in the Trinity sands outcrop belt is largely seasonal, with the highest water level typically in the spring and winter months, and lowest during the summer and fall months. A significant time lag for recharge to the water table is suggested by the graph. Rain in the fall and winter months (extending from 1970 to 1971), is followed by a response in the fall of 1971. Given the extended length of time (several months) for water level responses, this appears unlikely. Recharge occurs most often in the spring and winter months when precipitation is heavy and evapotranspiration is low. Lack of precipitation in the spring months results in little recharge reaching the water table, and the resulting drop of water levels in the summer and fall occurs as a result of evapotranspiration and pumping, even when precipitation is heavy. (Modified from Price et al., 1983)

AMOUNT OF EFFECTIVE RECHARGE

Effective recharge (the amount of groundwater entering the artesian Trinity aquifer from the Trinity aquifer recharge area) was determined by calculating the total volume of water the aquifer will transmit annually between the Trinity sands outcrop belt and the artesian Trinity aquifer (see Appendix I, Fig. 30). The annual volume of water the aquifer will transmit was based on 1969 water levels, and determined by the formula

$$Q = TIW$$

where

Q = volume of water in gallons/day moving through the aquifer;
T = transmissivity of the aquifer in gallons/day/square foot;
I = 1969 hydraulic gradient in feet/mile; and
W = width of the aquifer segment in miles normal to the gradient.

The line of section used to determine effective recharge is 106 miles in length along the 900-foot potentiometric head contour between the Paluxy and Lampasas Rivers (see Appendix I, Fig. 30), where it represents the total effective recharge from the Trinity aquifer recharge area. The assumptions are that the Paluxy and Lampasas Rivers are fully penetrating streams at the 900-foot equipotential head contour, and that the 900-foot equipotential head contour remains stationary throughout the year. However, because the Paluxy and Lampasas Rivers are not fully penetrating streams, this assumption introduces a small positive error in effective recharge calculations. Due to the slow movement of groundwater, individual recharge events in the Trinity sands outcrop belt and pumping trends should have a

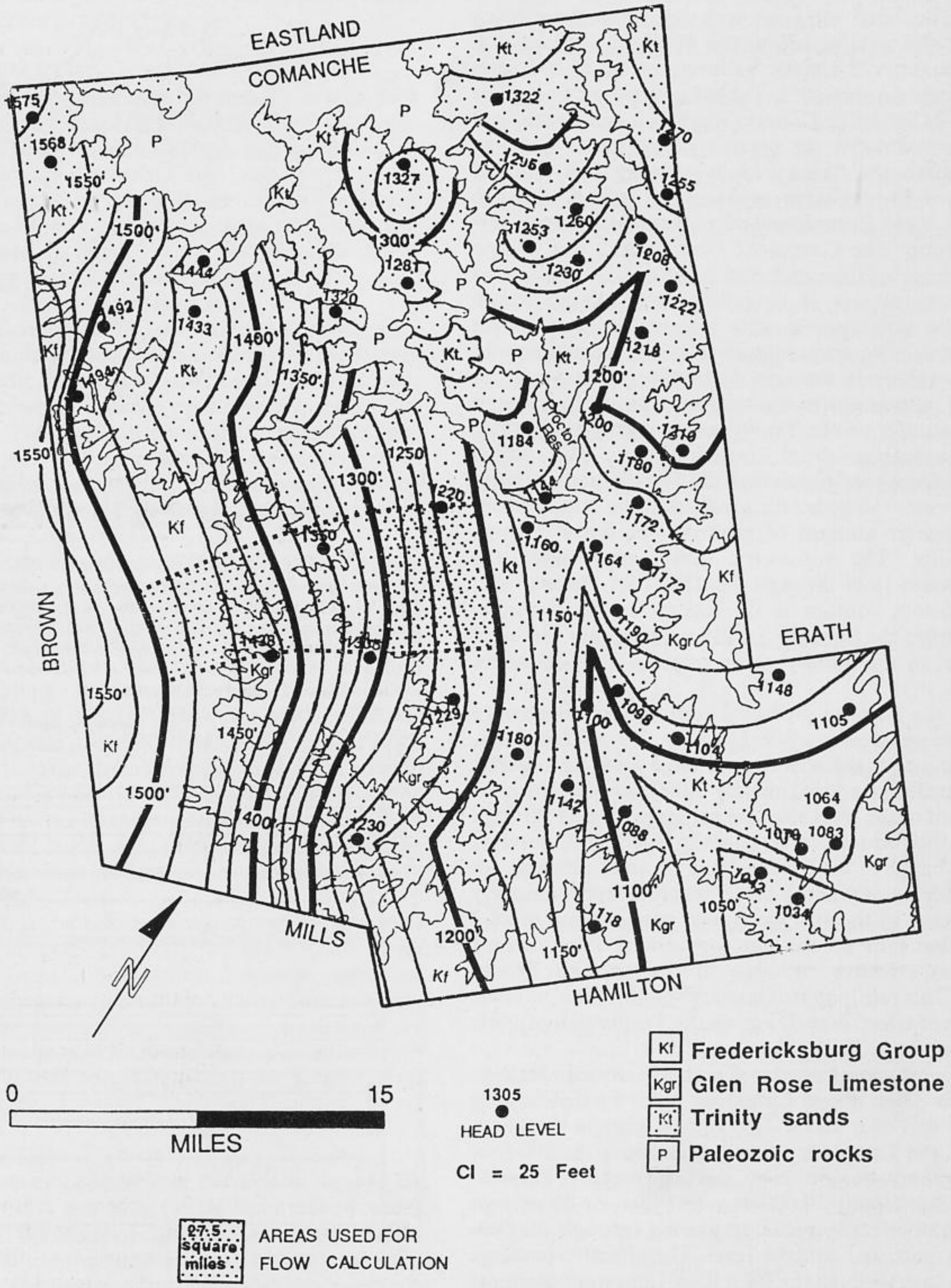

Fig. 25. Water level map of Comanche County, Texas. The relative recharge occurring on the outcrop belt compared to leakage through the Glen Rose Limestone and Fredericksburg Group was determined by the transmission capacity of the aquifer in equal (27.5 square mile) surface areas. Approximately 60 percent of the recharge occurs through leakage from the Glen Rose Limestone and Fredericksburg Group, and 40 percent in the Trinity sands outcrop belt. The increased gradient of the water table in the Trinity sands outcrop belt is created by both the leakage additions from the Glen Rose Limestone and Fredericksburg Group, and the decrease in aquifer thickness due to erosion. Recharge through leakage is a continual process, occurring throughout the year, while areal recharge on the outcrop belt is seasonal and largely dependent on rainfall. Thus a significantly greater amount of recharge occurs through leakage.

negligible effect on the hydraulic gradient in the artesian Trinity aquifer at the 900-foot equipotential head contour.

The calculated effective recharge annually moving through the aquifer below the 900-foot contour was approximately 22,326,600 gallons/day, or 25,000 acre-feet/year (see Appendix I, Table 1). Based on an aquifer section in Comanche County (Fig. 25), it was determined that approximately 40 percent of the areal recharge occurred on the Trinity sands outcrop belt, and 60 percent of the recharge occurred by leakage through the Glen Rose Limestone and rocks of the Fredericksburg Group. The Comanche County area was chosen to determine relative recharge contributions because of low concentrations of irrigation wells, adequate well control to determine aquifer dimensions, and simple topography. The covered portion of the Trinity aquifer shows a relatively uniform hydraulic gradient and an increase in gradient in the transition from the covered Trinity aquifer to the Trinity sands outcrop belt (Fig. 25). The leakage from overlying units plus added recharge from precipitation on the Trinity sands outcrop belt increases the hydraulic gradient in the outcrop belt, and a greater amount of groundwater flows through the aquifer. The volumetric difference between the groundwater flow through the 1350-foot contour and the 1200-foot contour is the leakage recharge contribution from the covered Trinity aquifer, and the areal recharge on the Trinity sands outcrop (see Appendix II).

Since the outcrop area contributing groundwater to the recharge area is approximately 760 square miles, or 45 percent of the effective recharge area, the outcrop belt contributes approximately 5,000 acre-feet/year, or 20 percent of the total effective recharge passing through the 900-foot equipotential contour level. This amounts to an average of 0.12 inches/year of areal recharge on the Trinity sands outcrop belt. Therefore, approximately 0.42 percent of the average annual precipitation of 28.2 inches that falls on the outcrop belt of Trinity sands results in effective recharge to the artesian Trinity aquifer. This rate is approximately one-third the previous estimate of effective recharge on the Trinity outcrop belt (Klemt et al., 1975, p. 11).

The Trinity aquifer receives recharge through leakage from the Glen Rose Limestone and Fredericksburg Group rocks over about 2350 square miles in the Leon, Paluxy, and Lampasas River basins above the 900-foot potentiometric contour level. Leakage recharge contributes approximately 20,000 acre-feet/year, or 80 percent of the total effective recharge passing through the 900-foot equipotential contour level. The effective recharge from leakage through the Glen Rose Limestone amounts to 0.159 inches/year.

In 1969 in Comanche County alone, 1000 irrigation wells withdrew in excess of 11,500 acre-feet, primarily to irrigate peanut crops (TDWR, 1981, p. 141) (Fig. 26). The return flow from irrigation is low, for most irrigation water is lost through evapotranspiration (Lomas and Levin, 1969, p. 223). Had this large amount of groundwater not been withdrawn from the unconfined

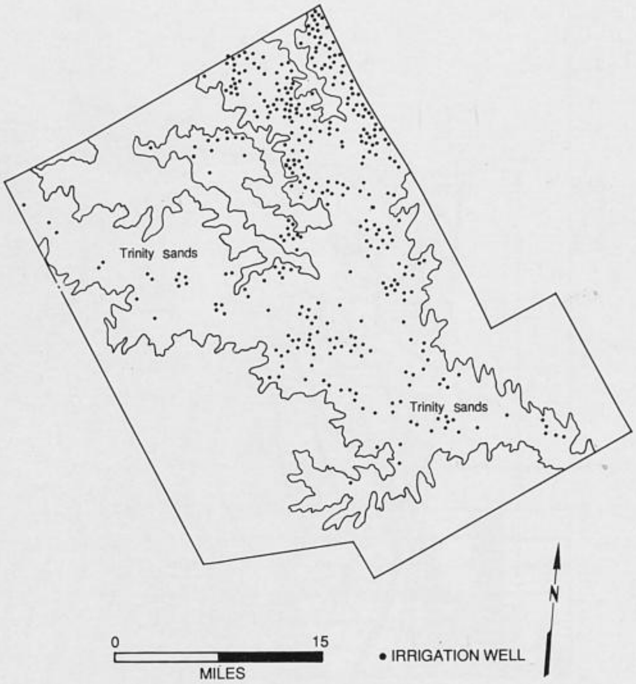

Fig. 26. Map of irrigation wells in Comanche County, Texas. Many of the irrigated fields in Comanche County contain more than one well. Therefore, only a small fraction of the 1000 irrigation wells is shown, although the concentration of wells is representative of well spacing in the county. (Modified from Klemt et al., 1975)

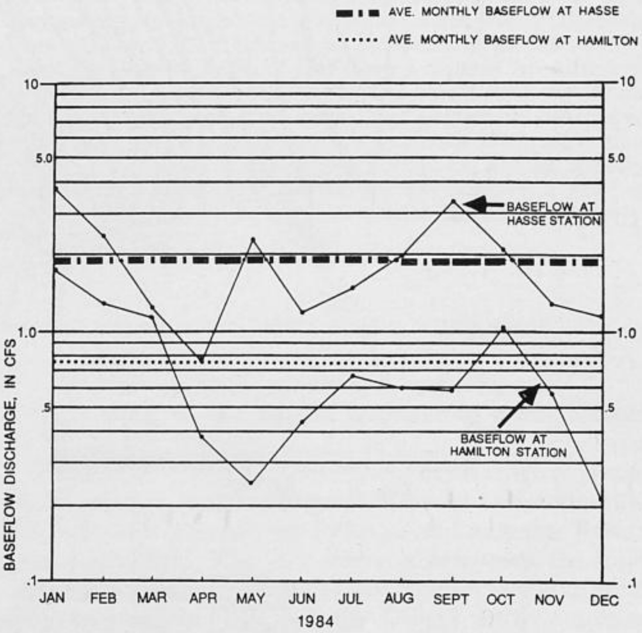

Fig. 27. Base flow discharge hydrograph from USGS gauging stations on the Leon River at Hamilton, Hamilton County, and Hasse, Comanche County, Texas. The average monthly baseflow at Hasse, 52 miles upstream from Hamilton, is consistently higher than at the Hamilton gauging station throughout the year. Variations in baseflow occur in response to recharge events, and under normal conditions baseflow should increase downstream from Hasse to Hamilton. However, there is clearly a loss of baseflow downstream, indicating that baseflow recharges the unconfined aquifer in the lower reaches of the Leon River in the Trinity sands outcrop belt.

Trinity aquifer, recharge on the Trinity sands outcrop belt would be approximately 3.2 percent of the average annual precipitation, which is significantly higher than the effective recharge of 0.42 percent.

DISCHARGE AREAS

Groundwater discharge occurs naturally as base flow to streams and by evapotranspiration. The discharge points in the Trinity sands outcrop belt occur in the channels of perennial streams: the Leon, Paluxy, and Lampasas Rivers. The Leon River drains the major portion of the Trinity aquifer recharge area, and was therefore studied in detail. While the channels of the Paluxy and Lampasas Rivers received less attention, they appeared to be discharge areas as well.

Base flow discharge to the Leon River is a consequence of the water table gradient in the vicinity of the stream channel. Periodic increases in base flow result from water table rises following recharge events, which tend to be seasonal (Fig. 27). Field observations suggest that base flow in the Leon River consistently decreases downstream in the lower reaches of the Trinity sands outcrop belt, indicating that water is lost from the channel to the aquifer.

The Leon River becomes perennial upon flowing over the Trinity sands, clearly indicating that it receives its base flow from the unconfined Trinity aquifer. Base flow hydrographs near Hamilton and Hasse, 52 miles upstream from Hamilton, show that somewhat less than half of the discharge at Hasse arrives at Hamilton (Fig. 27) (USGS, 1984, p. 316-317). However, the Leon River is a gaining stream from 30 to 45 miles downstream from Hasse, where the stream bed is composed of alluvial sands. Baseflow is lost through alluvial gravels in the stream bed from 7 to 22 miles upstream from Hamilton (Fig. 28). In this reach, the water table lies below the channel, and baseflow recharges the unconfined Trinity aquifer.

The concentrated discharge areas along river channels represent about 2 to 5 percent of the Trinity sands outcrop area. In addition to direct discharge, losses are attributed to evapotranspiration by floodplain woodlands along the rivers. This may equal or exceed the baseflow discharge to the rivers, but it is a loss that is difficult to assess, and was beyond the scope of this study.

GEOCHEMISTRY

Works on water chemistry in the Trinity aquifer by Henningsen (1962) and Hall (1976) have related water chemistry to recharge areas and to depositional environments. Published geochemical data (Klemt et al., 1975) support the findings from physical hydrogeology that water chemistry is most directly related to leakage from the overlying Glen Rose Limestone. Therefore, chemical analyses of waters from Trinity wells were used to define the suite of characteristic ions, which were then plotted on trilinear diagrams and related to ion sources.

Groundwater in the sandstones of the Trinity sands outcrop belt shows a distinctly different chemical ion suite in comparison to water recharging the Trinity aquifer through the Glen Rose Limestone (Fig. 29). Samples were analyzed along groundwater divides, where flow is essentially downward (Fig. 18), creating a suite of ions derived from the overlying material (Fig. 29).

Water moving downward from the Glen Rose Limestone into the Trinity aquifer is higher in sodium, chloride, and sulfate (Fig. 29). This signature is characteristic of leakage through the Glen Rose Limestone, and corresponds to Henningsen's (1962, p. 28) Llano source water mass both in chemistry and location.

Sodium bicarbonate-sodium sulfate groundwater occurs down-gradient from the Trinity sands outcrop belt, a product of mixing the recharge from the Trinity sands outcrop belt with leakage through the Glen Rose Limestone. The bicarbonate water from the outcrop belt mixes with sodium sulfate water from leakage, and the calcium bicarbonate water signature from the Trinity sands outcrop belt disappears. As groundwater migrates down its southeast flowpath, water chemistry changes

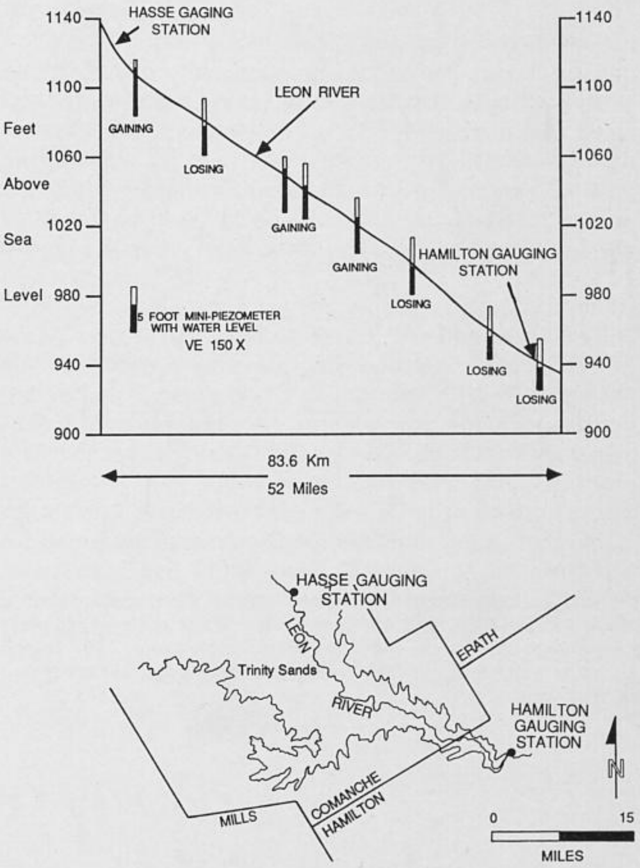

Fig. 28. Data from mini-piezometers installed in the Leon River stream bed, Comanche and Hamilton Counties, Texas. Higher water levels in the piezometer indicate the stream is gaining; lower water levels indicate the flow is downward, and the water table lies below the stream channel. The Leon channel lies above the water table from 7 to 22 miles upstream from the Hamilton gauge, as is evident from piezometers with lower water levels.

from calcium bicarbonate in the Trinity sands outcrop belt to sulfate water of leakage recharge, and eventually toward higher chloride concentrations as the residence time increases. Ion concentrations become more pronounced as water migrates eastward to the Balcones fault zone, where the dip of the rocks increases depth and temperature, leading to rapid increases in salinity eastward.

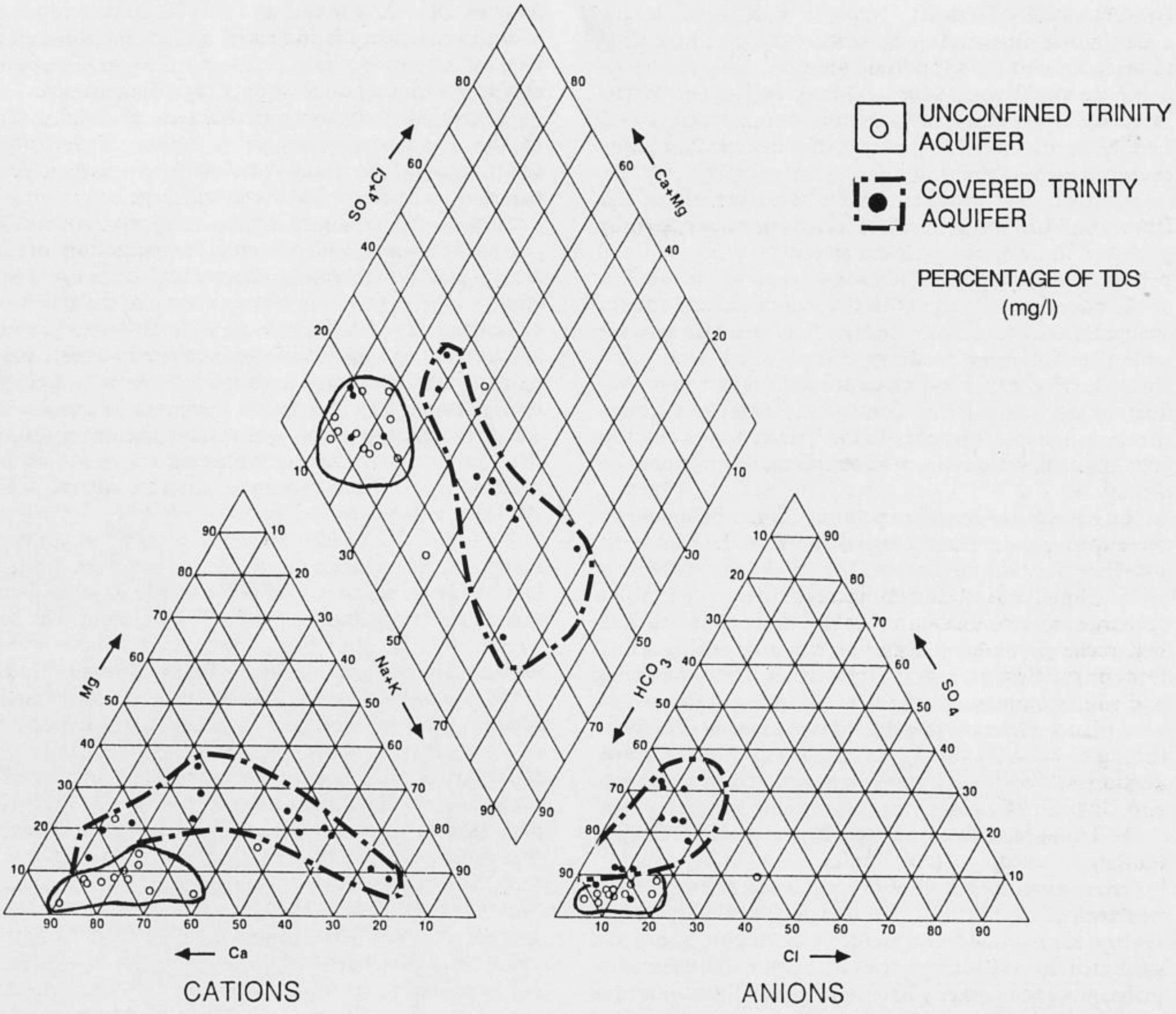

Fig. 29. Trilinear diagrams of water analyses from selected wells in the Trinity aquifer, central Texas. Water in the Trinity sands outcrop belt is dominated by calcium bicarbonate. Water chemistry in wells where the Trinity aquifer is overlain by the Glen Rose Limestone shows a significant increase in sodium, sulfate, and chloride. The increase in sodium and sulfate from the calcium bicarbonate phase apparently occurs as water recharges the Trinity aquifer through leakage from the Glen Rose Limestone. This strongly supports similar conclusions based on head data.

CONCLUSIONS

1. Local flow systems to the north and west and outliers of Trinity sands do not contribute groundwater to the artesian Trinity aquifer. This reduces the contributing area of Trinity sands outcrop by approximately 55 percent in the study area.

2. Recharge occurs through leakage from overlying formations as well as on the Trinity sands outcrop belt. Leakage from overlying units adds 75 percent more recharge area in this study.

3. Most of the effective recharge occurs as leakage from overlying formations (80 percent), rather than by precipitation on the Trinity sands outcrop belt (20 percent).

4. Effective recharge to the artesian Trinity aquifer is significantly reduced by heavy irrigation in the outcrop of the Trinity aquifer recharge area.

5. The covered Trinity aquifer in Comanche, Brown, Mills, and Lampasas Counties, along the major groundwater divides, has always received leakage from overlying formations. However, areas of the artesian Trinity aquifer to the east previously had wells flowing at the surface, and, with the reduction in artesian head, have thus only recently started receiving leakage from overlying formations.

6. Climatic factors that increase the potential for recharge increase eastward. In the Trinity sands outcrop belt recharge potential occurs primarily during short-term precipitation events (largely confined to the spring and winter months).

7. The Leon River is both a gaining and losing stream through the Trinity sand section, losing in the lower portions of the Trinity sands outcrop area in Comanche and Hamilton Counties.

8. Topography controls flow directions more directly than structural dip in the unconfined aquifer, as is evident by cross formational flow in local systems to the west and north.

9. Paleo-topography affected deposition, and subsequently affects groundwater flowpaths and recharge to the artesian Trinity aquifer. The major area of recharge in the Trinity aquifer recharge area is in eastern Comanche County, where the Hamilton Valley acts as a major groundwater flowpath from the Trinity sands outcrop belt to the artesian Trinity aquifer.

10. Where the Trinity aquifer is overlain by Glen Rose Limestone the water chemistry exhibits a significant increase in sodium sulfate and chloride ions. This change in water chemistry is indicative of leakage through the Glen Rose into the Trinity aquifer and supports conclusions based on flow data regarding leakage.

11. Recharge on the outcrop area of Trinity sands in the Leon, Paluxy, and Lampasas River basins contributes approximately 5,000 acre-feet/year, or 20 percent of the annual effective recharge to the artesian Trinity aquifer. This amounts to approximately 0.42 percent of the average annual precipitation of 28.2 inches, resulting in approximately 0.12 inches/year areal effective recharge on the Trinity sands outcrop belt.

12. Recharge to the covered Trinity aquifer from leakage through the overlying Glen Rose Limestone and Fredericksburg Group contributes 20,000 acre-feet/year, or 80 percent of the effective recharge to the artesian Trinity aquifer. The average specific discharge through the Glen Rose Limestone approximates 0.159 inches/year, or a vertical hydraulic conductivity of 4.2×10^{-10} feet/second.

13. Similarities based on the results of this study can be applied to other areas of the Trinity sands outcrop belt to determine areas that will contribute groundwater recharge to a regional "downdip" flow system. The basal Cretaceous Trinity Group crops out from southern Oklahoma into south-central Texas. Streams flowing southeast to the Gulf of Mexico have produced similar topographically controlled recharge basins along the outcrop belt.

14. Areas pumping heavily from the Trinity aquifer, such as the urban areas of Waco, Temple, Stephenville, and Hillsboro, are creating excessive drawdown, beyond the recharge capacity of the aquifer's flow system to replenish water removed from storage, and significantly lowering water levels. The leaky nature of the Glen Rose Limestone may allow significant amounts of more sulfate-rich water from the Glen Rose to be drawn into the depressed areas with continued pumpage. Reduction in artesian head will not only lower pumping levels and increase pumping costs, but possibly produce water of poorer quality.

RECOMMENDATIONS

1. Prior to the present study, the Trinity aquifer has been treated as a single major aquifer system. Because of regional and local flow systems, the Trinity aquifer should be divided into major and minor aquifers. The groundwater resources in the "major" Trinity aquifer should only include the artesian aquifer system and the contributing flow system. Outliers and local flow systems that do not contribute groundwater to the artesian Trinity aquifer have limited groundwater resources and should be considered a "minor" aquifer system.

2. The recent designation of central Texas as a water short area brings recharge studies and recharge areas into the management arena. As the aquifer conditions exist today, leakage will continue to occur through the Glen Rose Limestone. However, because the major recharge area to the artesian Trinity aquifer lies in eastern

Comanche County, this area deserves more attention from a management standpoint than any other area in the Trinity aquifer.

3. Additional study of the Trinity aquifer is needed to further define the effects of leakage from overlying formations. Leakage in the areas of major pumpage may produce significant and damaging chemical changes in the aquifer.

4. Due to the size and scope of this study, generalities are inherent. However, the urgency of the problem suggests that refinement would be both possible and extremely useful. Therefore, the following steps are recommended: a) to define the initial recharge contributions from separate facies in the Trinity sands outcrop belt by measurement of infiltration and direct recharge through the soil and unsaturated zone with tensiometers, gypsum blocks, lysimeters, or other infiltration tests; b) because recharge probably occurs within a few days after precipitation events, daily water balances should provide information on soil moisture storage and recharge to the water table (conventional water balance calculations such as the Thornthwaite method show no soil moisture storage on a monthly basis); and c) a detailed study of recharge from leakage through the Glen Rose Limestone and Fredericksburg Group should consider regional aquifer properties of the Glen Rose Limestone. Aquifer parameters of both Glen Rose Limestone and Fredericksburg rocks need to be determined. Observations from nested observation wells in the Glen Rose Limestone and Fredericksburg Group would be valuable, particularly in the areas of major pumpage (Waco, Temple, Hillsboro, Stephenville, Gatesville, and Hamilton).

5. Safe yield and other management-related factors should be carefully re-evaluated for the entire Trinity aquifer in central and north Texas.

APPENDIX I

EFFECTIVE RECHARGE

Effective recharge in the Trinity aquifer was determined by the total transmissive capacity of the Trinity aquifer at the 900-foot potentiometric level. Effective recharge by this method is the average recharge to the aquifer over several years. Annual effective recharge is the amount of groundwater flowing through a 106.4 mile aquifer segment through the 900-foot potentiometric level between the Paluxy and Lampasas Rivers (Fig. 30) (Freeze and Cherry, 1979, p. 203). The total transmission capacity was calculated by the formula,

$$Q = TIW$$

where

Q = volume of water in gallons/day moving through the aquifer;
T = transmissivity of the aquifer in gallons/day/square foot ($G/D/FT^2$);
I = 1969 hydraulic gradient in feet/mile; and
W = width of the aquifer segment in miles normal to the gradient.

The subsurface thickness of the aquifer, Hensel (T) and Hosston (H) Formations, was determined by superimposing the isopach thickness of each formation below the 900-foot potentiometric level (Klemt et al., 1975, p. 29, 32). The thickness of each formation was considered total aquifer thickness in cross section (Fig. 30), and divided into aquifer segments corresponding to thickness changes on the isopach map (example, T5 = 80 feet, H11 = 80 feet). Hydraulic conductivity was determined from aquifer tests in the Trinity aquifer (Klemt et al., 1975, p. 12-13). The hydraulic conductivity value for the Hensel (T) averaged 60 gallons/day/square foot, and the Hosston (H) averaged 77 gallons/day/square foot (Klemt et al., 1975, p. 12-13). Gradients were determined for each aquifer segment between the 1000-foot and 900-foot potentiometric contour levels. The width of aquifer segments corresponds to the changes in isopach thickness of the cross section along the 900-foot potentiometric contour (example, T5 = 9.86 miles, T6 = 2.76 miles, Table 1).

Total groundwater discharge (Table 1) through cross sectional area/day = 1 gallon/day x 0.00112 = 1 acre-feet/year;

Hensel Fm. = 11,254,900 G/D x .00112 = 12,600 acre-ft/yr
Hosston Fm. = 11,071,700 G/D x .00112 = 12,400 acre-ft/yr

TOTAL 22,326,600 G/D x .00112 = 25,000 acre-ft/yr

Table 1. Effective recharge

HENSEL FORMATION

$P(G/D/FT^2)$	b(FT)	I(FT/MI)	W(MI)	Q(G/D)
T1 = 60	160	100/5.91	19.72	3,203,200
T2 = 60	150	100/4.53	3.94	782,600
T3 = 60	130	100/3.15	7.89	1,953,300
T4 = 60	100	100/15.06	11.83	1,069,000
T5 = 60	80	100/12.83	9.86	607,200
T6 = 60	90	100/15.38	2.76	229,200
T7 = 60	110	100/20.79	3.94	540,600
T8 = 60	120	100/21.69	4.93	769,900
T9 = 60	110	100/15.64	4.93	508,900
T10 = 60	90	100/11.02	2.95	175,600
T11 = 60	70	100/10.92	5.91	271,000
T12 = 60	55	100/12.56	27.61	1,144,400
TOTAL	101 AVE	16.25 AVE	106.4	11,254,900

HOSSTON FORMATION

$P(G/D/FT^2)$	b(FT)	I(FT/MI)	W(MI)	Q(G/D)
H1 = 77	75	100/13.62	2.36	185,600
H2 = 77	80	100/15.89	5.91	578,500
H3 = 77	70	100/19.56	6.70	706,400
H4 = 77	50	100/20.08	2.56	217,700
H5 = 77	55	100/19.76	1.18	89,800
H6 = 77	70	100/20.04	2.36	200,300
H7 = 77	90	100/22.37	4.73	570,300
H8 = 77	100	100/36.49	4.93	1,246,700
H9 = 77	90	100/28.49	3.94	864,300
H10 = 77	80	100/14.92	9.07	937,800
H11 = 77	80	100/12.56	10.25	793,000
H12 = 77	80	100/15.06	2.56	237,500
H13 = 77	80	100/14.66	3.94	355,800
H14 = 77	80	100/18.11	4.73	527,700
H15 = 77	80	100/17.89	5.12	567,000
H16 = 77	80	100/12.78	3.15	248,000
H17 = 77	80	100/10.98	5.52	373,400
H18 = 77	80	100/11.27	4.33	300,600
H19 = 77	75	100/14.62	22.88	2,070,500
TOTAL	78.3 AVE	16.25 AVE	106.4	11,071,700

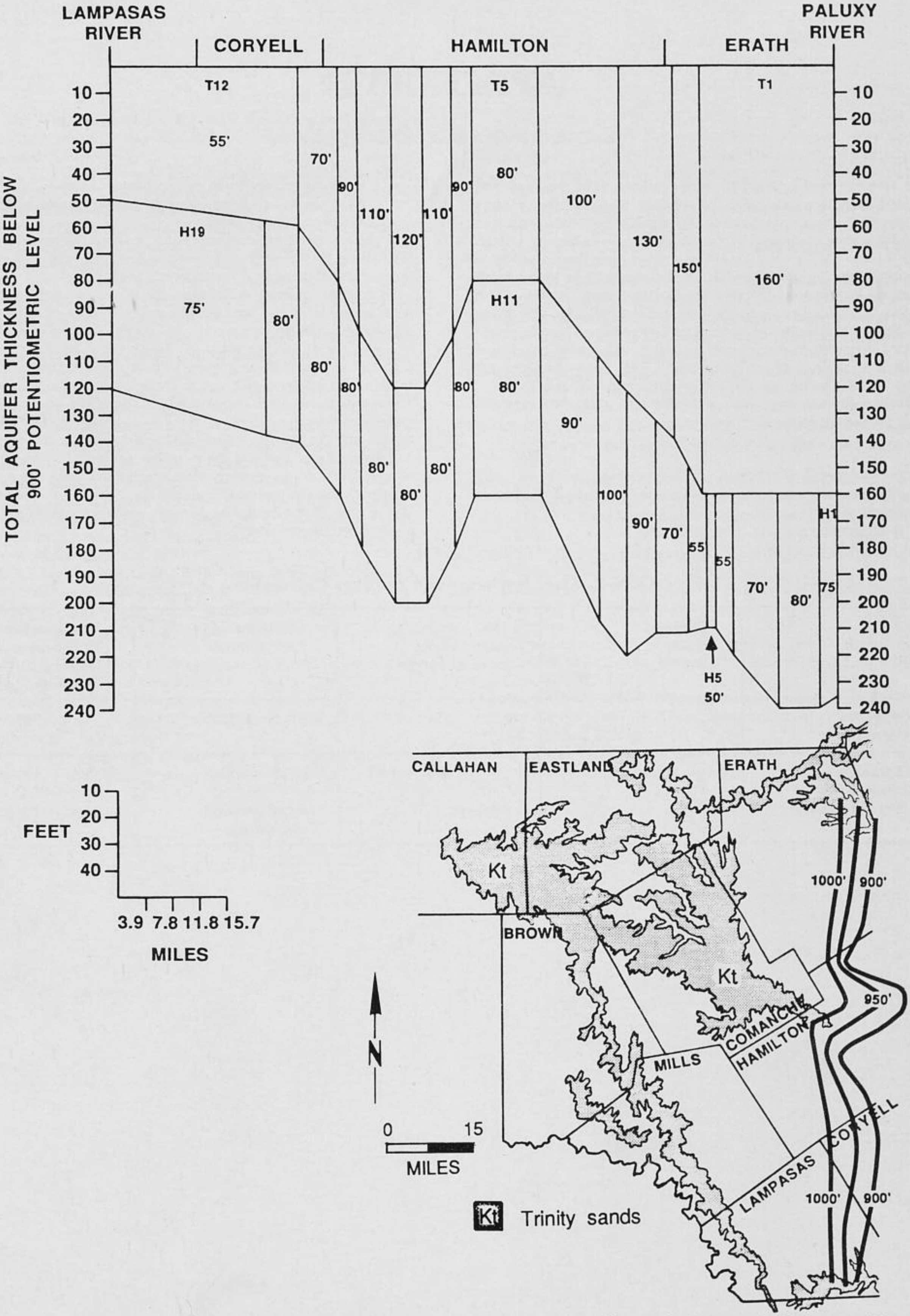

Fig. 30. The total transmission capacity of the Trinity aquifer along a 106-mile line of aquifer section between the Paluxy and Lampasas Rivers at the 900-foot potentiometric contour level. The upper diagram represents the aquifer section in total thickness, and does not represent an actual cross section, rather a stacking of the Hensel and Hosston Formations to determine annual groundwater flow. The aquifer was divided into slices where the isopach thickness changed along the 900-foot potentiometric level, and discharge through each section was calculated from the water table gradient and transmissivity of each aquifer section. The volume of groundwater flowing through the aquifer section at the 900-foot potentiometric level is given in Table 1 as the amount of effective recharge to the artesian Trinity aquifer.

APPENDIX II

AREAL RECHARGE AND LEAKAGE

The relative proportions of areal recharge and leakage were calculated based upon the principles of flow tubes and Darcy's Law. Using the water level contour map and parallel flow lines, two areas of equal size were compared within the outcrop area and the covered portion of the aquifer (Fig. 25). These areas were chosen based on well control and aquifer test data in the region. The methodology assumes no flow crosses the flow lines or the lower confining beds. Therefore, any changes along the flow tube result from lateral flow up-gradient or areal recharge and leakage from above. The calculations are based on average aquifer characteristics and yearly averages of flow. Discharges from groundwater withdrawal due to pumpage and baseflow loss to streams are not taken into consideration.

The calculations through each of the portions of the flow tube used Darcy's Law in the following form:

$$Q = KIA$$

where

Q = the volumetric flow rate in acre-feet per year;

K = the hydraulic conductivity in gallons per day/per foot times 365 days per year;

I = the hydraulic gradient in feet/feet; and

A = the cross-sectional area perpendicular to flow (aquifer thickness times the width of the flow tube in feet divided by the number of square feet per acre).

Amounts of areal recharge and leakage were determined by calculating the volumetric flow along the flow tube and subtracting the incoming lateral flow up-gradient (Table 2).

By comparing the leakage recharge in the covered portion to the areal recharge in the outcrop, the contributions of each area were calculated to be approximately 60 percent for the covered portion and 40 percent for the outcrop. These ratios were then combined with the percentage of the covered or outcrop portion within the region contributing effective recharge to the artesian portion of the aquifer. The results showed that the covered portion of the aquifer contributed approximately 80 percent of the effective recharge to the artesian aquifer and the outcrop contributed approximately 20 percent.

Areal recharge and leakage in inches per year for the outcrop and covered portions respectively were determined using the results from the flow tube calculations, dividing the volume of annual recharge by the area of the flow tube portion, and then converting to inches of precipitation per year.

Table 2. Areal Recharge and Leakage Calculations

	Divide to 1500′ contour	1500′ contour to 1400′ contour (covered portion, Fig. 25)	1400′ contour to 1300′ contour	1300′ contour to 1200′ contour (outcrop portion, Fig. 25)
Total Q in acre-feet	47	650	1120	1500
Changes in Q in acre-feet (effective recharge)	47	603 Leakage	470 Areal recharge and leakage	380 Areal recharge

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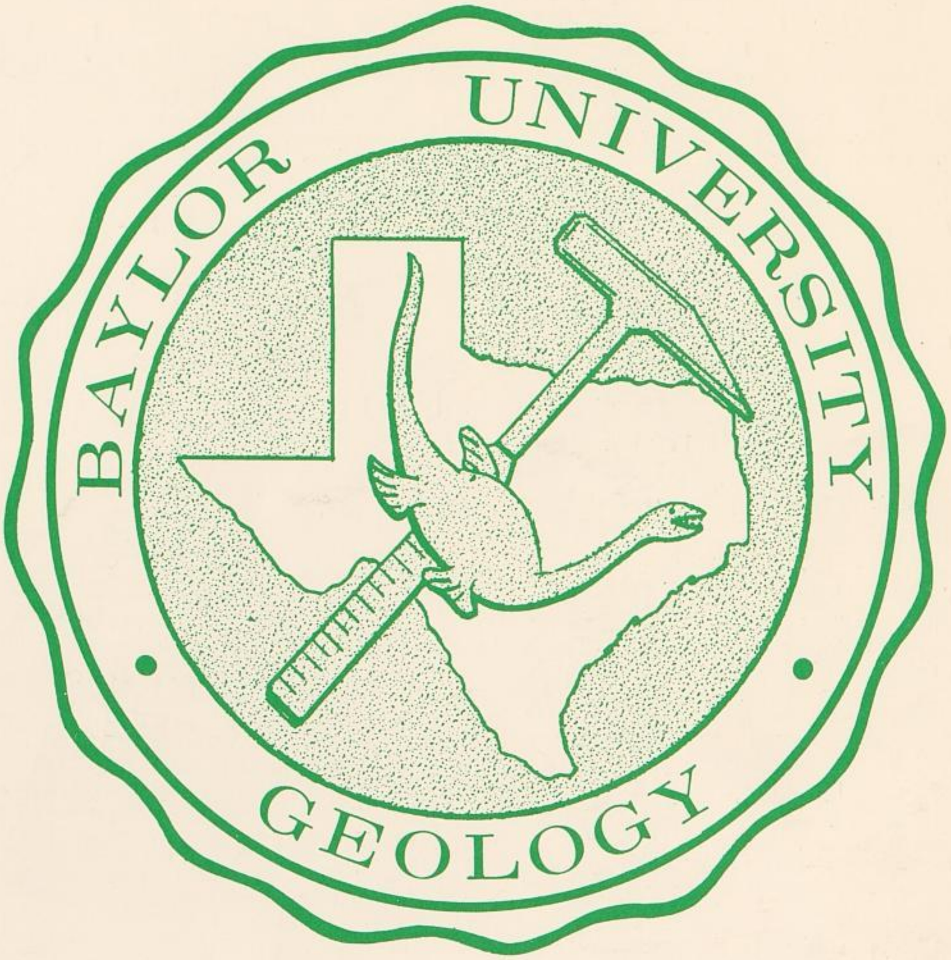
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