# Geologic and Hydrogeologic Framework of Regional Aquifers in the Twin Mountains, Paluxy, and Woodbine Formations near the SSC Site, North-Central Texas

Topical Report

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Alan R. Dutton, Robert E. Mace,
H. Seay Nance, and Martina Blüm

Prepared for

Texas National Research Laboratory Commission
under Contracts No. IAC(92-93)-0301 and No. IAC 94-0108

Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
University Station, Box X
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ABSTRACT

Water-utility districts and many municipalities in North-Central Texas recently obtained as much as 100 percent of their water supply from deep regional aquifers in Cretaceous formations. Use of ground water from the aquifers during the past century has resulted in water-level declines of as much as 850 ft (259 m), especially in Dallas and Tarrant Counties. Future water-level changes will depend on amount of ground water produced to help meet growing water-supply needs for municipalities, industries, and agriculture throughout North-Central Texas. It is probable that a significant part of the increased water demand will be met by ground water although at less than historic rates.

The objective of this study was to develop a predictive tool for studying the effect of future ground-water production from regional aquifers in North-Central Texas. To do this we reviewed the history of ground-water development, hydrogeology of the regional aquifers, and constructed numerical models of ground-water flow. A cross-sectional model of both aquifers and confining layers was used to evaluate model boundary conditions and the vertical hydrologic properties of the confining layers. Results and insights from the cross-sectional model were used in a three-dimensional simulation of ground-water flow in the deep aquifers. The layers of the regional confining system were not explicitly included in the three-dimensional model. Hydrogeologic properties were assigned on the basis of aquifer test results and stratigraphic mapping of sandstone distribution in the aquifer units.

Water levels are expected to recover as much as 200 to 300 ft (61 to 91.4 m) in the Twin Mountains and Paluxy aquifers and as much as 100-ft (30.5-m) in the Woodbine aquifer, assuming the projected future pumping rates. Water budget calculations suggest that most of the recharge to the unconfined part of the regional aquifers in their outcrops discharges in seeps and springs in the river valleys that cross the outcrops. Only a few percent enters the confined part of the outcrop. This percentage might have increased during the past century with ground-water production and drawdown in the potentiometric surface.

## INTRODUCTION

Interest in developing ground-water resources in North-Central Texas (fig. 1) mainly has focused on the Lower Cretaceous Twin Mountains and Paluxy Formations and the Upper Cretaceous Woodbine Formation (table 1). After the discovery in 1882 of flowing wells with artesian pressure in the Twin Mountains Formation in the Fort Worth area, about 150 to 160 wells had been drilled by 1897 (Hill, 1901). Waco had so many flowing wells that it was known as the "City of Geysers." By 1914, many wells had stopped flowing as hydraulic head decreased to beneath ground surface (Leggat, 1957). With growth in population and in agricultural and industrial output, ground-water use gradually increased during the twentieth century and accelerated during the past 40 yr. In Ellis County, for example, ground-water use more than doubled from 1974 to 1990, reaching almost 8,900 acre-ft/yr ($11 \times 10^6$ $m^3$/yr). The increased use of ground water resulted in marked declines of water levels

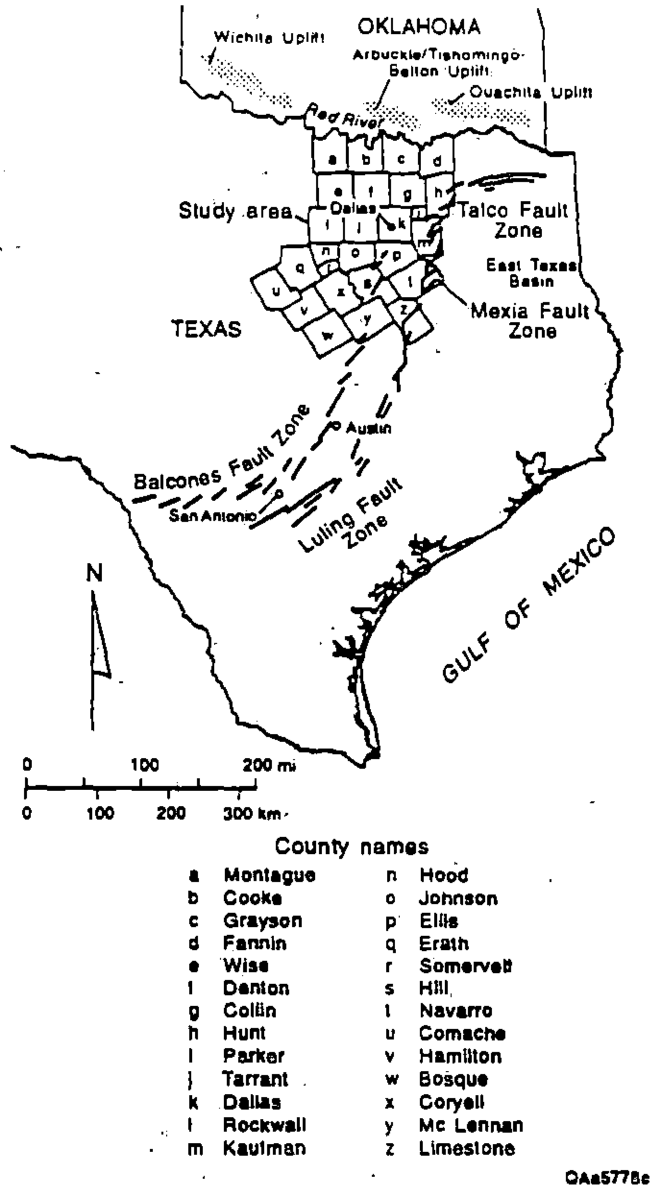


Figure 1. Location of study area in North-Central Texas.

Table 1. Major stratigraphic units in North-Central Texas.

<table>
<tr><th>Era</th><th>System</th><th>Series</th><th>Group</th><th colspan="2">Stratigraphic Unit</th></tr>
<tr><td rowspan="2">Cenozoic</td><td rowspan="2">Quaternary</td><td>Holocene</td><td></td><td colspan="2">Alluvium</td></tr>
<tr><td>Pleistocene</td><td></td><td colspan="2">Fluviatile terrace deposits</td></tr>
<tr><td rowspan="9">Mesozoic</td><td rowspan="9">Cretaceous</td><td rowspan="5">Gulf</td><td>Taylor</td><td colspan="2">Wolfe City Formation<br>Ozan Formation<br>"lower Taylor Marl"</td></tr>
<tr><td>Austin</td><td colspan="2">Austin Chalk</td></tr>
<tr><td>Eagle Ford</td><td colspan="2">Eagle Ford Shale Formation</td></tr>
<tr><td>Woodbine</td><td colspan="2">undifferentiated</td></tr>
<tr><td>Washita</td><td colspan="2">undifferentiated</td></tr>
<tr><td rowspan="4">Comanche</td><td rowspan="2">Fredericksburg</td><td colspan="2">undifferentiated</td></tr>
<tr><td rowspan="3">Antlers Formation</td><td>Paluxy Formation</td></tr>
<tr><td rowspan="2">Trinity</td><td>Glen Rose Formation</td></tr>
<tr><td>Twin Mountains Formation</td></tr>
</table>

Paluxy is in Antlers (Fig 2)

in the aquifers. Since the turn of the century, water levels in the Fort Worth area have declined nearly 850 ft (259 m) in the Twin Mountains Formation and 450 ft (137 m) in the Paluxy Formation, and water levels in the Dallas area have declined approximately 400 ft (123 m) in the Woodbine Formation. During the next 50 yr, rural and industrial use of ground water is projected to remain fairly constant. While some municipalities in North-Central Texas will increase their use of ground water, other municipalities are projected to decrease their ground-water use by as much as 60 percent by the year 2030, compared to 1980 usage (Texas Water Development Board [TWDB], unpublished information, 1987), partly as a response to the historic decline in water levels. Fort Worth already has abandoned many of its wells and has been using surface impoundments for water supply. Waxahachie and Ennis in Ellis County also have turned almost completely to surface-water sources.

The purpose of this study is to interpret and better understand the influence of future ground-water pumpage on water levels in the aquifers. Because of the complex interrelation of aquifer stratigraphy, hydrologic properties, ground-water availability, and water levels, predictions of future water-level decline in regional aquifers in North-Central Texas are based on a numerical model of ground-water flow. The cross-sectional and three-dimensional numerical models developed in this study were used as tools to estimate amounts of recharge and discharge, evaluate uncertain hydrologic characteristics of confining layers and aquifer boundaries, and quantitatively estimate how water levels will respond to future pumping rates.

Steps in defining the two numerical models included specifying

- hydrologic units to be modeled,
- finite-difference grid of blocks,
- hydrological properties to be assigned to each block in the grid, including transmissivity, storativity, and aquifer thickness, and
- location and type of model boundaries, including source terms such as natural recharge and discharge and well pumpage.

This topical report of ground-water resources in North-Central Texas documents the stratigraphic and hydrologic framework of the regional aquifers and builds on many previous studies. The areal distribution of hydrologic properties was estimated from aquifer test results and from maps of stratigraphy and depositional facies within the aquifers. Cross-sectional and three-dimensional models were calibrated by adjusting estimated or assumed hydrologic properties to obtain a best match between recorded and simulated hydraulic heads. A two-dimensional cross-sectional model was used to interpret hydrologic properties of confining layers and the down-gradient hydrologic boundary. The interpreted stratigraphic and hydrologic framework was used to define and calibrate a three-dimensional model of ground-water flow in the regional aquifers. First the models were calibrated for assumed steady-state conditions using turn-of-the-century hydrologic observations by Hill (1901). Second, a transient three-dimensional model was then calibrated using historical hydrograph data. Third, response of water levels to future demand for ground water, based on TWDB projections, was simulated using the calibrated three-dimensional model.

## REGIONAL HYDROGEOLOGIC SETTING

### Hydrologic Units

The main hydrostratigraphic units (table 1) in North-Central Texas are:

- a regional aquifer system with principal units being the Lower Cretaceous Twin Mountains and Paluxy Formations and Upper Cretaceous Woodbine Formation (Nordstrom, 1982), which are unconfined where each formation crops out at ground surface and confined in the subsurface;
- a regional *confining* system in Upper Cretaceous bedrock of the Eagle Ford Formation, Austin Chalk, and Taylor Group, which are weathered near ground surface; and
- local surficial aquifers in Quaternary alluvium (Wickham and Dutton, 1991).

### North-Central Texas Regional Aquifer System

The regional aquifers occur in Lower and Upper Cretaceous sandstones of the (stratigraphically, from bottom to top) Twin Mountains, Paluxy, and Woodbine Formations (table 1, fig. 2). The regional aquifer system is underlain by Pennsylvanian-age (Strawn Series) shales and limestones and by Jurassic-age Cotton Valley Group sandstones and shales. The Pennsylvanian and Jurassic formations are assumed to have low permeability (because of their depth of burial) and to not exchange appreciable amounts of ground water with the regional aquifers in Cretaceous formations. At its top the regional aquifer system is overlain and confined by the Eagle Ford Formation,

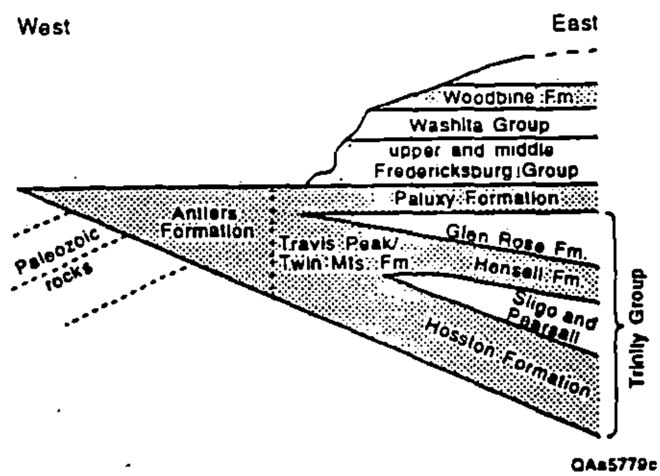


Figure 2. Schematic relationship between stratigraphic units. Sandstone-dominated intervals are stippled. Unconformity beneath the Hosston Formation is referred to as the Wichita Paleoplain. No scale.

Austin Chalk, and Taylor Group (table 1). The Pearsall and Sligo Formations, Glen Rose Formation, and Fredericksburg and Washita Groups make up confining layers within the regional aquifer system.

The Twin Mountains Formation is as much as 550 to 850 ft (168 to 259 m) thick in North-Central Texas and is composed principally of sandstone with a basal gravel and conglomerate section where most wells are completed. The Paluxy Formation decreases in thickness toward the southeast from a maximum of approximately 400 ft (122 m) in the northern part of North-Central Texas (Nordstrom, 1982). The 250- to 375-ft-thick (76- to 114-m) Woodbine Formation is a medium- to coarse-grained sandstone, with some claystone and lignite seams. The Woodbine lies 1,200 to 1,500 ft (370 to 460 m) above the top of the Twin Mountains. Most wells are completed in the lower part of the formation, which yields better quality ground water. In Ellis County, for example, the top of the Woodbine ranges from 600 to 1,000 ft (180 to 305 m) beneath ground surface and the top of the Twin Mountains is at depths from 2,000 to 3,000 ft (610 to 915 m) beneath ground surface.

## Regional Confining System

The Upper Cretaceous Eagle Ford Formation, Austin Chalk, and Taylor Group compose a regional confining system (table 1), which means that the low permeability of the rock retards the vertical and lateral flow of ground water and separates underlying aquifers from surficial aquifers. The Eagle Ford is composed of a dark shale with very thin limestone beds. The Austin Chalk is made up of fine-grained chalk and marl deposited in a deep-water marine-shelf environment (Hovorka and Nance, 1994). The Ozan and Wolfe

City Formations consist of fine-grained marl, calcareous mudstone, shale, and calcareous sandstone. Weathering and unloading have significantly increased porosity and permeability of the near-surface chalk and marl bedrock, allowing enhanced recharge, storage, and shallow circulation of ground water in otherwise low-permeability, fractured strata. Average hydraulic conductivity is almost 1,000 times higher in weathered chalk, marl, and shale than in unweathered bedrock (Dutton and others, 1994). Thickness of the weathered zone is generally less than 12 to 35 ft (3.7 to 10.7 m).

## Surficial Aquifers

Unconfined and semi-unconfined aquifers of limited extent occur in surficial Pleistocene and Holocene alluvium in parts of North-Central Texas (Taggart, 1953; Reaser, 1957; Wickham and Dutton, 1991). Only small amounts of ground water from the surficial alluvium historically have been used. The Pleistocene deposits are unconsolidated and typically consist of a thin, basal-pebble conglomerate overlain by stratified clay, sand, granules, and pebbles and capped by calcareous clay and clayey soil. Holocene floodplain deposits of clay and silty clay form an alluvial veneer along rivers and streams in the region and range in thickness from a few feet to more than 30 ft (9.1 m). The alluvial material is normally small in areal extent and typically less than 50 ft (15.2 m) thick. Erosion during the Holocene stripped most of the Pleistocene alluvium from the surface, and Modern streams locally have cut through to underlying Cretaceous bedrock, leaving isolated deposits (terraces) of Pleistocene alluvium at elevations higher than those of the surrounding strata (Hall, 1990; Wickham and Dutton, 1991).

## Regional Structure

The study area is located on the western margin of the East Texas Basin (fig. 1) at the northern limits of the Balcones Fault Zone, a zone of normal faulting that extends south toward Austin and San Antonio (Murray, 1961; Grimshaw and Woodruff, 1986; Collins and Laubach, 1990). The Mexia-Talco Fault Zone at the eastern side of the study area (figs. 1 and 3) is parallel to the Balcones Fault Zone. Its origin has been interpreted as resulting from sliding of Cretaceous sediments into the East Texas Basin upon Jurassic salt deposits (Jackson, 1982). The general structure of the study area includes an eastward descending ramp from formation outcrop areas in the west and a southward descending ramp from outcrop areas in the north. The hinge between the eastward and southward dipping ramps is the Sherman syncline northeast of Dallas in central Grayson and southwestern Hunt Counties (fig. 3). The stratigraphic horizons dip toward the East Texas Basin and increase in dip across the Balcones and Mexia-Talco Fault Zones (figs. 4 to 6). For example, dip of the top of the Paluxy Formation increases from about 0.33° in the western part of the study area to 0.81° in the Balcones Fault Zone in the western part of Ellis County, and again abruptly increases to 1.95° along the Mexia-Talco Fault Zone farther east (fig. 5).

Structural elevations on the bases of some Cretaceous stratigraphic horizons are quite variable. Several dip-oriented troughs record an erosional unconformity at the base of the Twin Mountains Formation (fig. 2). Hill (1901) called this unconformity the Wichita Paleoplain. The incised valley beneath basal Woodbine sandstones (discussed later) is perhaps typical of the

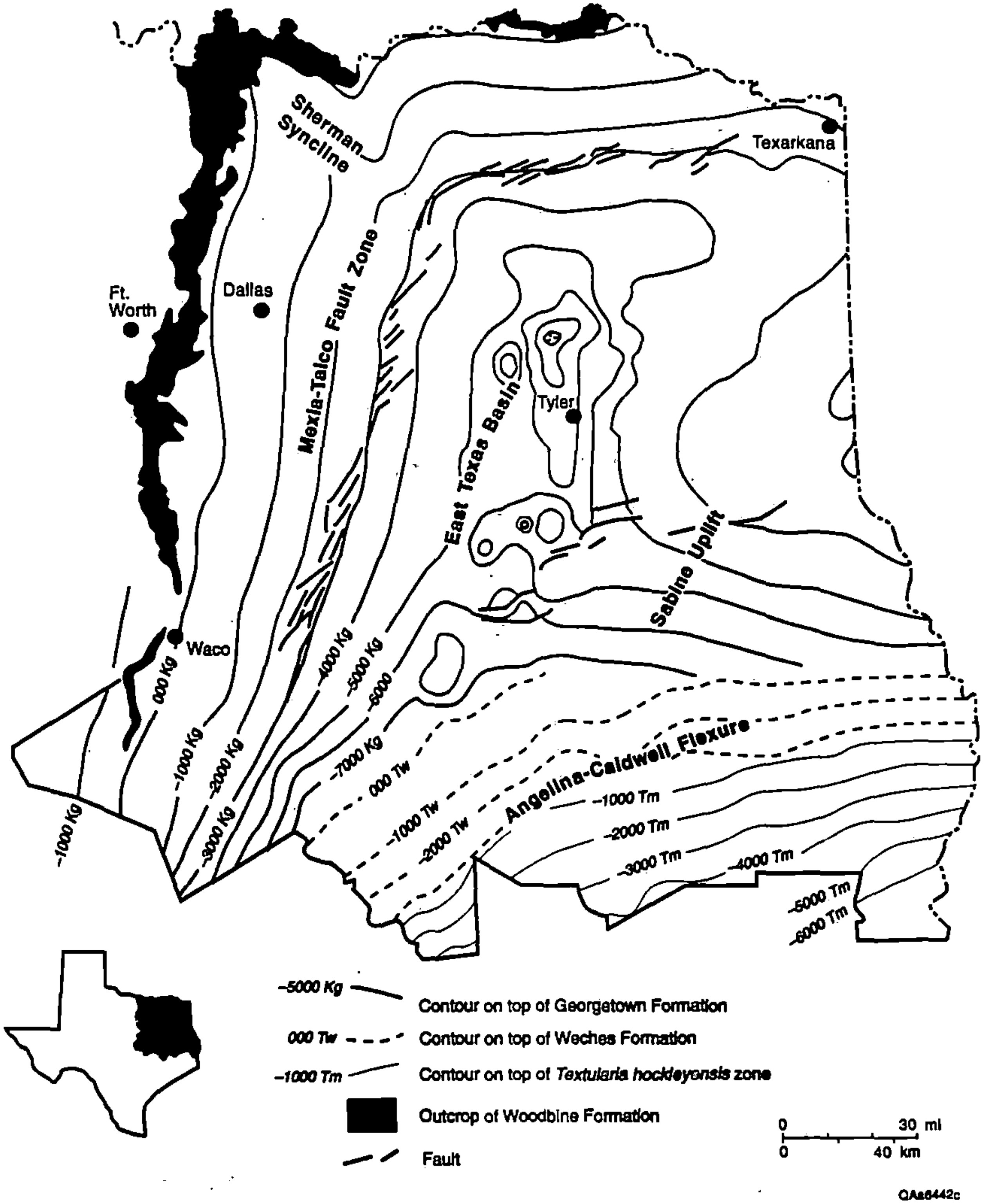


Figure 3. Major structural features and paleogeographic elements of the study area and East Texas basin. Study area is within the Central Texas Platform and extends west of the outcrop of the Woodbine Formation. Modified from Oliver (1971).

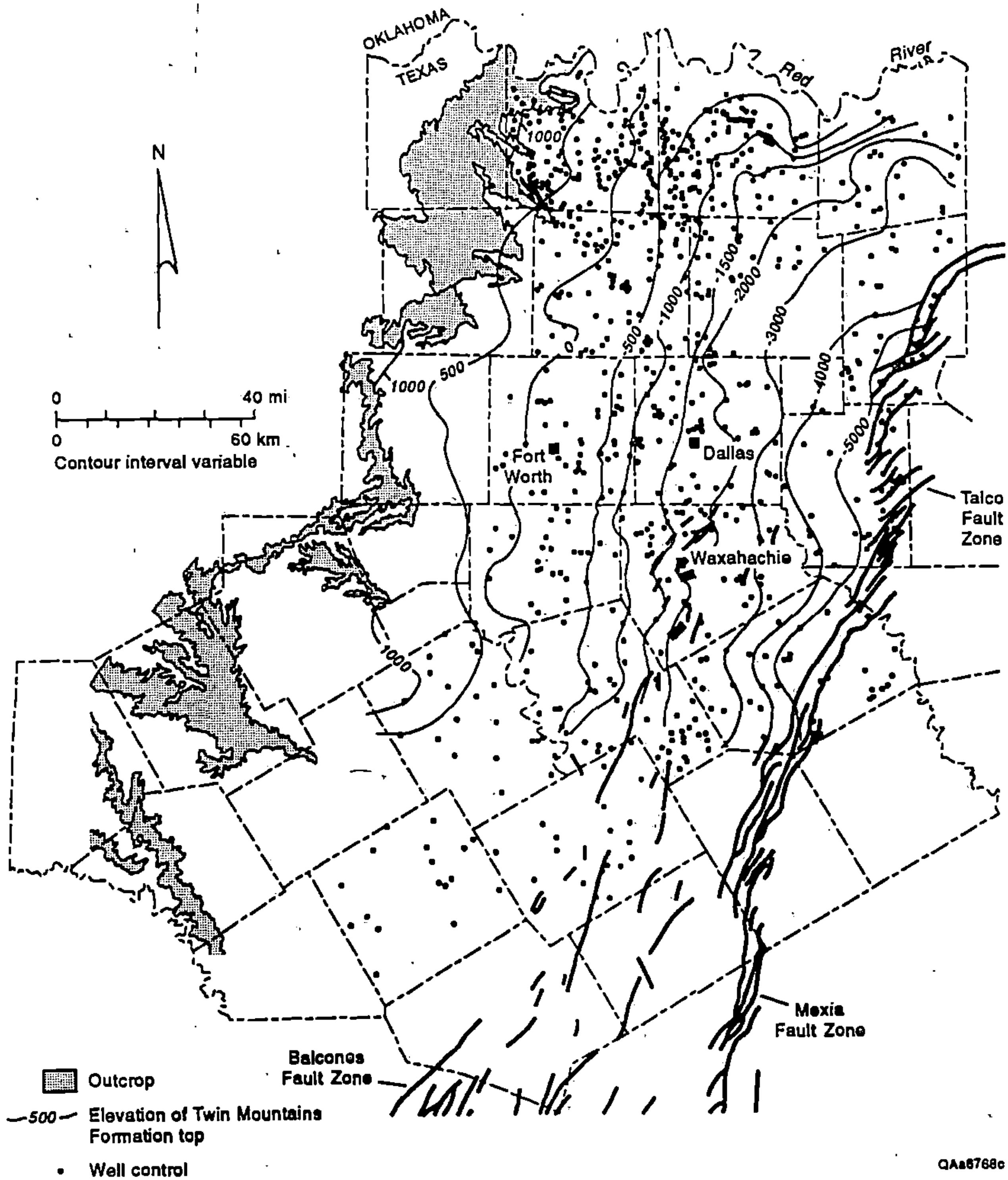


Figure 4. Elevation of the top of the Twin Mountains Formation. Westward excursions of contours from average trends (for example, in Wise and Denton Counties) may result from incised valley at top of the Trinity Group. Contour interval increases from 500 to 1,000 ft (152.4 to 304.8 m) along the north-south trending Balcones fault zone.

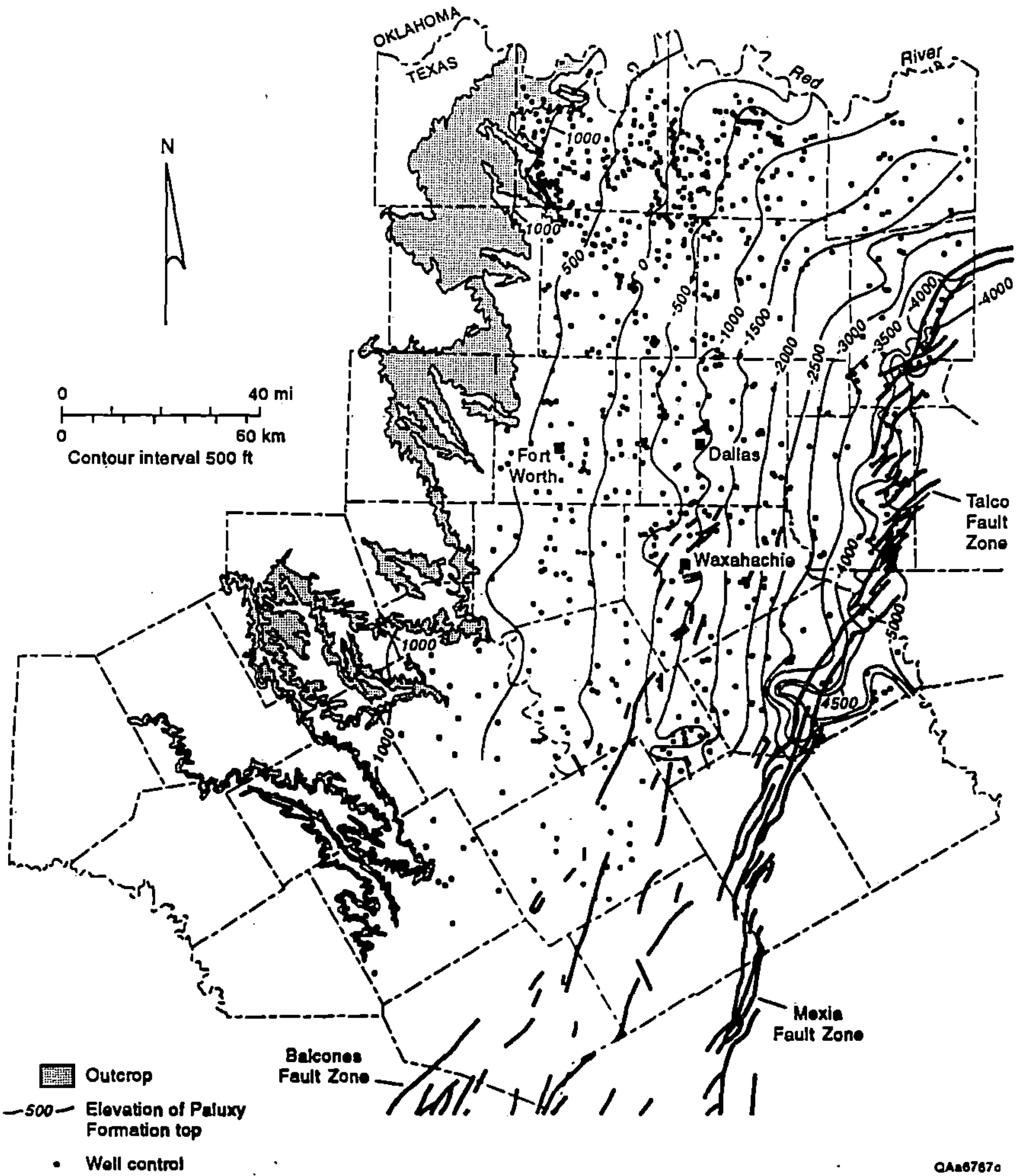


Figure 5. Elevation of the top of the Paluxy Formation. Contour interval increases from 100 to 500 ft (30.5 to 152.4 m) along the north-south trending Balcones fault zone (see fig. 4).

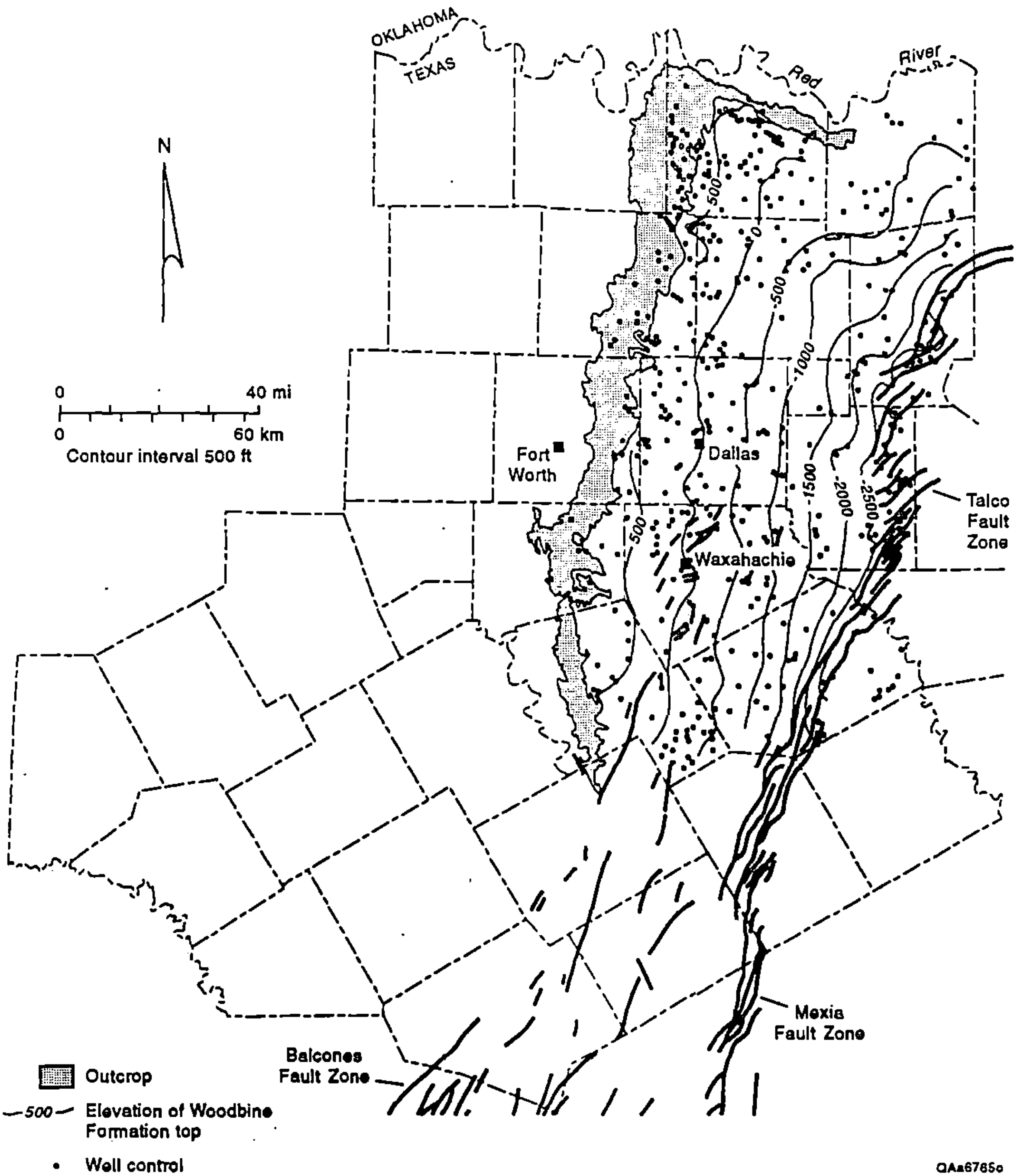


Figure 6. Elevation of the top of the Woodbine Formation. The Sherman syncline (fig. 3) is in the northwestern part of the map area.

regional unconformities beneath Cretaceous sandstone-dominated formations in the area.

## Physiography, Climate, and Land Use

Physiographic provinces in North-Central Texas include, from east to west, the Blackland Prairie, Eastern Cross Timbers, Grand Prairie, and Western Cross Timbers. Regional dip of the topographic slope is toward the southeast. Surface water in the study area drains in the Red River, Trinity River, and Brazos River watersheds. Drainage is largely dendritic, but stream positions might be locally controlled by joints or faults, for example, as in the Austin Chalk outcrop. Topography regionally consists of low floodplains, broad, flat upland terraces, and rolling hills. The low-relief hills of the Eastern and Western Cross Timbers provinces coincide with outcrops of the Lower and Upper Cretaceous sandstone-dominated formations, whereas the rolling Blackland Grand Prairie provinces coincide with outcrops of the Upper Cretaceous carbonate-dominated formations, such as the Austin Chalk. The White Rock Escarpment marks the western limit of the Austin Chalk. The Eagle Ford Formation is not very resistant to erosion and underlies the broad valley west of the White Rock Escarpment.

North-Central Texas lies in the subtropical humid and subtropical subhumid climatic zones (Larkin and Bomar, 1983). Major climatological patterns factors are the onshore flow of tropical maritime air from the Gulf of Mexico, eastward movement of jet stream Pacific air masses across the southwestern U.S., and the southeastward movement of arctic and continental air. Average annual precipitation decreases from 38 inches (970 mm) in the eastern part of Ellis County to less than 32 inches (813 mm) in Bosque County to the west (Larkin and Bomar, 1983). Winter and spring months are wettest, whereas summer rainfall is low. Average annual temperature increases from north to south from approximately 63°F (17.2°C) along the Red River to approximately 66°F (18.8°C) between Limestone and Bosque Counties (Larkin and Bomar, 1983). Temperature is coldest during January and hottest during August. Average annual gross lake-surface evaporation rate increases from approximately 63 inches (1600 mm) in the eastern part of Ellis County to more than 67 inches (1700 mm) in Bosque County (Larkin and Bomar, 1983).

## PREVIOUS GEOLOGIC STUDIES

This part of the report outlines the general stratigraphic relation between the aquifer units and associated confining beds and defines the names of units used in the report. Formation nomenclature differs between subsurface and equivalent outcropping stratigraphic units, and between areas where distinct stratigraphic units merge and formation boundaries are no longer mappable. Different formation names were often used in the literature for widely separated locations before rock equivalency was recognized. In addition, some intervals are considered formations in areas where lithology is uniform but are raised to group status where they can be subdivided into mappable units.

The Cretaceous section in the North-Central Texas study area ranges in thickness from a minimum at its eroded outcrop limit to over 7,000 ft (2,130 m) at the Mexia-Talco Fault Zone in Kaufman and Hunt Counties. The section comprises limestone, shale, sandstone, and siliciclastic mudstone strata of Early to Late Cretaceous age. Sandstone-dominated formations compose approximately 25 percent of the Cretaceous section in Kaufman County but compose almost all of the section in western extremes of the outcrop belt in Texas where only the basal Cretaceous sandstones are exposed.

Cretaceous strata have been divided into the Coahuilan, Comanchean, and Gulfian Series (Galloway and others, 1983; table 1). The Coahuilan Series comprises sandstone and mudstone of the Hosston Formation and limestone of the Sligo Formation. The outcrop of the Hosston (lower Twin Mountains Formation) defines the western boundary of the study area and is the westward limit of eastward-dipping Cretaceous deposits in North-Central Texas. The Hosston overlies Paleozoic strata that dip westward toward the Permian Basin area of West Texas. The Sligo limestone is mostly limited to the East Texas Basin and pinches out in the subsurface (fig. 2) along the Mexia-Talco Fault Zone.

The Comanchean Series includes strata of the upper Trinity, Fredericksburg, and Washita Groups. The upper Trinity Group includes limestone and shale of the Pearsall Formation, sandstone and mudstone of the Hensel Formation, limestone and shale of the Glen Rose Formation, and sandstone of the lower Bluff Dale Formation (table 1). The Fredericksburg Group includes sandstone of the upper Bluff Dale and Paluxy Formations as well as limestone and shale of the Walnut and Goodland Formations. The Washita Group includes limestone and shale of the Kiamichi, Georgetown, and Grayson Formations and limestone of the Buda Formation. The Georgetown Formation in North-Central Texas comprises several members with thick shale beds capped by one or more thick limestone beds, and in the northern part of the study area an upper member with more than 40 ft (12 m) of sandstone.

The Gulfian Series includes sandstone and mudstone of the Woodbine Formation; shale of the Eagle Ford Formation; chalk, marl, and sandstone of the Austin Group (including the Austin Chalk); marl, limestone, shale, and sandstone of the Taylor Group; and marl and shale of the Navarro Group.

## Trinity Group

The Trinity Division was named by Hill (1889) for the Glen Rose Formation and all underlying Cretaceous sandstones (Trinity Sandstone). Although Hill (1894) later included the Paluxy Formation in the Trinity Division, eventually Hill (1937) moved the upper boundary back to the top of the Glen Rose. Hill (1901) used the name Travis Peak for Trinity units underlying the Glen Rose (fig. 2). He further subdivided the Travis Peak and named the two major sandstone units the Sycamore and the Hensel Sandstones. The Hosston Formation has been interpreted to be the subsurface equivalent of the outcropping Sycamore Formation (Stricklin and others, 1971). The Hosston and Hensel Formations are indistinguishable in outcrop and are collectively called the Twin Mountains Formation (Fisher and Rodda, 1966, 1967). Hosston and Hensel sandstones are separated in the subsurface in the East Texas Basin by the limestone and shale of the Sligo and Pearsall Formations. Additional descriptions and depositional analyses of Trinity sandstones, as well as for their laterally equivalent carbonate and shale intervals, were given by Stricklin and others (1971).

Boone's (1968) comprehensive study of Trinity sandstones in the southwestern part of the study area included petrologic analyses and interpretation of depositional histories of the component units. More recently, Hall (1976) mapped Hosston, Hensel, and Twin Mountains sandstone in Central Texas and related sandstone distribution patterns to hydrologic and hydrochemical characteristics. Hall (1976) cited fluvial depositional models of Brown and others (1973), and deltaic depositional models of Fisher (1969) to explain facies occurrences and sandstone geometries.

Hill (1891) defined the "Bluff Dale Member of the Trinity Division" as fine-grained sandstone strata that lie stratigraphically between coarse-grained "Basement Sands" in Somerville and Hood Counties, Texas, and overlying limestone of the Glen Rose Formation. Rodgers (1967) interpreted the lower part of the Bluff Dale to be equivalent to the Hensel sandstone and the upper part to be up-dip clastic facies of the lowermost Glen Rose Formation. In Rodgers' (1967, p. 123) cross section, the up-dip section of the Glen Rose is capped by a thin sandstone interval that is unconformably overlain by Paluxy sandstone. This thin, unconformity-bounded sandstone is considered here to be the upper Bluff Dale.

## Paluxy Formation

Hill (1887) named the Paluxy Sand for outcrops along the Paluxy River in Hood and Somerville Counties, Texas. Hill (1937) reinterpreted the stratigraphic position of the Paluxy, removing it from the top of the Trinity Group and assigned it to the base of the Fredericksburg Group. Lozo (1949) concurred with Hill's reinterpretation. Atlee (1962), cited in Owen (1979), and Moore and Martin (1966) interpreted the Paluxy Formation as comprising marine-continental transitional deposits. Paluxy sandstones interfinger down dip with shale and claystone of the Walnut Formation, which Hayward and Brown (1967) and Fisher and Rodda (1967) interpreted as Fredericksburg. This suggests that the Paluxy and Walnut are of equivalent age. The Paluxy Formation and the underlying Twin Mountains Formation merge where the intervening Glen Rose Formation pinches out (Fisher and Rodda, 1966, 1967). Where they crop out in the northern part of the study area, the Paluxy and Twin Mountains Formations are undifferentiated and mapped as the Antlers Formation (originally called Antlers Sand by Hill [1893]).

Caughey (1977) suggested Paluxy sands were transported by rivers from source areas north and northeast of Texas and deposited mainly in moderately destructive deltaic barriers and strand plains. Thin sandstones and mudstones west of the fluvial-deltaic deposits were interpreted as strand-plain deposits. Caughey (1977) cited the destructive-deltaic depositional model of Fisher (1969) to explain Paluxy sandstone distribution.

Hendricks (1957) interpreted the Glen Rose-Paluxy contact as being conformable in Erath, Hood, Somerville, and Parker Counties. Owen (1979) concurred that the contact was conformable over most of Burnet and Wise Counties, Texas. Atlee (1962) interpreted the contact in Central Texas as being unconformable.

Atlee (1962), Moore and Martin (1966), and Owen (1979) interpreted the contact between the Paluxy and Walnut Formations as unconformable.

Interfingering of Walnut and Paluxy strata in the subsurface, however, indicates that a transitional relationship also exists and suggests that the unconformity between the formations is restricted to up-dip areas.

In this report the Paluxy is placed in the Fredericksburg Group because Paluxy sandstones interfinger with shales and claystones of the Walnut Formation. Fisher and Rodda (1966) show that the Paluxy and Walnut Formations interfinger, indicating approximate age equivalence for the two formations. The Walnut Formation is typically interpreted as part of the Fredericksburg Group (Haywood and Brown, 1967; Fisher and Rodda, 1967).

### Woodbine Formation

Hill (1901) subdivided the Woodbine Formation into Lewisville and Dexter Members. Adkins and Lozo (1951) raised the Woodbine interval to group status, subdivided into the Lewisville and Dexter Formations. Dodge (1969) interpreted paralic environments of deposition for the Woodbine Formation on the basis of outcrop studies. Nichols (1964) more generally interpreted continental, neritic, and transitional environments of deposition on the basis of subsurface studies. Cotera (1956) and Lee (1958 [cited in Oliver, 1971]), concluded from petrographic analyses that Woodbine source areas were in the southern Appalachians, the Ouachitas, and the Centerpoint volcanic area in Arkansas.

Oliver (1971) named the Dexter fluvial, Lewisville strand plain, and Freestone delta depositional systems on the basis of a study of well logs. The Dexter fluvial system consisted of dip-aligned tributaries laterally separated by floodplains. Tributaries from the northeast fed a 50- to 75-mi (80- to 121-km) wide meanderbelt that, in turn, fed channel-mouth bars, coastal barriers, and prodelta-shelf areas of a destructive delta system. Oliver (1971) used the Fisher (1969) depositional model for destructive deltaic deposition to explain Woodbine sandstone distribution.

## PREVIOUS HYDROGEOLOGIC STUDIES

Hill (1901) inventoried wells in the Twin Mountains, Paluxy, and Woodbine aquifers and provided early geologic and hydrologic data, including qualitative data on aquifer performance. George and Barnes (1945) reported results from hydrologic tests on three flowing wells in Waco in McLennan County. Sundstrom (1948) conducted hydrologic tests on water-supply wells in Waxahachie in Ellis County. Leggat (1957) studied the geology and ground-water resources of Tarrant County and reported on declining water levels. Rayner (1959) documented water-level fluctuations from 1930 through 1957 in Bell, McLennan, and Somervell Counties. Osburne and Shamburger (1960) discussed brine production from the Woodbine in Navarro County. Baker (1960) studied the geology and ground-water resources of Grayson County. Henningsen (1962) looked at ground-water chemistry in the Hosston and Hensel sands of Central Texas, particularly in relation to the Balcones Fault Zone. Henningsen (1962) interpreted change in water chemistry across the fault zone as perhaps indicating vertical mixing of waters. He also suggested that meteoric water was slowly displacing connate water in the formations to the east but that pumping of the aquifers might reverse this trend. Bayha (1967) investigated the occurrence and quality of ground water in the Trinity Group and deeper Pennsylvanian formations of

Montague County. Thompson (1967) conducted several aquifer tests in Ellis County. Myers (1969) included data from North-Central Texas in his compilation of aquifer tests. Thompson (1972) summarized the hydrogeology of Navarro County.

Klemt and others (1975) constructed a numerical model of ground-water flow to predict future water-level declines in the Hensel and Hosston Formations in Coryell and McLennan Counties. Klemt and others (1975) provided a record of wells, drillers' logs, water levels, and ground-water chemical analyses for the same area upon which the model was based.

Taylor (1976) compiled water-level and water-quality data for most of North-Central Texas. Nordstrom (1982) assessed the occurrence, availability, and chemical quality of ground water in the regional aquifers of North-Central Texas. Macpherson (1983) mapped regional trends in transmissivity and hydraulic conductivity of the the Twin Mountains, Paluxy, and Woodbine aquifers. Nordstrom (1987) investigated ground-water resources of the Antlers and Travis Peak Formations of North Central Texas. Rapp (1988) studied recharge in the Trinity aquifer in Central Texas. Baker and others (1990a) evaluated water resources in North-Central and Central Texas.

## METHODS AND DATA

### Stratigraphic Data

The stratigraphic occurrences of sandstone determines the architecture and fabric of the aquifer systems and the distribution of their hydrologic properties. Stratigraphic properties such as sandstone thickness, therefore, provided a basis for assigning hydrologic properties in the models of ground-water flow.

To construct the various stratigraphic and structural maps needed in the hydrologic study, data from approximately 1,200 geophysical well logs were compiled from files at the Surface Casing Unit of the Texas Water Commission (TWC) (now the Texas Natural Resources Conservation Commission [TNRCC]). Locations of wells were taken from maps maintained by the TWC. Spontaneous potential (SP) and resistivity logs were used to delineate sandstone intervals and qualitatively determine water salinity. Fresh-water zones in sandstones were inferred where resistivities >10 ohm-m corresponded to subdued or inverted SP responses. Salt-water bearing zones in sandstones were interpreted where resistivities of <5 ohm-m corresponded to well-developed SP responses. Shales or mudstones were defined where low resistivities (<5 ohm-m) corresponded to subdued or flat SP responses. Limestones were logged where exceptionally high resistivities (generally >20 ohm-m) corresponded to subdued but not inverted SP responses.

Cross sections for specific stratigraphic intervals were made to correlate formation boundaries and sandstone intervals between well logs. Formation boundaries then were extended to correlate sandstone intervals in wells near the cross sections. Maps of the structural elevation of formation boundaries and formation and sandstone thicknesses were made once formation boundaries were determined from the well logs.

## Hydrologic Data

Data on water levels and hydrologic properties were compiled from Hill (1901), Baker (1960), Thompson (1967, 1969, 1972), Myers (1969), Klemt and others (1975), Nordstrom (1982, 1987), and from open and digitized data files of the Texas Water Development Board (TWDB) and TWC/TNRCC.

A total of 22,241 measurements of water levels in North-Central Texas dating from 1899 to 1993 are included in the computerized water-level data base provided by the TWDB. However, the majority of the data has been collected since 1960; few water levels were measured from 1901 to 1936 (fig. 7). Hill (1901) provided numerous measurements and qualitative estimates of water levels in the Twin Mountains, Paluxy, and Woodbine aquifers in North-Central Texas. He also reported information about wells and water levels provided by cities and town officials. Much of those data are anecdotal and qualitative, often only reporting the formation, approximate location, and whether the well flowed or not at land surface.

Water-level maps for the Twin Mountains, Paluxy, and Woodbine aquifers were made for the turn of the century using the quantitative and qualitative water-level data from Hill (1901). The potentiometric surfaces drawn from these data are as close to a "predevelopment" surface as can be obtained, although the presence of numerous flowing wells most likely had already resulted in some drawdown in hydraulic head by the time of Hill's (1901) compilation.

In addition to an estimated predevelopment potentiometric surface drawn on the basis of on Hill's (1901) data, water-level maps were made for

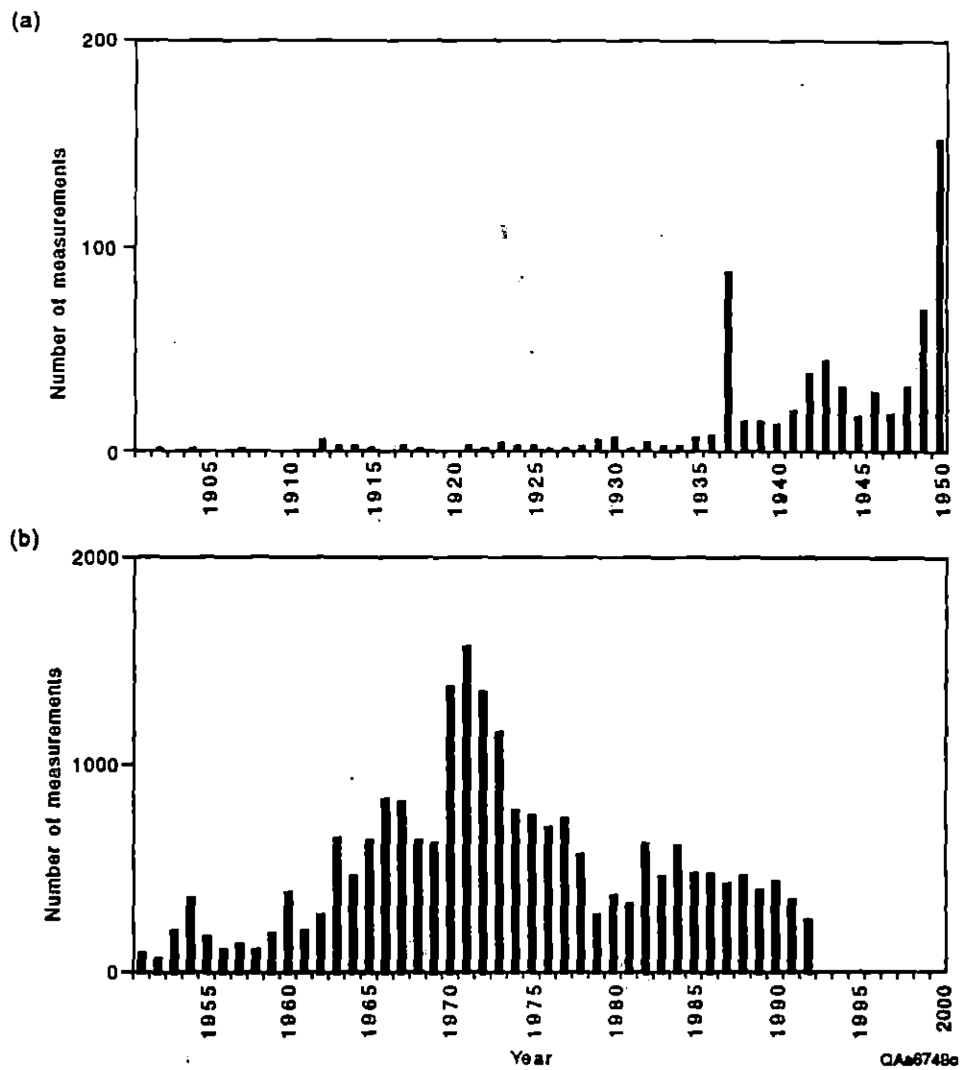


Figure 7. Histogram of water-level measurements made in the study area from (a) 1901 to 1950 and (b) 1951 through 1992. Different vertical scales in (a) and (b).

1935, 1955, 1970, and 1990 on the basis of digitized TWDB data. The 1935 water-level map was made by combining water levels collected from 1930 to 1939 because data from any given year in this decade are sparse. The 1955 maps of the potentiometric surfaces are modified from Nordstrom (1982), in which measurements from 1950 to 1959 were combined. Potentiometric surfaces for 1970 and 1990 were derived from the more extensive TWDB data. Seventy-seven wells had 30 or more water-level measurements. Hydrographs for many of these wells were used for evaluating the numerical model.

Deterministic models of ground-water flow require information on the spatial distribution of hydrological properties. Assigning an uniform distribution of properties to all blocks or nodes of a computer model does not take into account the heterogeneity in geologic and hydrologic properties that affects aquifer performance. Subdividing the model area around aquifer test locations results in unnatural, discontinuous distribution of hydrologic properties. These discontinuities can lead to spurious results, for example, in simulated flow paths and velocities. Assigning hydraulic properties on the basis of both aquifer tests and spatial stratigraphic variables such as sandstone thickness, however, provides a basis for a more realistic, continuous distribution of hydrologic properties for use in models.

Hydrologic properties for use in the numerical model were inferred from records of aquifer (pumping) tests and from specific capacity tests. Transmissivity, which is a bulk hydrologic property related to the thickness and vertical distribution of layers of varying hydraulic conductivity, was determined either from long-term aquifer tests or predicted from short-term specific-capacity tests (Thomasson and others, 1960; Theis, 1963; Brown, 1963). Razack and Huntley (1991) showed that empirical relationships should be used to predict transmissivity because analytical predictions usually do not agree with measured transmissivities. In this study, transmissivity was related to specific capacity on the basis of the abundant aquifer-test data (table 2). Specific capacity was graphed against transmissivity measured in 291 wells for which specific capacity was also reported. One end of the regression line was fixed at the origin—where transmissivity is zero, specific capacity is also zero. The slope was determined from the data by minimizing squared residuals. The relation between specific capacity and transmissivity for the Twin Mountains, Paluxy, and Woodbine aquifers is shown in figure 8. Transmissivities of the Twin Mountains, Paluxy, and Woodbine aquifers were then predicted from the specific-capacity data given for another 1,973 wells.

A total of 85 storativity measurements were compiled: 64 from the Twin Mountains, 9 from the Paluxy, and 7 from the Woodbine aquifer.

## Numerical Modeling of Ground-Water Flow

MODFLOW, a block-centered finite-difference computer program (McDonald and Harbaugh, 1988), was used to simulate ground-water flow. The program's governing equation is the three-dimensional, partial differential equation describing transient ground-water flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}+W \qquad (1)$$

Table 2. Comparison of transmissivities ($ft^2$/day) from aquifer and specific capacity tests.

| Source | Twin Mountains | Paluxy | Woodbine |
|---|---|---|---|
| Aquifer tests | | | |
| Mean | $10^{2.91}$ | $10^{2.79}$ | $10^{2.60}$ |
| Standard deviation | $10^{0.33}$ | $10^{0.27}$ | $10^{0.45}$ |
| Minimum | $10^{1.38}$ | $10^{2.23}$ | $10^{1.65}$ |
| Maximum | $10^{3.60}$ | $10^{3.27}$ | $10^{3.55}$ |
| Number of tests | 205 | 35 | 36 |
| Specific capacities | | | |
| Mean | $10^{2.59}$ | $10^{2.37}$ | $10^{2.49}$ |
| Standard deviation | $10^{0.53}$ | $10^{0.43}$ | $10^{0.54}$ |
| Minimum | $10^{0.48}$ | $10^{0.74}$ | $10^{0.89}$ |
| Maximum | $10^{4.11}$ | $10^{3.46}$ | $10^{3.68}$ |
| Number of tests | 1067 | 375 | 236 |
| Combined | | | |
| Mean | $10^{2.64}$ | $10^{2.40}$ | $10^{2.50}$ |
| Standard deviation | $10^{0.51}$ | $10^{0.47}$ | $10^{0.53}$ |

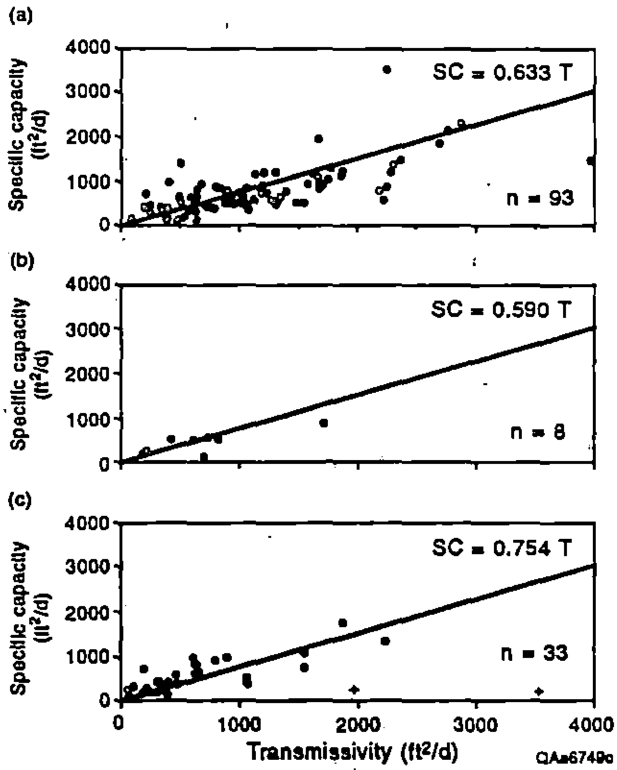


Figure 8. Relation between specific capacity and transmissivity for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. SC is specific capacity, T is transmissivity, *n* is sample size. Regression lines are fixed at origin and represent the least-squares fit to data. Some data (+) not included in least squares regression.

where $x$, $y$, and $z$ are Cartesian coordinates of the system, $K_{xx}$, $K_{yy}$, and $K_{zz}$ are hydraulic conductivities in the $x$, $y$, and $z$ directions, $h$ is the hydraulic head, $S_S$ is the specific storage, $t$ is time, and $W$ represents sources and sinks as a volumetric flux per unit volume.

MODPATH (Pollock, 1989) was used to find residence time of ground water in the cross-sectional model. MODPATH uses two output files from MODFLOW—hydraulic head and cell-by-cell flow—along with porosity data. Ground-water velocity, $v$, is found by dividing the darcy flux, $q$, by the effective porosity, $n_e$

$$v = \frac{q}{n_e} \tag{2}$$

Cross-Sectional Model

A two-dimensional, steady state, cross-sectional model was used to evaluate boundary conditions, vertical hydraulic conductivities of confining layers, and hydraulic-conductivity distributions in the aquifers. A cross-sectional model has several layers but only one horizontal dimension. For example, the model has numerous horizontal columns one row wide in each layer. A cross-sectional model assumes that all flow is within the plane of the profile (Anderson and Woessner, 1992). Aquifers in the Twin Mountains, Paluxy, and Woodbine Formations were included in the cross-sectional model. The Glen Rose, Fredericksburg, Washita, Eagle Ford, Austin, Taylor, and Navarro stratigraphic units were explicitly included in the cross-sectional model as confining layers with low hydraulic conductivity.

Nordstrom's (1982) cross section C-C′ was used to build the cross-sectional model (fig. 9). This profile is oriented predominantly along estimated predevelopment ground-water flow paths in the Twin Mountains, Paluxy, and Woodbine aquifers. The model extends 111 mi (178 km) from the Trinity Formation outcrop in Parker County, through Tarrant and Dallas Counties, and ends at the Mexia-Talco Fault Zone in Kaufman County (fig. 9). The model grid consisted of 54 columns, 1 row, and 10 layers (fig. 10). A total of 340 active blocks was used. Columns were all a uniform length of 10,828 ft (3,300 m). The row was 100 ft (30.5 m) in width. The layers were assigned variable thicknesses on the basis of top and bottom elevations shown in figure 9. The vertical height of the section is 8,000 feet (2,440 m).

Hydrologic properties for aquifer units were initially assigned on the basis of available hydrologic data. Properties then were adjusted by trial-and-error comparison of simulated hydraulic heads and water-level measurements reported by Hill (1901). Initial hydrologic parameters are summarized in table 3.

Direct measurement of hydrogeologic properties for confining layers is uncommon. For the cross-sectional model, vertical hydraulic conductivities of aquifer units were assumed to be 10 times less than the horizontal hydraulic conductivities (table 3). Vertical hydraulic conductivities of confining units were assumed to be 100 times less than horizontal hydraulic conductivities. Vertical and horizontal hydraulic conductivities and porosity of the Navarro Group were assumed to be the same as those of the Taylor Group. Hydraulic conductivity and porosity of Eagle Ford Shale were assumed to be typical of shales (Freeze and Cherry, 1979). Hydrologic

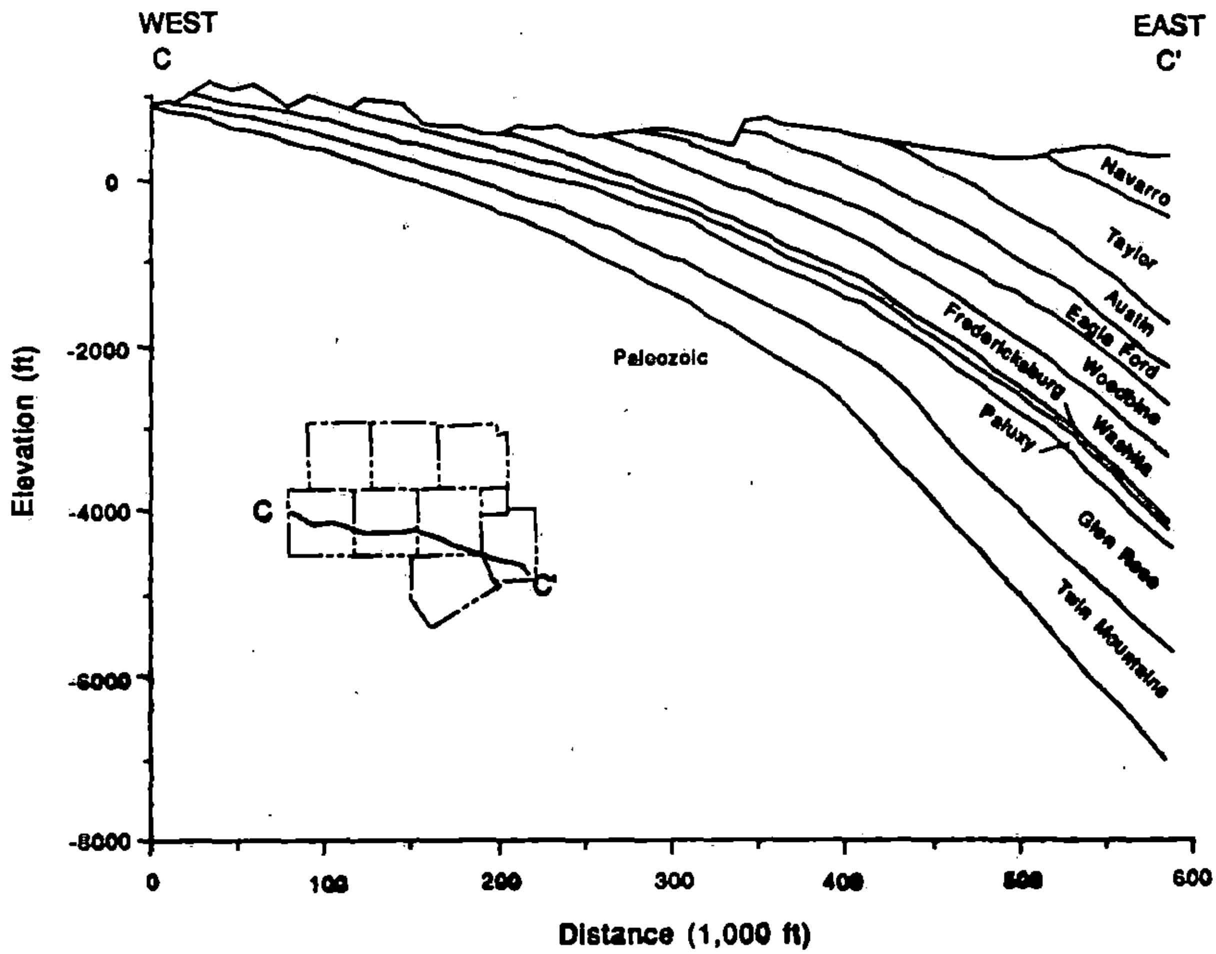


Figure 9. Geologic cross section showing hydrostratigraphic units used for numerical profile model. Modified from Nordstrom (1982).

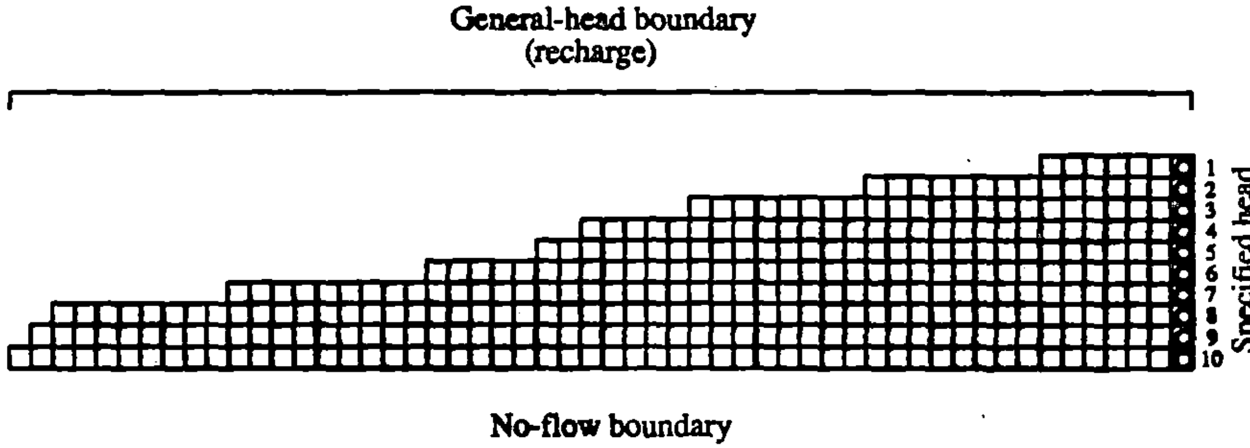


Figure 10. Finite-difference grid used for numerical cross-sectional model. Hydrologic properties were assigned and hydraulic heads calculated for the center of each grid cell. Layers are (1) Navarro Group,(2) Taylor Group, (3) Austin Chalk, (4) Eagle Ford Group, (5) Woodbine Formation, (6) Washita Group, (7) Fredericksburg Group, (8) Paluxy Formation, (9) Glen Rose Formation, and (10) Twin Mountains.

Table 3. Initial hydrologic parameters used in cross-sectional model.

| Formation | Composition | Horizontal hydraulic conductivity (ft/day) | Vertical hydraulic conductivity (ft/day) | Porosity |
|---|---|---|---|---|
| Navarro | Shale | $10^{-5.49}$ | $10^{-7.49}$ | 0.35 |
| Taylor | Shale | $10^{-5.49}$ | $10^{-7.49}$ | 0.35 |
| Austin | Chalk | $10^{-4.24}$ | $10^{-6.24}$ | 0.27 |
| Eagle Ford | Shale | $10^{-6.00}$ | $10^{-8.00}$ | 0.10 |
| Woodbine | Sandstone | $10^{+0.63}$ | $10^{-0.37}$ | 0.05 |
| Washita | Shale & limestone | $10^{-2.22}$ | $10^{-7.60}$ | 0.16 |
| Fredericksburg | Shale & limestone | $10^{-2.22}$ | $10^{-7.60}$ | 0.16 |
| Paluxy | Sandstone | $10^{+0.75}$ | $10^{-0.25}$ | 0.05 |
| Glen Rose | Shale & limestone | $10^{-2.22}$ | $10^{-7.60}$ | 0.16 |
| Twin Mountains | Sandstone | $10^{+0.80}$ | $10^{-0.20}$ | 0.05 |

parameters for the Glen Rose Formation and Fredericksburg and Washita Groups were not found. These units are composed of approximately 40 percent shale and 60 percent limestone, as indicated by resistivity well logs located along the C-C′ line of section. Properties of these hydrologic units were estimated on the basis of rock type, as follows. A typical value of hydraulic conductivity for shale is $10^{-6}$ ft/d ($10^{-6.5}$ m/d), and a typical value of hydraulic conductivity for limestone is $10^{-2}$ ft/d ($10^{-2.5}$ m/d) (Freeze and Cherry, 1979). The arithmetic mean of horizontal hydraulic conductivity, $K_a$, between two formations is given by

$$K_a = \frac{K_l L_l + K_s L_s}{L} \tag{3}$$

where $L$ is total thickness of the formations (1.0), $L_l$ is the thickness of the limestone (0.6), $L_s$ is the length of the shale (0.4), $K_l$ is the hydraulic conductivity of limestone, and $K_s$ is the hydraulic conductivity of shale. The arithmetic mean of horizontal hydraulic conductivity of the confining layers in the Glen Rose Formation and Fredericksburg and Washita Groups—$10^{-2.22}$ ft/d [$10^{-2.74}$ m/d]—was used in the cross-sectional model.

The geometric mean (calculated as average of logarithm of data) of vertical hydraulic conductivities of shale and limestone, $10^{-8}$ and $10^{-4}$ ft/d ($10^{-8.5}$ and $10^{-4.5}$ m/d), respectively, was determined from

$$K_g = \frac{L}{\frac{L_l}{K_l} + \frac{L_s}{K_s}} \tag{4}$$

where $K_g$ is the geometric mean of hydraulic conductivity. The geometric mean of vertical hydraulic conductivity was set to $10^{-7.60}$ ft/d ($10^{-8.1}$ m/d) for the confining layers in the Glen Rose Formation and Fredericksburg and

Washita Groups. A geometric mean for porosity was used on the assumption that only cross-formational or vertical flow would occur through the confining layers.

Because the cross-sectional model is shaped like a wedge, three boundaries need to be assigned: top, bottom, and down-dip boundaries. The general head boundary (GHB) package of MODFLOW (McDonald and Harbaugh, 1988) was used to prescribe the top boundary at a constant hydraulic head. The hydraulic-head value was placed at the mean annual water level of surficial aquifers, which is about 8 ft (2.4 m) below ground surface in the Ellis County area (Dutton and others, 1994). The presence of shallow, hand-dug wells throughout the study area, including the outcrops of aquifers in the Twin Mountains, Paluxy, and Woodbine Formations, indicate that the use of an average water table in surficial unconfined aquifers is reasonable. The GHB boundary simulates recharge and discharge as head-dependent inflow and outflow at the upper boundary. The bottom boundary of the model, which represents the upper surface of Pennsylvanian and Jurassic formations beneath the Cretaceous section, was considered to be impermeable. Various down-dip boundaries at the Mexia-Talco Fault Zone were tested for the model—no-flow, hydrostatic, and a highly permeable fault zone—to determine which best reproduced hydraulic head. Vertical hydraulic conductivities of aquifer units were set in the cross-sectional model at ten times less than the horizontal hydraulic conductivity values.

## Three-Dimensional Model

### Model Size and Finite-Difference Grid

The hydrogeologic data and insights from the cross-sectional model were used in building a three-dimensional simulation of ground-water flow in the Twin Mountains, Paluxy, and Woodbine aquifers. The model grid represents a 30,600-mi$^2$ (78,340-km$^2$) region in North-Central Texas with 95 rows and 89 columns. Uniform row and column widths of 2 mi (3220 m) were assigned to all model blocks. This block size allows allocation of pumping within individual counties. The three principal aquifer units are represented in three model layers. Active finite-difference blocks within each layer are circumscribed by outcrop locations and lateral flow boundaries. The Twin Mountains has 5,377 active blocks (fig. 11), the Paluxy has 3,662 active blocks (fig. 12), and the Woodbine has 2,058 active blocks (fig. 13), for a total of 11,097 active blocks in the model. Confining layers were not explicitly included in the three-dimensional model but were represented by an estimated vertical conductance or leakage factor that restricted vertical flow in the subsurface between aquifers.

### Boundary Conditions

The up-dip limits of formation outcrops form one set of lateral boundaries for each model layer (figs. 11 to 13). The Red River valley was treated as a no-flow boundary because ground-water flow paths are assumed to converge or diverge but not pass beneath major river valleys. No-flow boundaries also were used at the southern edge of the model for each layer, representing (1) the natural limit of influence of the major area of ground-

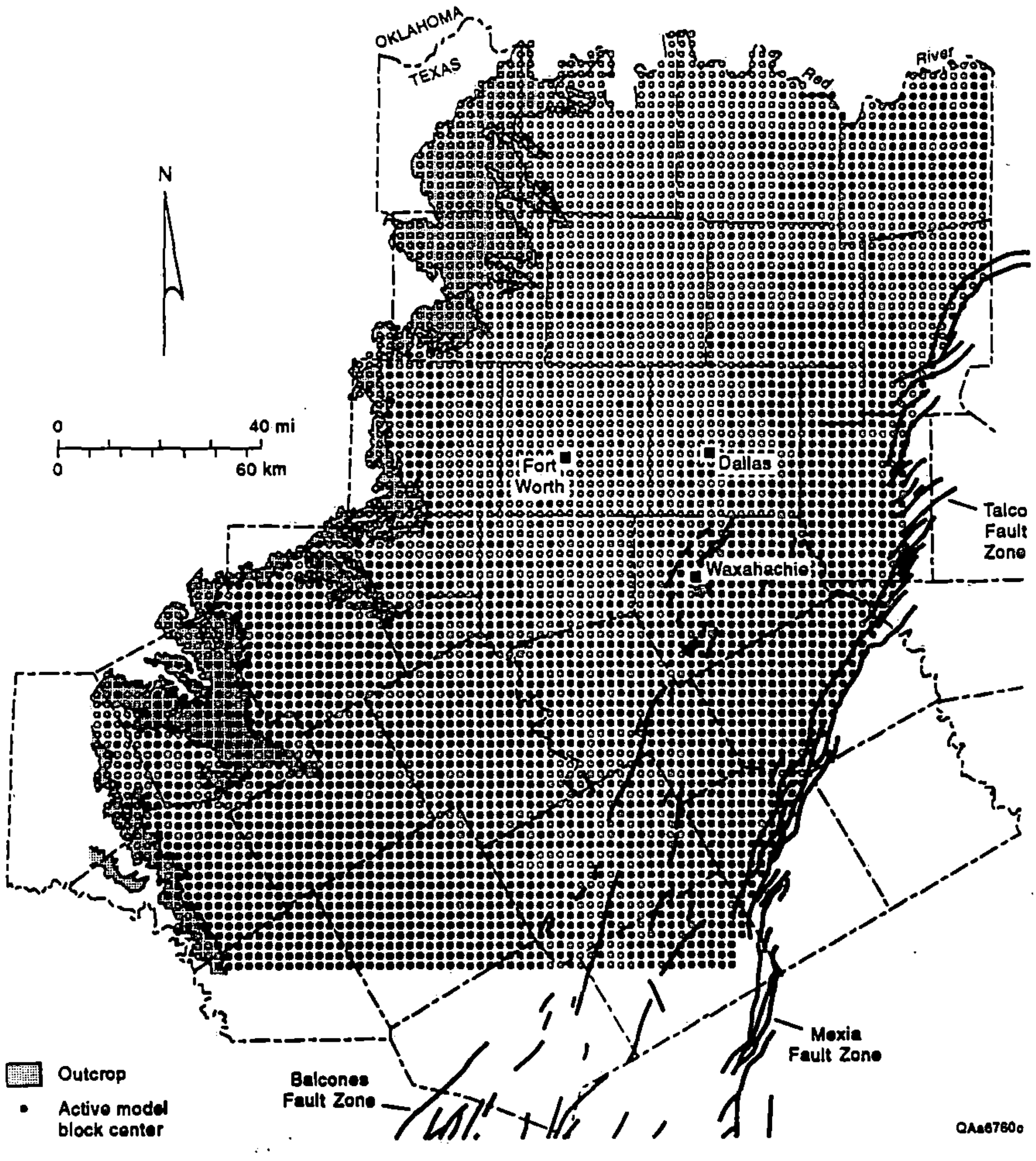


Figure 11. Active blocks used in the three-dimensional model to represent the Twin Mountains Formation.

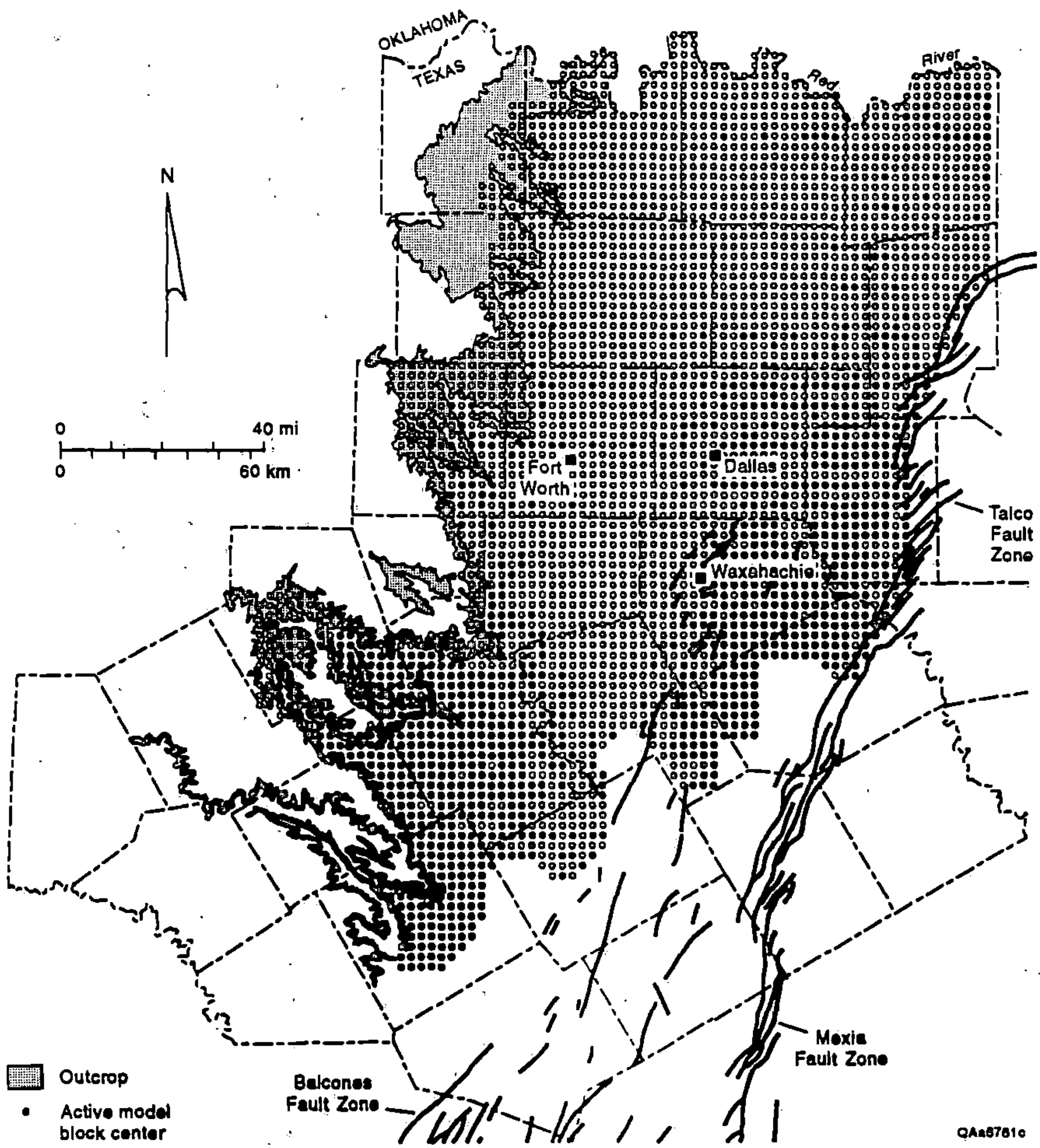


Figure 12. Active blocks used in the three-dimensional model to represent the Paluxy Formation.

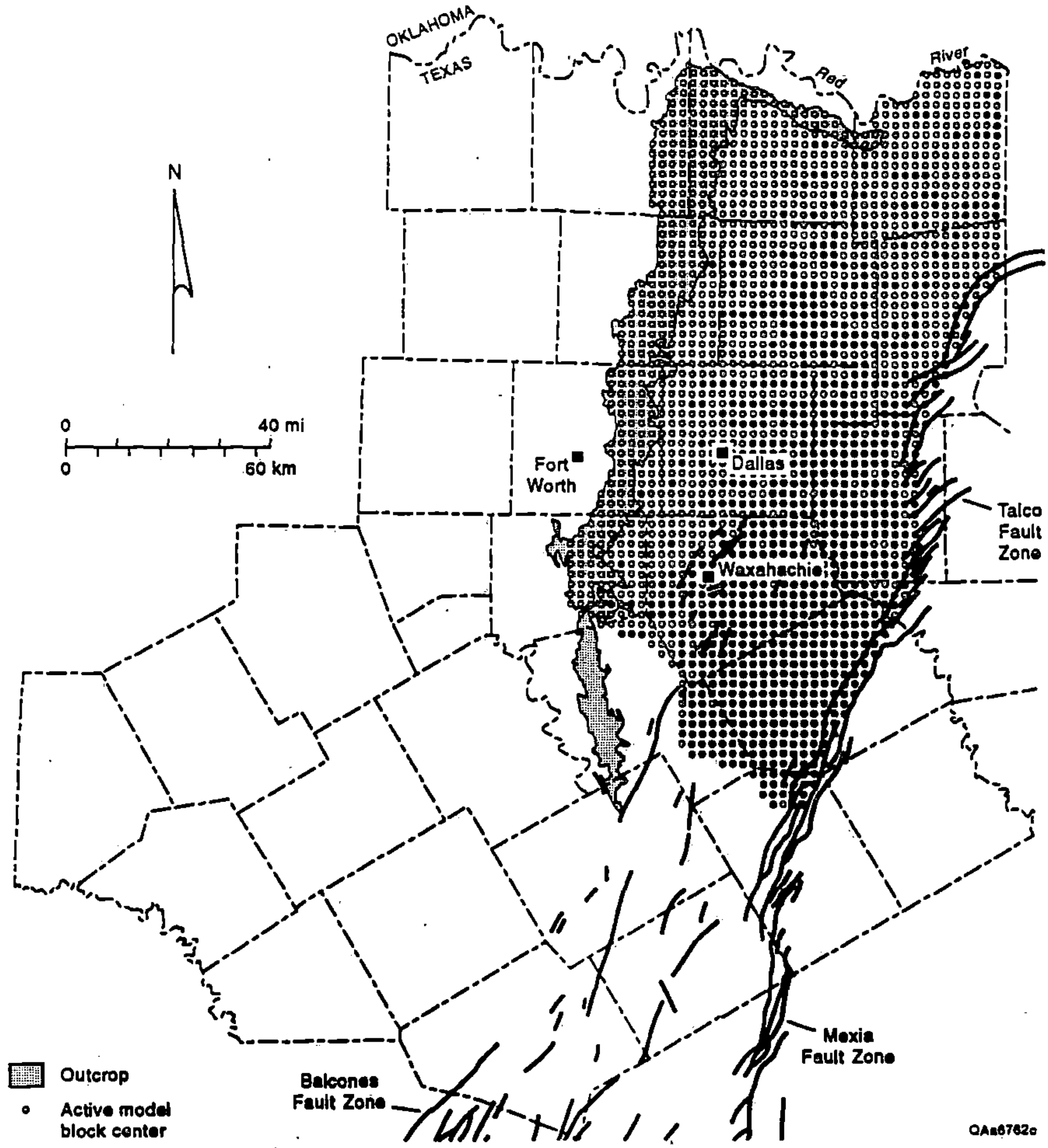


Figure 13. Active blocks used in the three-dimensional model to represent the Woodbine Formation.

water production in Dallas and Tarrant Counties, (2) the thinning, pinch out, or facies change in each formation, and (3) the approximate southeastward direction of pre-development ground-water flow. The east side of each model layer was located at the Mexia-Talco Fault Zone. Several boundary conditions also were evaluated in the three-dimensional model. One type of boundary condition at the Mexia-Talco Fault Zone prescribed the vertical gradient in hydraulic head. This was considered, however, to be too prescriptive. The final boundary condition for the east side of the model used the Drain Module of MODFLOW with the head of the drain set to 5 ft (1.52 m) beneath ground surface to simulate the discharge of ground water from the regional flow system. The base of the three-dimensional model overlying Pennsylvanian and Jurassic formations was assumed to be impermeable.

The GHB-package was used to simulate recharge and discharge. A head-dependent flux boundary was assigned to the uppermost active blocks in the model, representing the outcrop of each aquifer layer as well as vertical leakage into and out of the aquifer where it is confined in the subsurface. The GHB-package determines the movement of water from the gradient between the calculated hydraulic head in the aquifer block and the hydraulic head in an imaginary bounding block that represents a near-surface water table. The value of vertical conductance assigned to a given block in the GHB-package along with the calculated gradient determines the rate of recharge or discharge.

Boundary configurations constrain flow paths in the aquifer units to be down dip from the westernmost outcrop limits and directed toward the

Mexia-Talco Fault Zone. Vertical flow of ground water between formations, for example, beneath river valleys, upland areas, and near the Mexia-Talco Fault Zone, is controlled by the vertical gradient in hydraulic head and vertical hydraulic conductivity (expressed in the numerical model as vertical conductance). Flow through the confining layers is assumed to be vertical, which is generally true of most regional flow systems and consistent with results of the cross-sectional model.

Hydraulic Properties and Calibration

Transmissivity in general varies directly with sandstone content and inversely with shale content. Transmissivity could not be predicted numerically from sandstone thickness because there is not a unique relationship between the two variables. Fluvial and deltaic sandstones appear to have different transmissivity distributions. Transmissivity, therefore, was mapped for each hydrostratigraphic unit on the basis of aquifer tests and sandstone distribution. The logarithm of transmissivity values was posted on a map, which was overlain on a map of sandstone thickness. The latter was used as a guide for contouring the transmissivity distribution. Transmissivity distributions mapped on the basis of field tests and sandstone thickness maps were then digitized and extrapolated for each active block of the finite difference grid. These extrapolated values were completely honored and were not adjusted during model calibration.

Vertical conductances were assigned based on the hydraulic conductivities and the thicknesses of the confining layers and aquifers at each block location. The conductance of a layer, $C_i$, is defined as the hydraulic conductivity ($K_i$) in direction $i$, divided by the height ($d_i$) in direction $i$:

$$C_i = \frac{K_i}{d_i} \tag{5}$$

A harmonic mean must be used to define the vertical conductance term for a confining layer between two aquifers of different hydraulic conductivity:

$$C_z = \frac{1}{\frac{d_k/2}{K_k} + \frac{d_c}{K_c} + \frac{d_{k+1}/2}{K_{k+1}}} \tag{6}$$

where $C_z$ is the conductance in the z direction, $d_k$ is the thickness of the overlying aquifer, $d_c$ is the thickness of the confining layer, $d_{k+1}$ is the thickness of the underlying aquifer, $K_k$ is the hydraulic conductivity of the overlying aquifer, $K_c$ is the hydraulic conductivity of the confining layer, and $K_{k+1}$ is the hydraulic conductivity of the underlying aquifer. Where the aquifer is overlain only by a confining layer, vertical conductance was defined by

$$C_{ghb} = \frac{1}{\frac{d_c}{K_c} + \frac{d_{k+1}/2}{K_{k+1}}} \tag{7}$$

where $C_{ghb}$ is the conductance term for the GHB in the z direction, $d_c$ is the thickness of the overlying confining layers, $d_{k+1}$ is the thickness of the underlying aquifer, $K_c$ is the harmonic mean of the hydraulic conductivities for the overlying confining layers, and $K_{k+1}$ is the hydraulic conductivity of the underlying aquifer.

Storativity is the volume of water released from or taken into storage in an aquifer for a given change in hydraulic head per unit area. Storativity initially was assigned as a covarying function of depth and transmissivity and constrained by the mean and range of values determined from aquifer tests (table 4). The highest values of storativity were assigned to the outcrop (zero depth of confinement). The smallest storativities were assigned where the aquifers were buried to greatest depth. Storativity was assumed to be higher in zones of the aquifer with greater thickness of sandstone and higher transmissivity. To calibrate storativity, simulation results were compared to water-level hydrographs. Figure 14 shows the locations of wells with hydrographs that were used in trial-and-error adjustment of storativity values to obtain a good match between simulated and historic rates of water-level decline in the regional aquifer. Simulated results initially differed from recorded hydrographs for two areas in the Twin Mountains model layer: the area around McLennan County and the area around the Dallas-Fort Worth metroplex including Ellis County. Initial estimates of storativity for these two areas were changed by a factor between 5 and 10 to improve the apparent match of simulated heads and water-level hydrographs.

Hydraulic heads simulated by the finite-difference model in its steady-state mode were compared to plan-view maps of the potentiometric surfaces of the Twin Mountains, Paluxy, and Woodbine aquifers that were drawn on the basis of the earliest reported data (Hill, 1901). These potentiometric surfaces were assumed to approximate the "predevelopment" surface, as discussed later. Boundary conditions and hydrologic properties were slightly adjusted to improve the qualitative match between simulated and 1900 potentiometric surfaces. Once a "best fit" solution was accepted, the simulated steady-state hydraulic heads were used as initial hydraulic heads for the simulation of historical development of the aquifers. For the historical

Table 4. Summary of storativities measured in aquifer tests.

| | Twin Mountains | Paluxy | Woodbine |
|---|---|---|---|
| Mean | $10^{-3.49}$ | $10^{-3.73}$ | $10^{-3.88}$ |
| Standard deviation | $10^{1.07}$ | $10^{0.81}$ | $10^{0.49}$ |
| Minimum | $10^{-4.70}$ | $10^{-4.40}$ | $10^{-4.70}$ |
| Maximum | $10^{-0.89}$ | $10^{-1.72}$ | $10^{-3.13}$ |
| Number of tests | 63 | 9 | 7 |

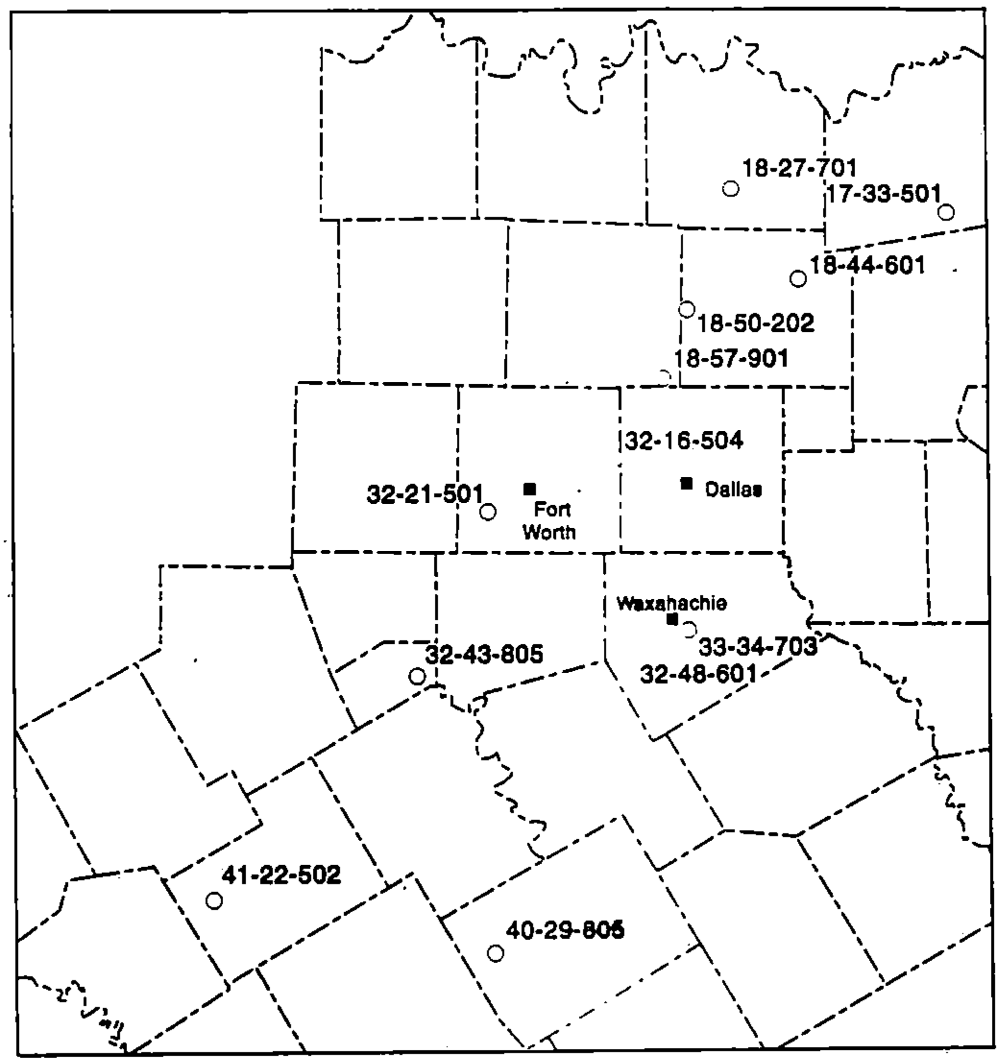


Figure 14. Location of selected water wells for comparison between recorded and simulated water levels.

model, stress periods were set to 10-year lengths, for example, 1891-1900, 1901-1910, ..., 1961-1970, and so on. Stress periods were divided into 12 time steps and run with a time-step acceleration parameter of 1.2 (McDonald and Harbaugh, 1988). The convergence criterion for hydraulic head change was set to 0.001 ft (0.0003 m).

Estimates of Pumping Rates

Ground-water pumping represents historical and projected future water demand (tables 5 to 10). Few records are available for ground-water production in North-Central Texas during the late 19th and early 20th centuries. Hill (1901) describes the early artesian condition of the aquifers and provides information on aquifer development and well records. During the early period of aquifer development (that is, approximately 1890 to 1920) a large part of the discharge was uncontrolled from flowing wells, which is difficult to reconstruct with great confidence. Hill (1901) cites for many counties the number and capacity of flowing and non-flowing (pumped) wells. While early rates of discharge undoubtedly were large, rate of discharge most likely decreased rapidly once fluid pressures were drawn down to ground surface and more and more wells ceased to freely flow. Farther east flowing wells were less prevalent (Livingston, 1945; Rose, 1945; Texas Board of Water Engineers, 1961; Thompson, 1972; Baker, 1960).

Total ground-water production in the artesian belt during the period from 1930 to 1970 has been estimated in a variety of reports, but not broken out by aquifer (Fiedler, 1934; Leggat, 1957; Russell, 1963; Thompson, 1967, 1969; Taylor, 1976). There also are data on production where the aquifers crop out

Table 5. Simulated ground-water production from the Twin Mountains Formation (acre-ft/yr), historical stress period (1891-2000)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 6,671 | 5,051 | 3,073 | 2,477 | 423 | 0 | 107 | 0 | 555 | 258 | 0 |
| 1901-1910 | 4,203 | 3,182 | 3,073 | 2,477 | 423 | 0 | 107 | 0 | 555 | 258 | 0 |
| 1911-1920 | 3,071 | 1,741 | 3,073 | 2,477 | 423 | 0 | 107 | 0 | 555 | 258 | 0 |
| 1921-1930 | 1,939 | 300 | 2,973 | 2,842 | 745 | 0 | 847 | 560 | 827 | 306 | 189 |
| 1931-1940 | 807 | 300 | 2,873 | 3,207 | 1,011 | 3,187 | 1,587 | 1,120 | 1,099 | 354 | 378 |
| 1941-1950 | 639 | 2,621 | 2,773 | 3,572 | 1,277 | 6,374 | 2,327 | 1,680 | 1,371 | 402 | 567 |
| 1951-1960 | 558 | 4,942 | 2,673 | 3,937 | 1,543 | 9,561 | 3,067 | 2,242 | 1,643 | 442 | 756 |
| 1961-1970 | 477 | 7,263 | 2,573 | 4,302 | 1,809 | 12,748 | 3,807 | 1,836 | 1,915 | 623 | 940 |
| 1971-1980 | 467 | 9,585 | 2,632 | 5,221 | 2,488 | 18,318 | 5,010 | 1,966 | 2,429 | 1,369 | 1,996 |
| 1981-1990 | 1,176 | 12,131 | 3,440 | 6,256 | 3,250 | 16,268 | 7,513 | 5,250 | 2,406 | 3,694 | 6,528 |
| 1991-2000 | 1,177 | 11,597 | 4,113 | 6,307 | 1,111 | 9,277 | 7,209 | 5,159 | 2,310 | 3,680 | 6,250 |

| Years | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 1,695 | 975 | 65 | 38 | 49 | 250 | 0 | 336 | 72 | 90 | 0 |
| 1901-1910 | 1,051 | 975 | 65 | 38 | 49 | 250 | 0 | 336 | 72 | 90 | 0 |
| 1911-1920 | 1,051 | 975 | 65 | 38 | 49 | 250 | 0 | 336 | 72 | 90 | 0 |
| 1921-1930 | 1,427 | 1,328 | 144 | 134 | 132 | 349 | 424 | 1,029 | 913 | 211 | 16 |
| 1931-1940 | 1,803 | 1,681 | 223 | 230 | 215 | 448 | 848 | 1,721 | 1,755 | 326 | 30 |
| 1941-1950 | 2,207 | 2,034 | 302 | 326 | 298 | 547 | 1,272 | 2,413 | 2,596 | 433 | 45 |
| 1951-1960 | 5,116 | 2,387 | 381 | 422 | 381 | 645 | 1,695 | 3,105 | 3,438 | 534 | 76 |
| 1961-1970 | 5,662 | 2,740 | 462 | 518 | 464 | 550 | 1,674 | 9,713 | 3,977 | 629 | 102 |
| 1971-1980 | 11,300 | 2,985 | 1,560 | 821 | 697 | 1,344 | 1,422 | 13,452 | 10,247 | 789 | 139 |
| 1981-1990 | 11,584 | 1,267 | 1,629 | 900 | 797 | 3,145 | 1,203 | 22,247 | 11,040 | 598 | 106 |
| 1991-2000 | 9,680 | 1,119 | 1,335 | 874 | 1,070 | 3,488 | 1,176 | 25,694 | 11,318 | 703 | 100 |

| Years | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 56 | 331 | 0 | 0 | 0 | 10 | 0 | 678 | 0 | 23,260 |
| 1901-1910 | 56 | 351 | 0 | 0 | 0 | 10 | 0 | 678 | 0 | 18,299 |
| 1911-1920 | 56 | 371 | 0 | 0 | 0 | 10 | 0 | 678 | 0 | 15,746 |
| 1921-1930 | 56 | 391 | 0 | 0 | 15 | 10 | 0 | 811 | 0 | 18,918 |
| 1931-1940 | 148 | 411 | 0 | 5 | 30 | 10 | 0 | 944 | 71 | 26,822 |
| 1941-1950 | 197 | 431 | 0 | 11 | 45 | 113 | 0 | 1,078 | 71 | 38,022 |
| 1951-1960 | 1,916 | 406 | 0 | 16 | 60 | 470 | 0 | 1,211 | 71 | 53,694 |
| 1961-1970 | 3,879 | 620 | 0 | 22 | 74 | 336 | 0 | 1,097 | 0 | 70,812 |
| 1971-1980 | 5,804 | 1,036 | 0 | 32 | 94 | 445 | 0 | 2,018 | 0 | 105,666 |
| 1981-1990 | 10,951 | 1,757 | 0 | 56 | 44 | 405 | 0 | 3,924 | 0 | 139,565 |
| 1991-2000 | 11,387 | 1,823 | 0 | 12 | 70 | 567 | 0 | 4,831 | 0 | 133,437 |

Table 6. Simulated ground-water production from the Paluxy Formation (acre-ft/yr), historical stress period (1891-2000)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 0 | 0 | 16 | 1,081 | 81 | 0 | 3,391 | 0 | 25 | 0 | 103 |
| 1901-1910 | 0 | 0 | 16 | 1,081 | 81 | 0 | 2,136 | 0 | 25 | 0 | 103 |
| 1911-1920 | 0 | 0 | 16 | 1,081 | 81 | 0 | 1,218 | 0 | 25 | 0 | 103 |
| 1921-1930 | 0 | 0 | 14 | 927 | 39 | 634 | 300 | 2 | 37 | 0 | 477 |
| 1931-1940 | 90 | 0 | 12 | 773 | 53 | 1,267 | 300 | 4 | 49 | 0 | 851 |
| 1941-1950 | 71 | 0 | 10 | 619 | 67 | 1,901 | 502 | 6 | 61 | 0 | 1,225 |
| 1951-1960 | 62 | 0 | 8 | 465 | 81 | 2,535 | 704 | 8 | 73 | 0 | 1,598 |
| 1961-1970 | 53 | 0 | 6 | 311 | 95 | 2,125 | 906 | 11 | 85 | 0 | 2,000 |
| 1971-1980 | 52 | 0 | 1 | 52 | 131 | 1,880 | 1,109 | 6 | 106 | 0 | 1,562 |
| 1981-1990 | 131 | 0 | 0 | 0 | 171 | 1,627 | 835 | 0 | 82 | 0 | 881 |
| 1991-2000 | 131 | 0 | 0 | 0 | 58 | 928 | 801 | 0 | 74 | 0 | 790 |

| Years | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 4,442 | 32 | 0 | 0 | 0 | 59 | 0 | 0 | 861 | 0 | 5 |
| 1901-1910 | 2,754 | 32 | 0 | 0 | 0 | 59 | 0 | 0 | 861 | 0 | 5 |
| 1911-1920 | 2,754 | 32 | 0 | 0 | 0 | 59 | 0 | 0 | 861 | 0 | 5 |
| 1921-1930 | 3,636 | 0 | 0 | 0 | 0 | 62 | 47 | 0 | 741 | 11 | 5 |
| 1931-1940 | 4,518 | 0 | 0 | 0 | 0 | 66 | 94 | 0 | 661 | 18 | 6 |
| 1941-1950 | 5,396 | 0 | 0 | 0 | 0 | 69 | 141 | 0 | 582 | 24 | 6 |
| 1951-1960 | 9,474 | 0 | 0 | 0 | 0 | 72 | 188 | 0 | 382 | 31 | 8 |
| 1961-1970 | 8,288 | 0 | 0 | 0 | 0 | 61 | 186 | 0 | 442 | 38 | 11 |
| 1971-1980 | 6,304 | 0 | 0 | 0 | 0 | 149 | 158 | 0 | 1,139 | 44 | 9 |
| 1981-1990 | 4,965 | 0 | 0 | 0 | 0 | 349 | 169 | 0 | 1,227 | 31 | 24 |
| 1991-2000 | 4,148 | 0 | 0 | 0 | 0 | 388 | 196 | 0 | 1,258 | 37 | 30 |

| Years | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 108 | 277 | 0 | 0 | 0 | 0 | 0 | 86 | 0 | 10,567 |
| 1901-1910 | 108 | 238 | 0 | 0 | 0 | 0 | 0 | 86 | 0 | 7,585 |
| 1911-1920 | 108 | 199 | 0 | 0 | 0 | 0 | 0 | 86 | 0 | 6,628 |
| 1921-1930 | 50 | 160 | 0 | 0 | 0 | 0 | 0 | 497 | 0 | 7,639 |
| 1931-1940 | 50 | 121 | 0 | 1 | 0 | 0 | 0 | 909 | 0 | 9,843 |
| 1941-1950 | 75 | 82 | 0 | 1 | 0 | 0 | 0 | 1,320 | 0 | 12,158 |
| 1951-1960 | 101 | 45 | 0 | 2 | 0 | 0 | 0 | 1,731 | 0 | 17,568 |
| 1961-1970 | 204 | 69 | 0 | 2 | 0 | 0 | 0 | 1,054 | 0 | 15,947 |
| 1971-1980 | 306 | 115 | 0 | 4 | 0 | 0 | 0 | 794 | 0 | 13,921 |
| 1981-1990 | 576 | 195 | 0 | 6 | 0 | 0 | 0 | 436 | 0 | 11,705 |
| 1991-2000 | 599 | 203 | 0 | 1 | 0 | 0 | 0 | 537 | 0 | 10,179 |

Table 7. Simulated ground-water production from the Woodbine Formation (acre-ft/yr), historical stress period (1891-2000)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 0 | 0 | 0 | 0 | 0 | 3,449 | 373 | 1,171 | 23 | 0 | 271 |
| 1901-1910 | 0 | 0 | 0 | 0 | 0 | 3,449 | 373 | 1,171 | 23 | 0 | 271 |
| 1911-1920 | 0 | 0 | 0 | 0 | 0 | 3,449 | 373 | 1,171 | 23 | 0 | 271 |
| 1921-1930 | 0 | 0 | 0 | 0 | 0 | 3,377 | 423 | 1,439 | 34 | 0 | 334 |
| 1931-1940 | 0 | 0 | 0 | 0 | 0 | 3,305 | 473 | 1,707 | 45 | 0 | 397 |
| 1941-1950 | 0 | 0 | 0 | 0 | 0 | 3,233 | 523 | 1,975 | 56 | 0 | 460 |
| 1951-1960 | 0 | 0 | 0 | 0 | 0 | 3,159 | 573 | 2,242 | 67 | 0 | 523 |
| 1961-1970 | 0 | 0 | 0 | 0 | 0 | 4,979 | 623 | 3,510 | 78 | 0 | 680 |
| 1971-1980 | 0 | 0 | 0 | 0 | 0 | 2,080 | 711 | 2,756 | 99 | 0 | 452 |
| 1981-1990 | 0 | 0 | 0 | 0 | 0 | 1,178 | 1,445 | 2,683 | 31 | 0 | 688 |
| 1991-2000 | 0 | 0 | 0 | 0 | 0 | 811 | 1,844 | 2,440 | 17 | 0 | 858 |

| Years | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 3,893 | 0 | 0 | 0 | 0 | 0 | 299 | 0 | 0 | 0 | 27 |
| 1901-1910 | 2,414 | 0 | 0 | 0 | 0 | 0 | 299 | 0 | 0 | 0 | 27 |
| 1911-1920 | 2,414 | 0 | 0 | 0 | 0 | 0 | 299 | 0 | 0 | 0 | 283 |
| 1921-1930 | 1,809 | 0 | 0 | 0 | 0 | 0 | 446 | 0 | 0 | 0 | 539 |
| 1931-1940 | 1,204 | 0 | 0 | 0 | 0 | 0 | 593 | 0 | 0 | 0 | 795 |
| 1941-1950 | 572 | 0 | 0 | 0 | 0 | 0 | 740 | 0 | 0 | 0 | 1,051 |
| 1951-1960 | 379 | 0 | 0 | 0 | 0 | 0 | 886 | 0 | 0 | 0 | 1,307 |
| 1961-1970 | 189 | 0 | 0 | 0 | 0 | 0 | 909 | 0 | 0 | 0 | 1,768 |
| 1971-1980 | 74 | 0 | 0 | 0 | 0 | 0 | 1,189 | 0 | 0 | 0 | 2,327 |
| 1981-1990 | 9 | 0 | 0 | 0 | 0 | 0 | 877 | 0 | 0 | 0 | 2,697 |
| 1991-2000 | 4 | 0 | 0 | 0 | 0 | 0 | 862 | 0 | 0 | 0 | 2,192 |

| Years | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 1891-1900 | 968 | 0 | 83 | 762 | 0 | 0 | 470 | 0 | 0 | 11,789 |
| 1901-1910 | 646 | 0 | 90 | 762 | 0 | 0 | 470 | 0 | 0 | 9,995 |
| 1911-1920 | 704 | 0 | 96 | 762 | 0 | 0 | 470 | 0 | 0 | 10,315 |
| 1921-1930 | 762 | 0 | 102 | 670 | 0 | 0 | 780 | 0 | 0 | 10,715 |
| 1931-1940 | 820 | 0 | 109 | 578 | 0 | 0 | 621 | 0 | 0 | 10,647 |
| 1941-1950 | 1,094 | 0 | 115 | 486 | 0 | 0 | 462 | 0 | 0 | 10,767 |
| 1951-1960 | 3,419 | 0 | 121 | 394 | 0 | 0 | 303 | 0 | 0 | 13,373 |
| 1961-1970 | 4,155 | 0 | 214 | 302 | 0 | 0 | 146 | 0 | 0 | 17,553 |
| 1971-1980 | 4,891 | 0 | 344 | 152 | 0 | 0 | 219 | 0 | 0 | 15,294 |
| 1981-1990 | 5,627 | 0 | 348 | 62 | 0 | 0 | 123 | 0 | 0 | 15,768 |
| 1991-2000 | 5,060 | 0 | 376 | 82 | 0 | 0 | 128 | 0 | 0 | 14,674 |

Figure 8. Simulated ground-water production from the Twin Mountains Formation (acre-ft/yr), future stress period (2001-2050)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 555 | 1,914 | 2,289 | 4,099 | 2,574 | 3,578 | 5,808 | 4,778 | 1,509 | 1,119 | 2,624 |
| 2011-2020 | 555 | 1,757 | 2,356 | 3,947 | 2,574 | 2,730 | 5,808 | 4,588 | 1,307 | 1,119 | 2,563 |
| 2021-2030 | 555 | 1,756 | 2,361 | 3,983 | 2,574 | 2,730 | 5,808 | 4,588 | 1,321 | 1,119 | 2,563 |
| 2031-2040 | 443 | 1,467 | 1,948 | 3,345 | 1,859 | 2,399 | 4,698 | 3,605 | 1,101 | 891 | 2,196 |
| 2041-2050 | 443 | 1,467 | 1,963 | 3,385 | 1,859 | 2,399 | 4,698 | 3,605 | 1,115 | 891 | 2,196 |

| | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 4,746 | 2,066 | 1,190 | 1,758 | 1,785 | 4,539 | 2,708 | 1,483 | 1,708 | 304 | 492 |
| 2011-2020 | 4,219 | 1,906 | 1,194 | 1,805 | 1,782 | 4,511 | 2,578 | 1,506 | 1,708 | 304 | 533 |
| 2021-2030 | 4,227 | 1,936 | 1,199 | 1,991 | 1,784 | 4,486 | 2,701 | 1,633 | 1,708 | 304 | 535 |
| 2031-2040 | 1,370 | 1,708 | 1,085 | 1,581 | 1,748 | 3,799 | 2,399 | 1,586 | 1,708 | 174 | 528 |
| 2041-2050 | 1,377 | 1,723 | 1,087 | 1,646 | 1,753 | 3,778 | 2,399 | 1,587 | 1,708 | 174 | 529 |

| | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 1,510 | 2,092 | 0 | 1,125 | 27 | 1,248 | 0 | 3,498 | 281 | 63,407 |
| 2011-2020 | 1,674 | 2,057 | 0 | 1,125 | 45 | 1,281 | 0 | 3,106 | 250 | 60,888 |
| 2021-2030 | 1,673 | 2,055 | 0 | 1,125 | 27 | 1,405 | 0 | 3,112 | 250 | 61,509 |
| 2031-2040 | 1,649 | 1,679 | 0 | 942 | 28 | 1,347 | 0 | 2,579 | 250 | 50,090 |
| 2041-2050 | 1,648 | 1,681 | 0 | 942 | 26 | 1,366 | 0 | 2,581 | 250 | 50,276 |

Figure 9. Simulated ground-water production from the Paluxy Formation (acre-ft/yr), future stress period (2001-2050)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 29 | 0 | 121 | 216 | 136 | 188 | 306 | 251 | 79 | 0 | 138 |
| 2011-2020 | 29 | 0 | 124 | 208 | 136 | 144 | 306 | 241 | 69 | 0 | 135 |
| 2021-2030 | 29 | 0 | 124 | 210 | 136 | 144 | 247 | 241 | 70 | 0 | 135 |
| 2031-2040 | 23 | 0 | 103 | 176 | 98 | 126 | 247 | 190 | 58 | 0 | 116 |
| 2041-2050 | 23 | 0 | 103 | 178 | 98 | 126 | 247 | 190 | 59 | 0 | 116 |

| Years | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 250 | 109 | 63 | 93 | 94 | 239 | 143 | 0 | 90 | 16 | 5 |
| 2011-2020 | 222 | 100 | 63 | 95 | 94 | 237 | 136 | 0 | 90 | 16 | 5 |
| 2021-2030 | 223 | 102 | 63 | 105 | 94 | 236 | 142 | 0 | 90 | 16 | 5 |
| 2031-2040 | 72 | 90 | 57 | 82 | 92 | 200 | 126 | 0 | 90 | 9 | 5 |
| 2041-2050 | 72 | 91 | 57 | 187 | 92 | 199 | 126 | 0 | 90 | 9 | 6 |

| Years | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2010 | 80 | 110 | 119 | 59 | 3 | 0 | 0 | 184 | 0 | 3,121 |
| 2011-2020 | 88 | 108 | 119 | 59 | 5 | 0 | 0 | 163 | 0 | 2,992 |
| 2021-2030 | 88 | 108 | 119 | 59 | 3 | 0 | 0 | 164 | 0 | 2,953 |
| 2031-2040 | 87 | 88 | 109 | 50 | 3 | 0 | 0 | 136 | 0 | 2,433 |
| 2041-2050 | 87 | 89 | 109 | 50 | 3 | 0 | 0 | 136 | 0 | 2,543 |

Figure 10. Simulated ground-water production from the Woodbine Formation (acre-ft/yr), future stress period (2001-2050)

| Years | Somervell | McLennan | Bosque | Cooke | Coryell | Dallas | Denton | Ellis | Hill | Hood | Johnson |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000-2009 | 0 | 0 | 0 | 440 | 0 | 864 | 1,010 | 1,670 | 343 | 0 | 761 |
| 2010-2019 | 0 | 0 | 0 | 440 | 0 | 840 | 1,010 | 1,571 | 401 | 0 | 838 |
| 2020-2029 | 0 | 0 | 0 | 440 | 0 | 815 | 1,010 | 1,571 | 401 | 0 | 866 |
| 2030-2039 | 0 | 0 | 0 | 440 | 0 | 770 | 1,010 | 1,472 | 458 | 0 | 463 |
| 2040-2049 | 0 | 0 | 0 | 440 | 0 | 791 | 1,010 | 1,473 | 458 | 0 | 463 |

| | Tarrant | Bell | Brown | Lampasas | Mills | Wise | Collin | Comanche | Erath | Falls | Fannin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000-2009 | 76 | 0 | 0 | 0 | 0 | 0 | 457 | 0 | 0 | 0 | 2,929 |
| 2010-2019 | 191 | 0 | 0 | 0 | 0 | 0 | 402 | 0 | 0 | 0 | 3,172 |
| 2020-2029 | 191 | 0 | 0 | 0 | 0 | 0 | 402 | 0 | 0 | 0 | 3,386 |
| 2030-2039 | 268 | 0 | 0 | 0 | 0 | 0 | 366 | 0 | 0 | 0 | 2,221 |
| 2040-2049 | 268 | 0 | 0 | 0 | 0 | 0 | 366 | 0 | 0 | 0 | 2,302 |

| | Grayson | Hamilton | Hunt | Kaufman | Limestone | Montague | Navarro | Parker | Rockwall | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2000-2009 | 4,156 | 0 | 89 | 762 | 33 | 0 | 60 | 0 | 0 | 13,650 |
| 2010-2019 | 4,650 | 0 | 89 | 762 | 33 | 0 | 60 | 0 | 0 | 14,459 |
| 2020-2029 | 4,650 | 0 | 89 | 762 | 33 | 0 | 60 | 0 | 0 | 14,676 |
| 2030-2039 | 5,221 | 0 | 89 | 670 | 33 | 0 | 60 | 0 | 0 | 13,541 |
| 2040-2049 | 5,221 | 0 | 89 | 578 | 33 | 0 | 60 | 0 | 0 | 13,552 |

(Texas Board of Water Engineers, 1944; Stramel, 1951; Bayha, 1967; Nordstrom, 1987). Taylor (1976) gives data on annual ground-water production for municipal and industrial uses for the period of 1955-1972 for most of the counties in the study area. Ground water produced for irrigation in 1958, 1964, 1969, 1974, and 1979 was estimated by Texas Water Development Board (1986); amounts were averaged for each stress period. Pumping data for 1972, 1974, 1980, and the 1984-91 period provided by the Texas Water Development Board were also used in the ground-water flow model.

In order to estimate ground-water production for the earliest period several assumptions were made:

- Hill's (1901) records of flowing and non-flowing wells provide the best basis for reconstructing average discharge rates;
- discharge decreased from high levels in the late 1800s to minimum levels during the 1930s;
- Somervell County had the highest early production rates;
- where Hill (1901) does not report well data, discharge was based on an assumed yield of 10 gallons per minute (gpm [$6.31 \times 10^{-4}$ $m^3/s$]) for pumped wells and 155 gpm ($9.78 \times 10^{-4}$ $m^3/s$) for flowing wells;
- production from counties within the artesian belt decreased rapidly when wells stopped flowing; and
- in the few counties where reported production from the Paluxy is grouped together with that from the Twin Mountains, production from the Paluxy was assumed to be ≤ 10 percent of the total discharge.

Having made county-by-county estimates of ground-water discharge for each 10-yr stress period, discharge within each county was assigned randomly to the finite-difference blocks using a binomial distribution. Each block within a county had equal probability of receiving pumping and the pumping rate was assigned by a binomial probability density function controlled by the number of blocks per county and total pumping in the county. The pumping distribution was randomly reassigned at the start of each stress period. Depending on the stress period, 32 to 47 percent of the active blocks in the model had some pumping assigned. The greater the pumping for a given county, the greater the number of blocks that had pumping assigned.

The randomized pumping distribution provides a reasonable approximation of historical pumping and is justified for three reasons. First, historical data on the number, location, and amount of pumping are inadequate to underwrite any unique distribution. Second, the fact that different randomizations resulted in minor variations in drawdown suggests that total regional pumping might be as important as the actual distribution of pumping. Third, the distribution of wells across the study area appears fairly uniform with the possible exception of the Dallas-Fort Worth metropolitan area. Almost half of the model blocks include at least one well.

Pumping rates for the period from 2001 to 2050 (tables 8 to 10) were based predictions of total water demand in each county made by the Texas Water Development Board. The distribution of pumping rates for "future" stress periods used the same proportional distribution of pumping in blocks.

# STRATIGRAPHY

## Stratigraphic Occurrences of Sandstone

Cretaceous strata record variations in carbonate and siliciclastic deposition that undoubtedly influence occurrence and movement of ground water on both local and regional scales. The deposition of carbonate and siliciclastic rocks took place during an overall rise in relative sea level during the Cretaceous. This interpretation is based on three observations. First, the vertical sequence of depositional facies within an individual formation suggests deepening of depositional environments on a local scale. For example, basal Trinity and Woodbine sandstone beds are fluvial, whereas uppermost beds are more marine (Oliver, 1971; Hall, 1976). Second, carbonate formations interfinger with and eventually overlap sandstone formations on a regional scale (fig. 2). For example, marine limestones and claystones of the Walnut Formation interfinger with and overlap deltaic sandstones and mudstones of the Paluxy Formation. Third, also on a regional scale, younger Cretaceous carbonate formations generally pinch out farther up dip than do older ones, suggesting marine environments progressively reached farther landward (fig. 2). The oldest (Coahuilan Series) carbonates are truncated along the eastern margin of the Mexia-Talco Fault Zone. The lower Comanchean Series carbonates pinch out in the central part of the study area, and the overlying upper Comanchean carbonates are present up dip of the Glen Rose pinchout. The Eagle Ford Formation and Austin Chalk, judging from the thickness of remaining deposits and facies compositions, probably pinched out even farther up dip than the upper Comanchean carbonates.

Depositional environments of the Trinity, Paluxy and Woodbine were probably similar in paleogeography. The fluvial-deltaic depositional systems extended along a coastline from Texas to Florida subparallel to the present Gulf Coast (Saucier, 1985; Bebout and others, 1992). The formations are composed of depositional elements typical of fluvial and destructive-deltaic systems (Fisher, 1969). Preceding deposition of the Trinity and Woodbine sands, and probably preceding deposition of Paluxy sands, erosional unconformities were developed during relative sea-level lowstands. Fluvial-dominated constructive components include dip-aligned, stacked sandbodies deposited in distributaries and channel-mouth bars. Destructive marine-dominated facies include aprons of sand deposited on coastal barriers and strandplains oriented perpendicular to dip, giving a generally arcuate to multi-lobate form to the gross deposit (fig. 15). Sand source areas during the Early Cretaceous were probably toward the north and northwest (fig. 16), including Paleozoic rocks in the Wichita, Arbuckle and Ouachita Mountain Uplifts (McGowen and Harris, 1984).

## Description of Aquifer Units and Depositional Systems

The aquifer units in Cretaceous formations may be generalized as being in basal sandstone members of unconformity-bounded sandstone-carbonate couplets (Lozo and Stricklin, 1956). The Hosston–Pearsall makes up one sandstone-carbonate couplet in the study area; three others are the Hensel–Glen Rose, Paluxy–Georgetown, and Woodbine–Eagle Ford couplets. The limestone and shale at the top of each couplet make up a confining layer that

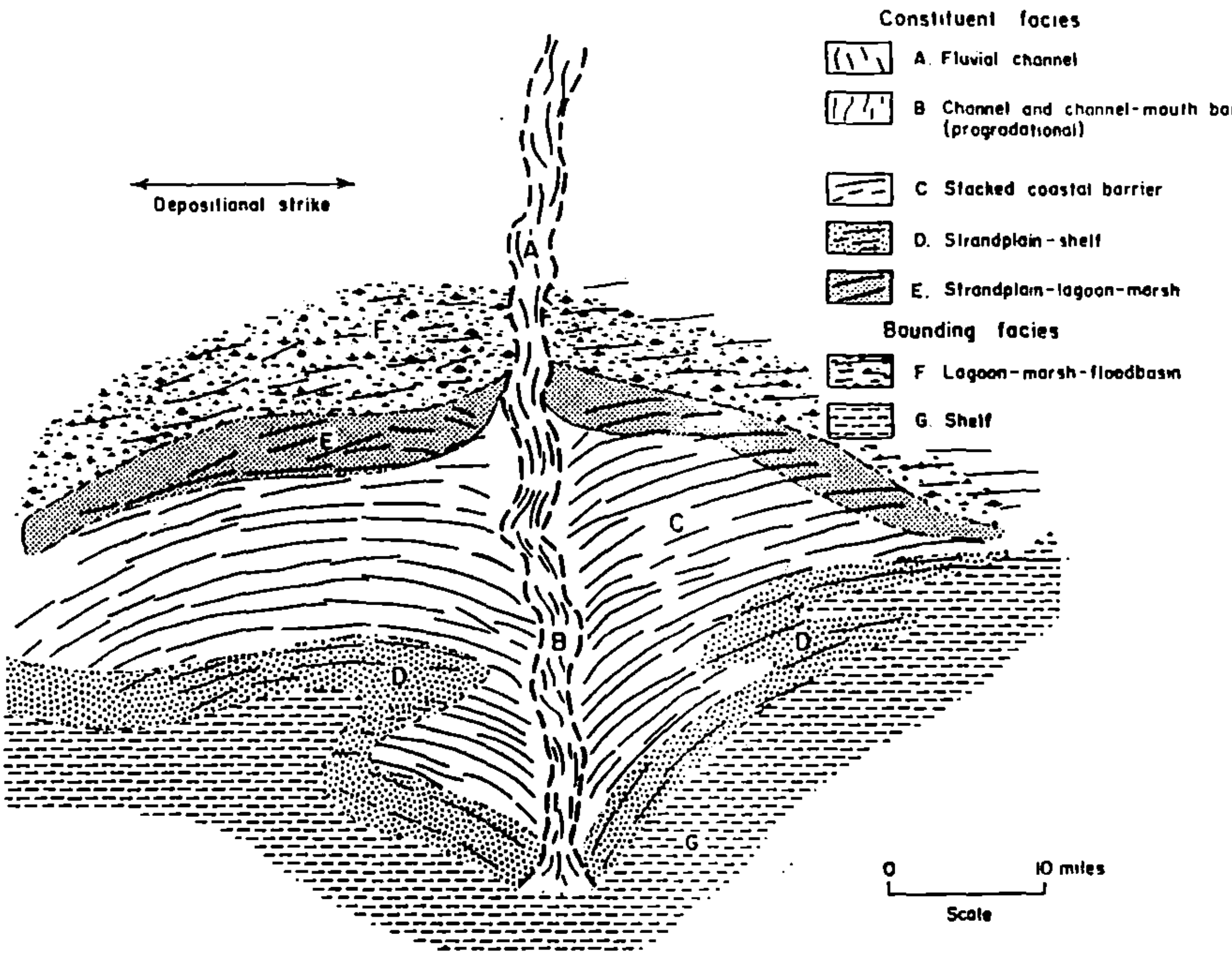


Figure 15. Model of high-destructive delta system. From Fisher (1969).

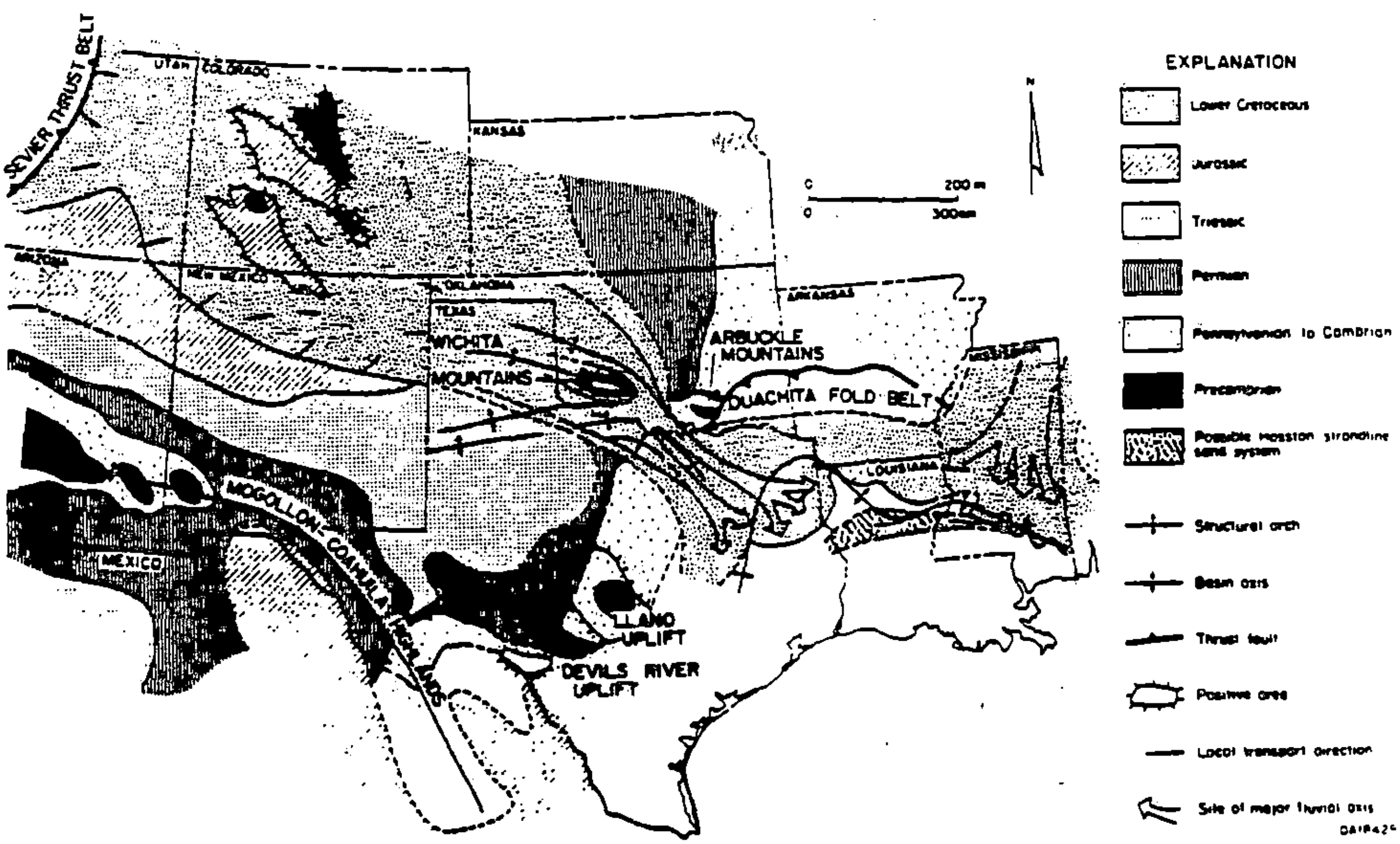


Figure 16. Early Cretaceous (Coahuilan) paleogeology and paleogeography of south-central and southwestern United States showing general sediment-source areas and gross directions of transport. Similar paleogeography characterized the other siliciclastic depositional periods of the Cretaceous. From Saucier (1985).

locally restricts vertical movement of ground water between the sandstones of different couplets.

The concept of aquifer and confining-bed couplets does not apply where the carbonate and sandstone deposits are laterally instead of vertically adjacent. For example, the Glen Rose limestone is absent in the northern and western parts of the study area. The Antlers Formation, named where Cretaceous sandstone formations crop out, is equivalent to four subsurface sandstone formations (Hosston, Hensel, Bluff Dale, and Paluxy Formations), each of which have laterally equivalent limestone formations. The Bluff Dale sandstone, for example, interfingers with the Glen Rose and thickens as the Glen Rose limestone thins. Lack of the low-permeability limestone and shale beds means that resistance to vertical flow between sandstone beds is less in and near the outcrop within the Antlers Formation than within its equivalent subsurface section.

## Twin Mountains Formation

Across North-Central and East Texas, the Trinity Group includes two couplets of aquifers and confining beds: Hosston–Pearsall and Hensel–Glen Rose. Only a thin interval of the Pearsall Formation, however, extends into North-Central Texas; the Hosston Formation, which makes up the bulk of the Trinity Group sandstones in the study area, and the Hensel Formation are undivided in most of the study area. Hosston, Hensel, and lower Bluff Dale sandstones, therefore, are mapped together as Twin Mountains sandstone in this report (fig. 17).

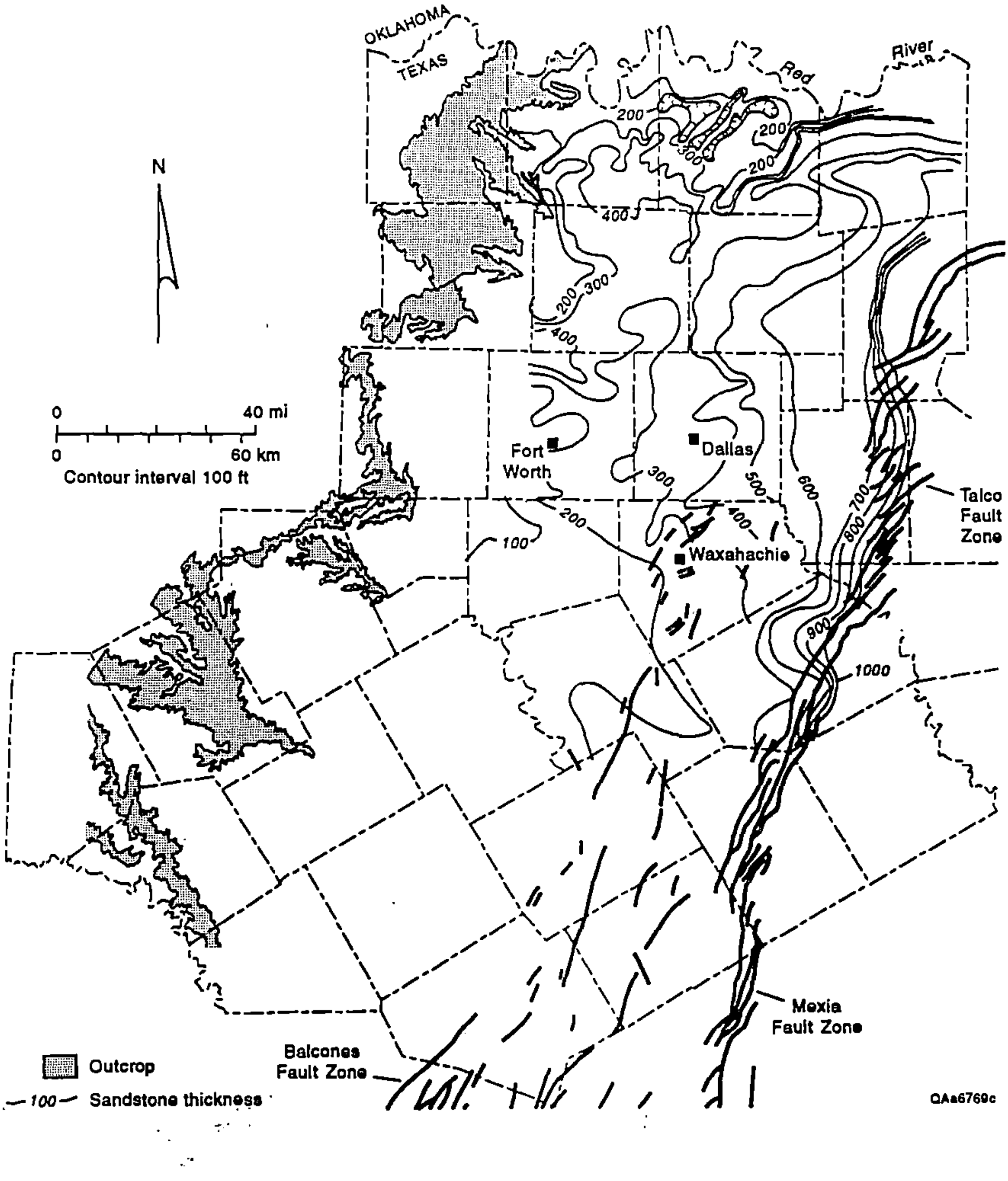


Figure 17. Net sandstone map of the Twin Mountains sandstones (Hosston and Hensel Formations and equivalents).

The top of the Twin Mountains Formation dips eastward, and dip increases across the Balcones and Mexia-Talco Fault Zones (fig. 4). Thickness of Trinity sandstone increases from its outcrop to more than 2,000 ft (610 m) at the Mexia-Talco Fault Zone in Kaufman County. In outcrop the Hosston interval is composed of fine- to medium-grained quartz sandstone interbedded with sandy mudstone and muddy pebbly sandstone. Beds are thin to massive, with cross bedding common in the conglomeratic intervals (Boone, 1968). The fact that composition and grain size distribution are similar suggests that the probable source of the basal Trinity conglomerates seen in outcrop is the Triassic-age Dockum Group to the northwest (Boone, 1968). Hensel sandstone is fine- to medium-grained and moderately to well sorted. Lenses of muddy conglomerate occur throughout. Beds are commonly cross-bedded to massive, with some laminated sandstone and mudstone (Boone, 1968). Updip equivalents of the Hosston and Hensel sandstones (Twin Mountains Formation) include pebble conglomerates, sandstone, and sandy mudstone (Boone, 1968). Lower Bluff Dale sandstone includes interbedded muddy sandstone and sandy mudstone with thin interbeds of mudstone and limestone (Boone, 1968). Lower Antlers sandstone was a local source for sand in the Hensel and Bluff Dale. This is inferred because the Hensel and Bluff Dale thin and appear to pinch out onto stratigraphically underlying Cretaceous sandstone.

The distribution of sandstone in the Twin Mountains suggests deposition by fluvial-deltaic systems (Hall, 1976). Three areas have more than 400 ft (122 m) of sandstone in the Hosston Formation (fig. 17). One center of deposition is in Grayson, Collin, Dallas, and Ellis Counties. There is also more than 250 ft (76 m) of Bluff Dale sandstone in this area. Thickness of sandstone abruptly increases near the Mexia-Talco Fault Zone and probably indicates that these growth faults were active during Hosston deposition. The second area is in southern Denton and northern Tarrant Counties. The third center of deposition with more than 400 ft (122 m) of sandstone is in southern Cooke County.

## Paluxy Formation

The Paluxy depositional system was much smaller in extent than the earlier Trinity or later Woodbine depositional systems. Trinity sandstones extend farther south of the study area (Stricklin and others, 1971), and Trinity and Woodbine sandstones are twice as thick as those in the Paluxy. Thickness of the Paluxy Formation along the outcrop ranges from approximately 50 ft (15 m) in Coryell County to more than 320 ft (98 m) in Hunt County. The Paluxy merges with the underlying Twin Mountains Formation to form the Antlers Formation in Montague and Wise Counties where the Glen Rose pinches out. In the subsurface the Paluxy Formation thins to the south and is replaced by claystone and limestone of the overlying Walnut Formation (fig. 5). In a previous study of ground-water resources of North-Central Texas, the Paluxy was treated as the upper part of the aquifer in Trinity Group sandstones (Nordstrom, 1982).

There are two areas where net thickness of Paluxy sandstones are more than 200 ft (61 m) (fig. 18). The largest center of deposition is in Hunt and Kaufman Counties; a smaller center of deposition is in Wise and Denton Counties. Lying between the two depositional centers is a belt with a net

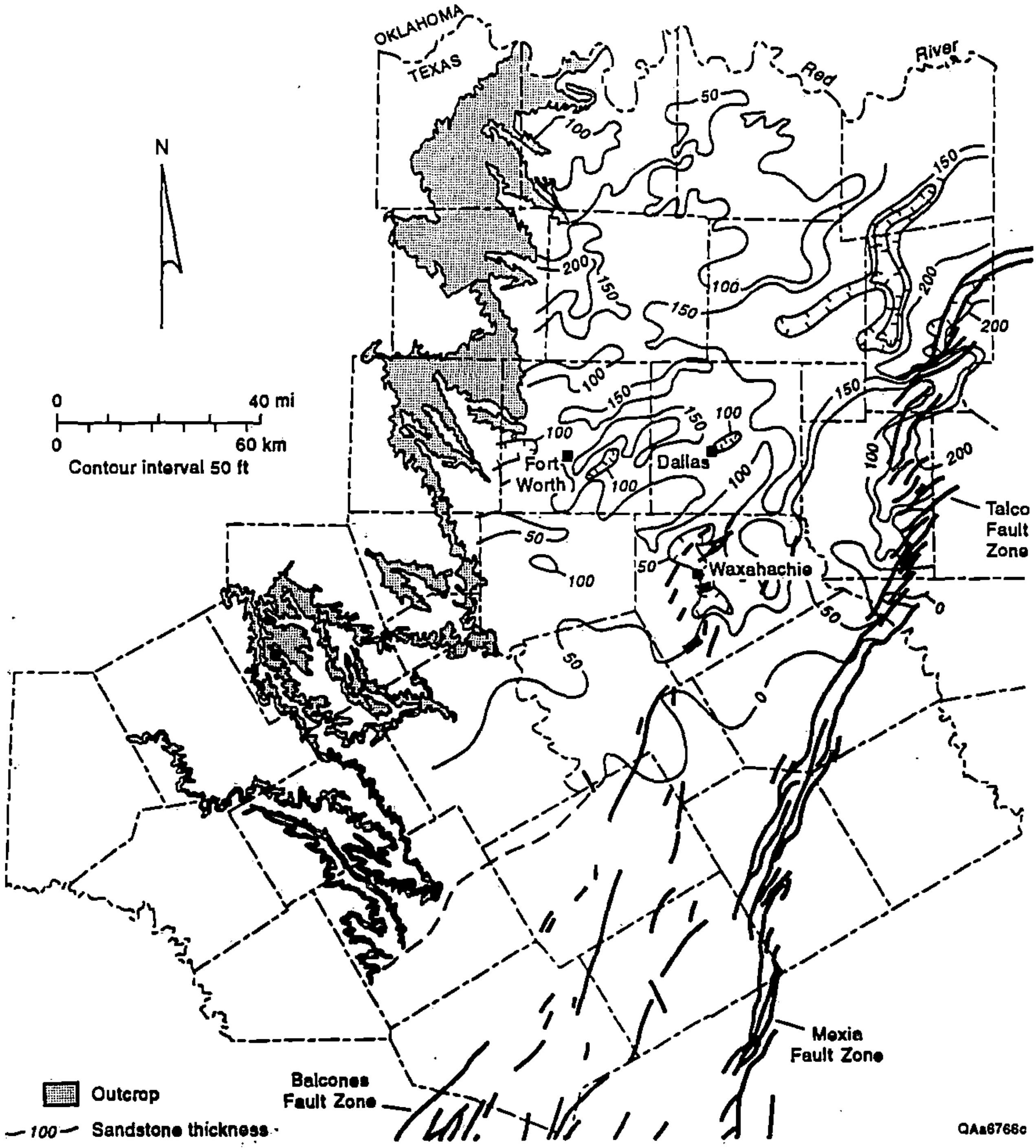


Figure 18. Net sandstone map of the Paluxy Formation.

thickness of sandstone of as much as 150 to 200 ft (46 to 61 m). Caughey (1977) interpreted the regional patterns of sandstone thickness as suggesting destructive deltaic processes whereby onshore wind and wave action reworked dip-aligned, fluvially transported sand into strike-aligned coastal barriers.

## Woodbine Formation

The top of the Woodbine Formation dips eastward and dip increases across the Balcones and Mexia-Talco Fault Zones (fig. 6). Thickness of the Woodbine Formation increases from its outcrop to more 800 ft (244 m) in Hunt and Kaufman Counties. The Woodbine Formation has been divided into several members in its northern outcrop but is undivided in its western outcrop south of Denton County (Oliver, 1971; McGowen and others, 1987, 1991). The lower part of the Woodbine comprises mainly fluvial-deltaic sandstone, whereas the upper Woodbine is dominated by strand-plain and distal-deltaic sandstones and shelf mudstone.

The Woodbine Formation was deposited upon a regional unconformity that developed during a relative sea-level lowstand, recorded by truncated upper Washita strata (fig. 2). The erosional surface mapped in this study forms a series of west-east-oriented, incised valleys in southwestern Grayson County. There is one major and one minor center of deposition in the Woodbine Formation (fig. 19). More than 400 ft (122 m) of Woodbine sandstone lies along the Mexia-Talco Fault Zone. Rapid lateral changes in net sandstone values along the Mexia-Talco Fault Zone probably indicate that these growth faults were active during Woodbine deposition (Barrow, 1953;

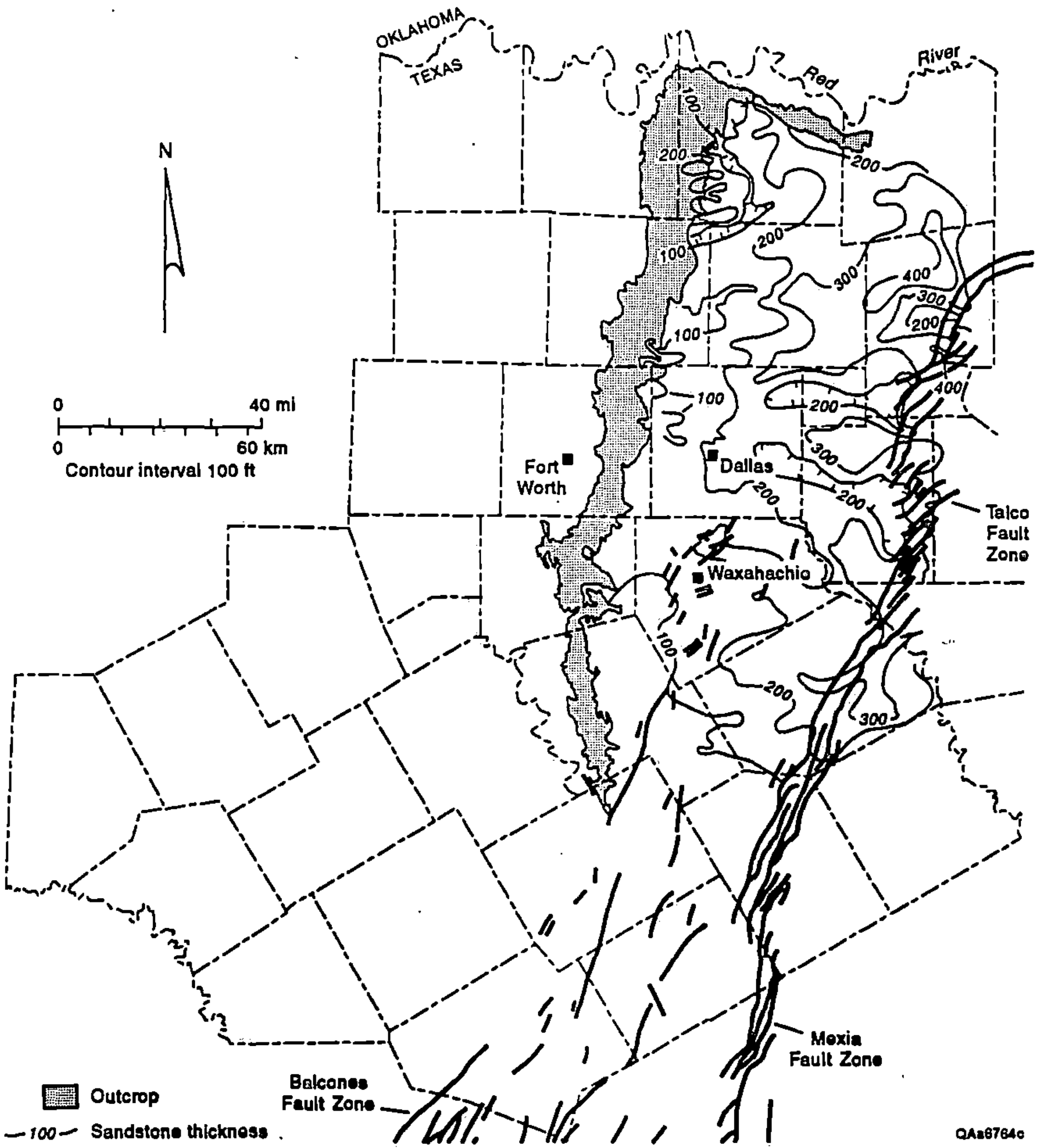


Figure 19. Net sandstone map of the Woodbine Formation.

Oliver 1971). More than 200 ft (61 m) of Woodbine sandstone lies in the Sherman syncline in the northwestern corner of the study area (fig. 19), just down dip of the outcrop belt in Cooke, Grayson, Denton, and Collins Counties. Sandstone thickness, however, is much greater than the 70-ft (21-m) relief of the incised valleys. Sediment deposition, therefore, continued in this area after the valleys were filled by the basal Woodbine sand.

Lewisville strand plain–mudstone facies in the eastern part of the study area are stratigraphically equivalent to Eagle Ford shelf-mudstone and shale facies. Eagle Ford Formation shale interfingers with and overlies the Woodbine Formation and records progressive deepening of the marine environment, as previously described.

## Summary of Aquifer Stratigraphic Framework

- Each of the three main aquifers in the Lower Cretaceous Twin Mountains and Paluxy Formations and Upper Cretaceous Woodbine Formation (Nordstrom, 1982) have dominant centers of deltaic deposition in the eastern and northeastern parts of the study area and subordinate centers of fluvial deposition on the west side.
- The dominant structure of the area is that of an eastward descending ramp with two north-trending strike-aligned hinges. The westernmost hinge coincides with the Balcones Fault Zone; the easternmost hinge coincides with the Mexia-Talco Fault Zone.
- Sandstone units that make up the aquifers are evenly bedded to cross bedded, moderate to well sorted, very fine- to medium-grained quartzose sandstone. Aquifer sandstones are locally bounded by

mudstone, shale, and limestone and regionally confined by the underlying Pennsylvanian section and by the overlying carbonate-dominated (Comanchean Series) upper Fredericksburg and Washita Groups and (Gulfian Series) Eagle Ford through Navarro Groups.

- The Twin Mountains and Woodbine Formations are underlain by regional unconformities formed by valley incision during emergent perioc: rior to deposition. These valleys were filled with sands during initial Twin Mountains and Woodbine deposition. There also are local unconformities at the base of the Paluxy Formation.
- The Twin Mountains sandstones extend into southern Texas, whereas the Paluxy and Woodbine sandstones are essentially limited at their southern margins to the study area.

## HYDROGEOLOGY

### Ground-Water Production

In the late 1800s, artesian ground water was discovered and a large amount of ground water was discharged in a broad belt of counties to the east of the outcrop of the regional aquifers, including Somervell, Bosque, Coryell, Bell, McLennan, Cooke, Dallas, Denton, Ellis, Hill, Johnson, and Tarrant Counties. Artesian ground water occurs where the fluid pressure in the confined aquifer rises the ground water to a level above ground surface. "Flowing wells" result where well heads allow unrestricted discharge of the pressurized ground water. Hill (1901) reports discharge rates for the flowing wells ranging from 1 to 694 gallons per minute ($10^{-4.2}$ to $10^{-1.4}$ $m^3/s$) for flowing wells depending on the aquifer and the well location. Somervell had the wells with the greatest discharge rates. Discharge is estimated to have been approximately 25,000 acre-ft/yr ($30.8 \times 10^6$ $m^3$/yr) from wells in the Twin Mountains (fig. 20).

Artesian conditions were quickly exploited and discharge rates declined after 1900 (Hill, 1901) (fig. 20). Pumping rates here were small during the early part of the century in non-artesian areas but steadily increased in all three aquifers during the century (tables 5 to 7). Pumping rates during the early century were small across the eastern side of the study area where depth to the aquifers is greatest, drilling cost high, and ground-water quality generally poor (Hill, 1901). Counties in the northeastern part of the study area also had few flowing wells because this area's surface elevation is higher than that of the recharge area (Hill, 1901).

Ground-water production increased markedly after World War II (fig. 20) with the growth in population, industry, and agriculture in the region. The increase in ground-water production came about through the drilling of new water wells. Production of ground water decreased, however, since the 1970s as water levels in the aquifers markedly dropped and reliance on surface-water resources increased. The small cities of Italy, Glenn Heights, and Midlothian in Ellis County perhaps are typical; they recently used ground water for as much as 60 percent of their water.

## Hydraulic Head

Predevelopment water levels in the confined aquifers were reportedly near or above land surface, and many water wells flowed at land surface at the beginning of the twentieth century (Hill, 1901; Thompson, 1967). A well

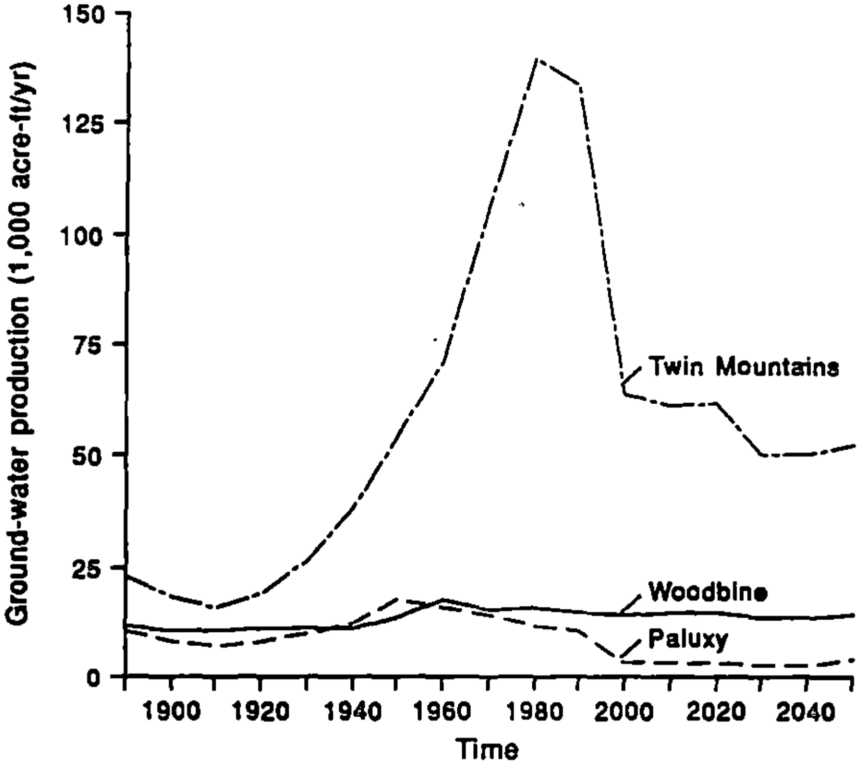


Figure 20. Estimated historical and projected future ground-water production, 1891–2050, from the Twin Mountains, Paluxy, and Woodbine.

drilled into the Twin Mountains aquifer in Fort Worth in 1890 had pressure equal to a water level 90 to 100 ft (27 to 30 m) above ground surface. By 1914, many wells had stopped flowing as hydraulic head decreased to beneath ground surface (Leggat, 1957). Rate of decline in ground-water pressure was rapid in the early part of the twentieth century but slowed for a time after World War I as development slowed (Leggat, 1957). For example, the Tucker Hill Experimental Well was drilled into the Paluxy in 1890 in Fort Worth. The water level fell from 90 ft (27 m) below ground surface in 1890, to 277 ft (84 m) in 1942, and 285 ft (87 m) below ground surface in 1954. Water levels in the Fort Worth area have declined nearly 850 ft (259 m) in the Twin Mountains since the turn of the century (fig. 21). Water levels have declined approximately 450 ft (137 m) in the Paluxy aquifer near Fort Worth and approximately 400 ft (123 m) in the Woodbine aquifer near Dallas (fig. 21). Water levels in the Paluxy suggest either short-term recovery or a decrease in rate of decline since 1976, perhaps because municipalities have turned to surface-water sources.

Direction of ground-water flow before ground-water development is inferred to have been to the southeast (Nordstrom, 1982). Because early-1900 data are sparse and regional aquifers already were heavily tapped, synoptic water-level measurements are inadequate for mapping a truly "predevelopment" potentiometric surface of the aquifers. Figures 22a, 23a, and 24a show estimated potentiometric surfaces for the Twin Mountains, Paluxy, and Woodbine aquifers, respectively for 1900, based on both quantitative and qualitative water-level data of Hill (1901).

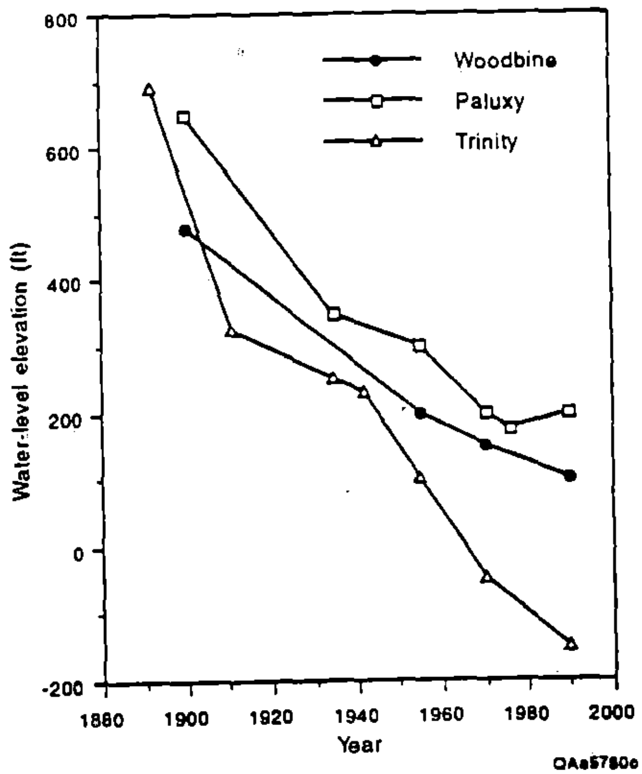


Figure 21. Water-level declines in the (a) Twin Mountains Formation in the Fort Worth area, (b) Paluxy Formation near Fort Worth, and (c) Woodbine Formation near Dallas.

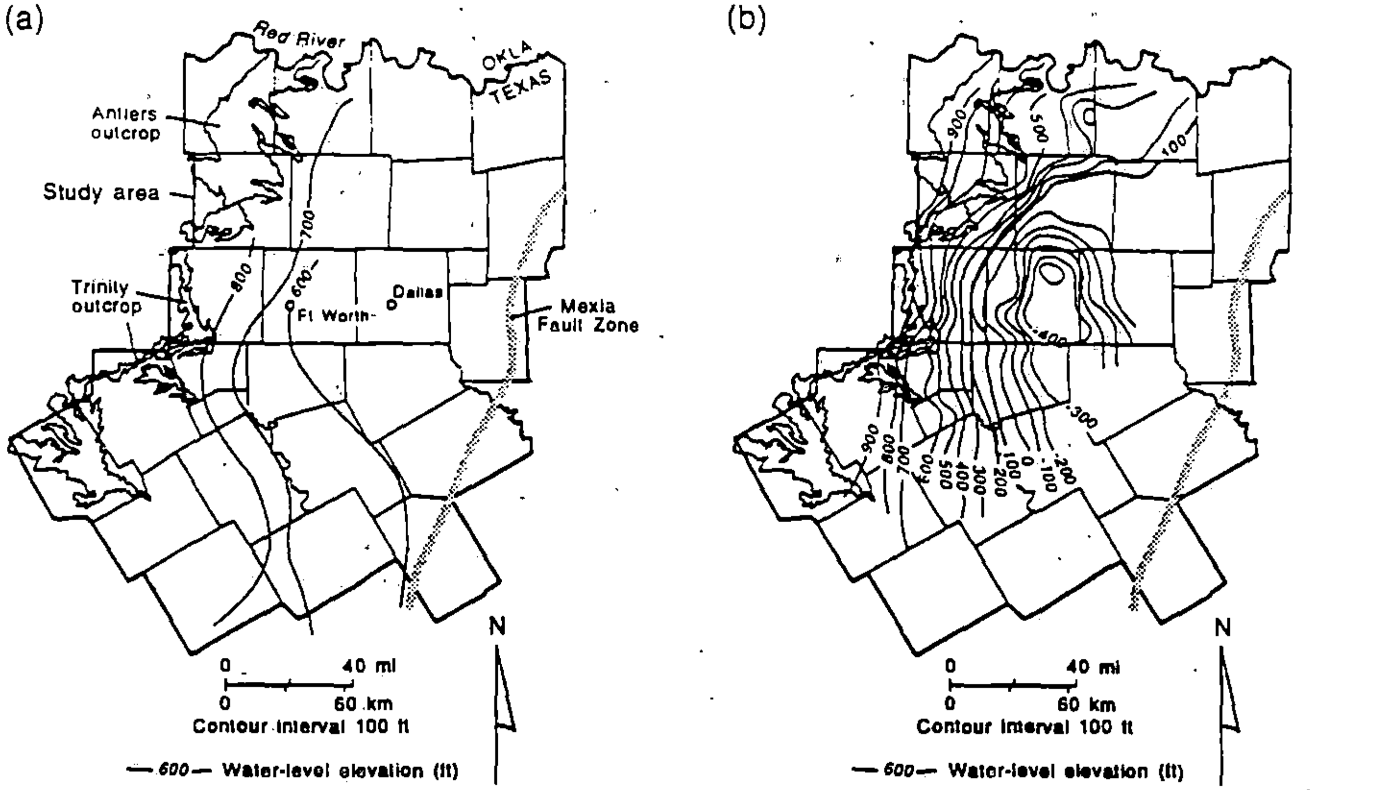


Figure 22. Estimated potentiometric surfaces for the Twin Mountains Formation in (a) 1900 and (b) 1990.

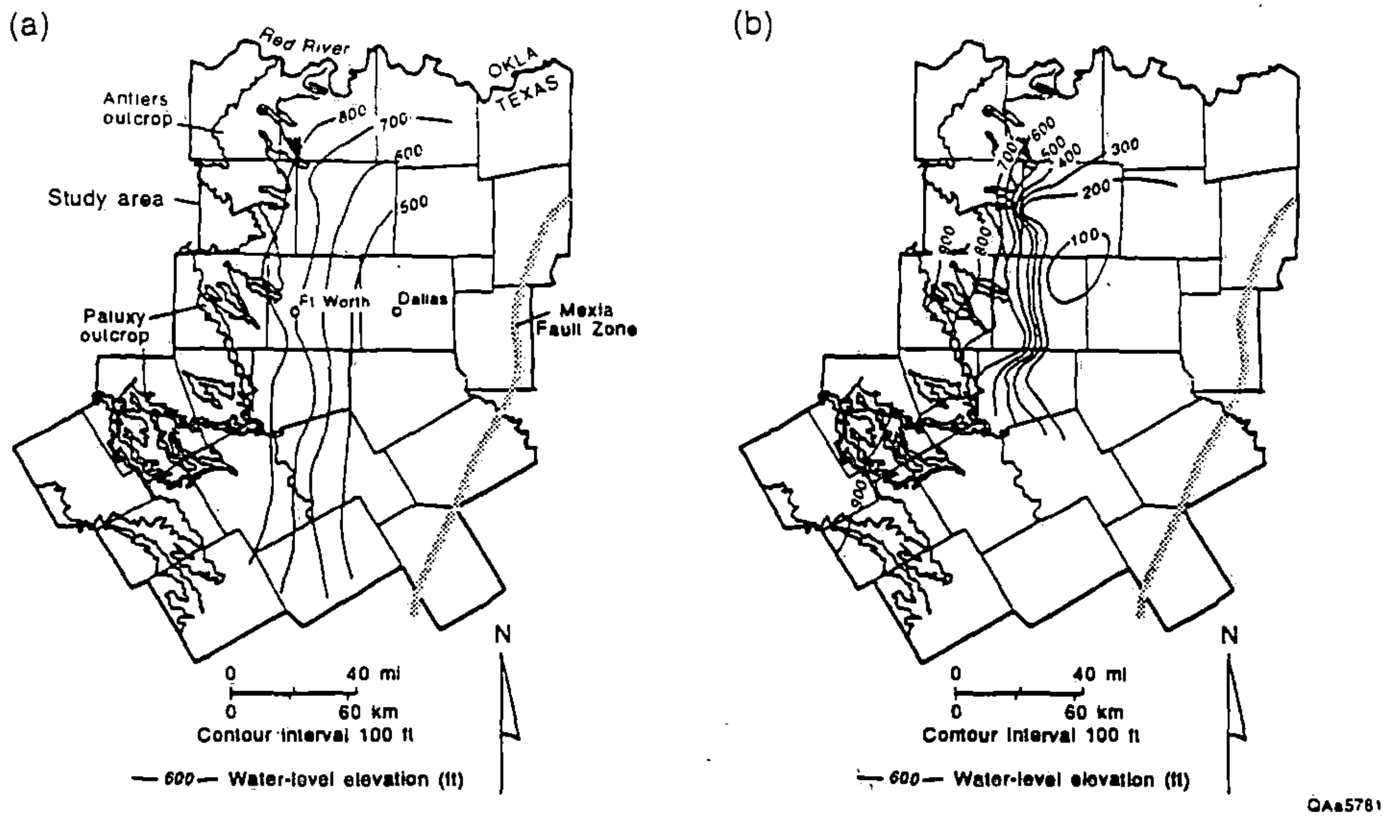


Figure 23. Estimated potentiometric surfaces for the Paluxy Formation in (a) 1900 and (b) 1990.

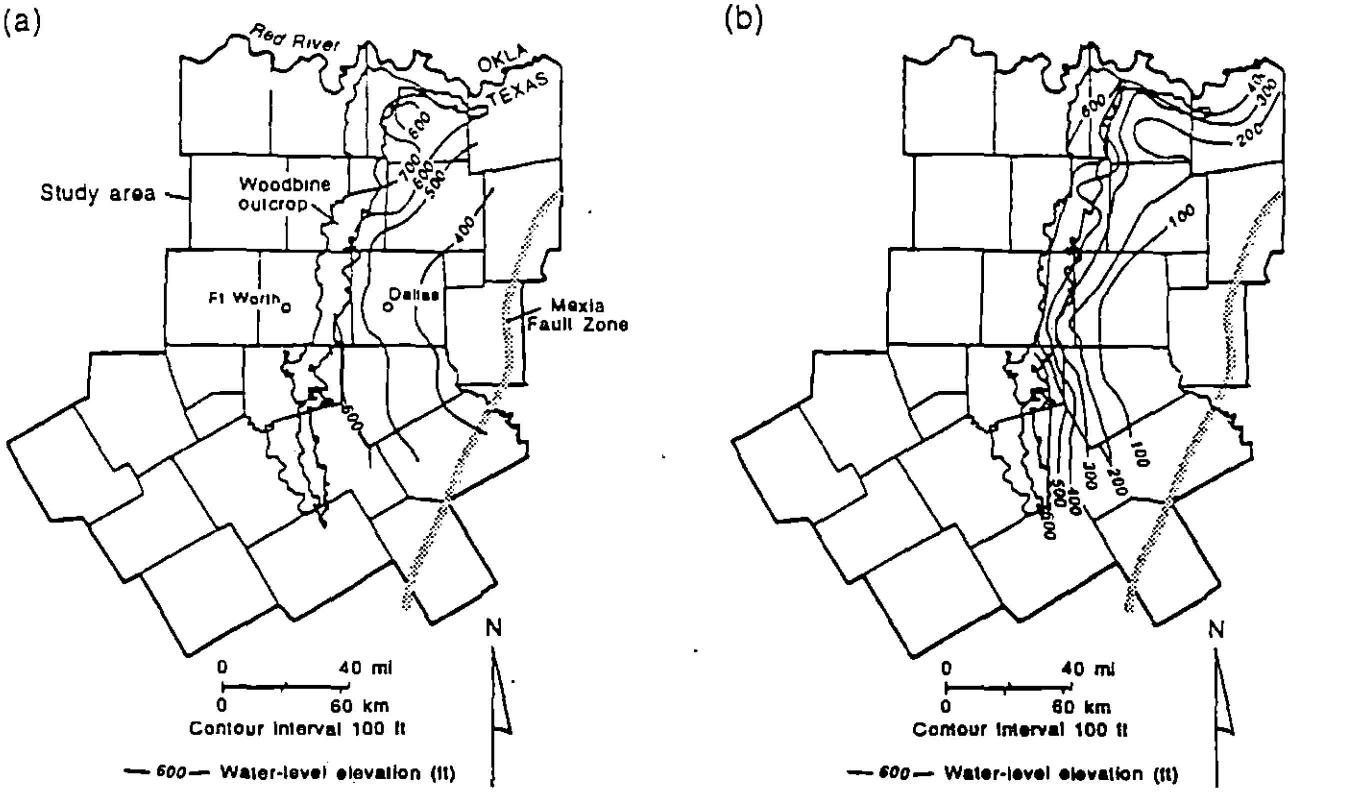


Figure 24. Estimated potentiometric surfaces for the Woodbine Formation in (a) 1900 and (b) 1990.

Figures 22b, 23b, and 24b show 1990 water-level elevations for the Twin Mountains, Paluxy, and Woodbine and aquifers, respectively. Hydraulic-head decline has resulted in a regional depression of the potentiometric surface centered in the Twin Mountains and Paluxy aquifers (fig. 22b and 23b) in the Dallas–Fort Worth metropolitan area (Nordstrom, 1982). The regional depression affects direction of ground-water flow throughout North-Central Texas. Under present conditions the direction of ground-water flow in the Twin Mountains aquifer inferred from the potentiometric surface, for example, in Ellis County (fig. 22b), actually is northwestward toward the Dallas–Fort Worth area.

## Hydrologic Properties

Transmissivity has a log-normal distribution for the Twin Mountains, Paluxy, and Woodbine aquifers (fig. 25). Geometric means of transmissivity were 437 $ft^2/d$ (40 $m^2/d$) for the Twin Mountains, 251 $ft^2/d$ (23 $m^2/d$) for the Paluxy, and 316 $ft^2/d$ (29 $m^2/d$) for the Woodbine. Transmissivities determined from aquifer tests generally had a higher geometric mean but a much smaller sample size than transmissivities determined from specific-capacity tests (table 2).

Transmissivity shows a continuous regional distribution within each of the aquifers (figs. 26 to 28). Areas that have a greater thickness of sandstones in general have higher transmissivities and sandstone-poor areas have low transmissivities. The fact that the distribution of transmissivity in the Twin Mountains Formation is determined primarily by the distribution of sandstones is shown clearly in the area around Erath, Hood, and Somervell

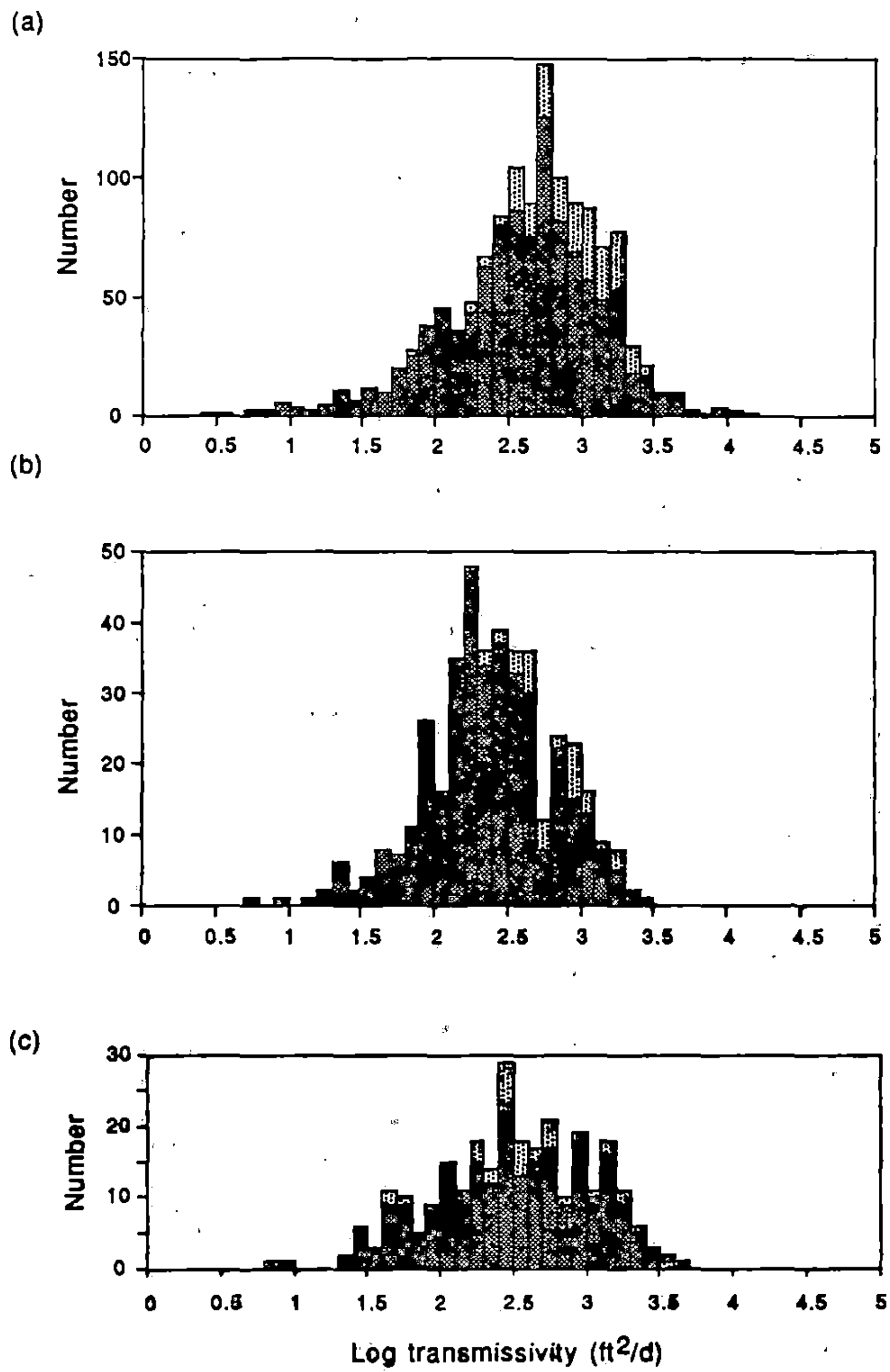


Figure 25. Histogram of transmissivity for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Solid bar represents transmissivities determined from aquifer tests and shaded bar represent transmissivities determined from empirical relationships between specific capacity and transmissivity.

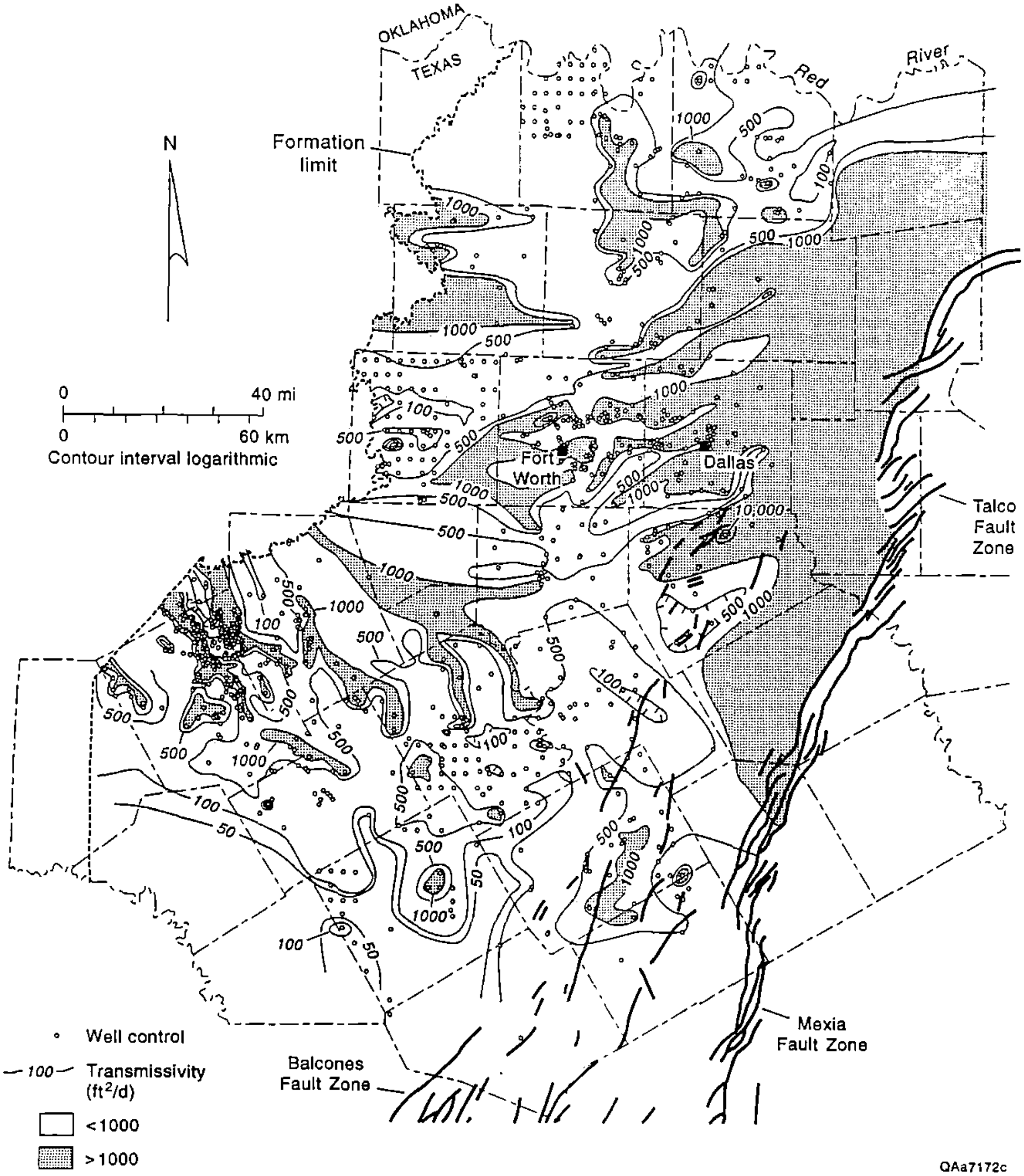


Figure 26. Aquifer transmissivity in the Twin Mountains Formation mapped on the basis of aquifer tests in wells and sandstone-thickness maps.

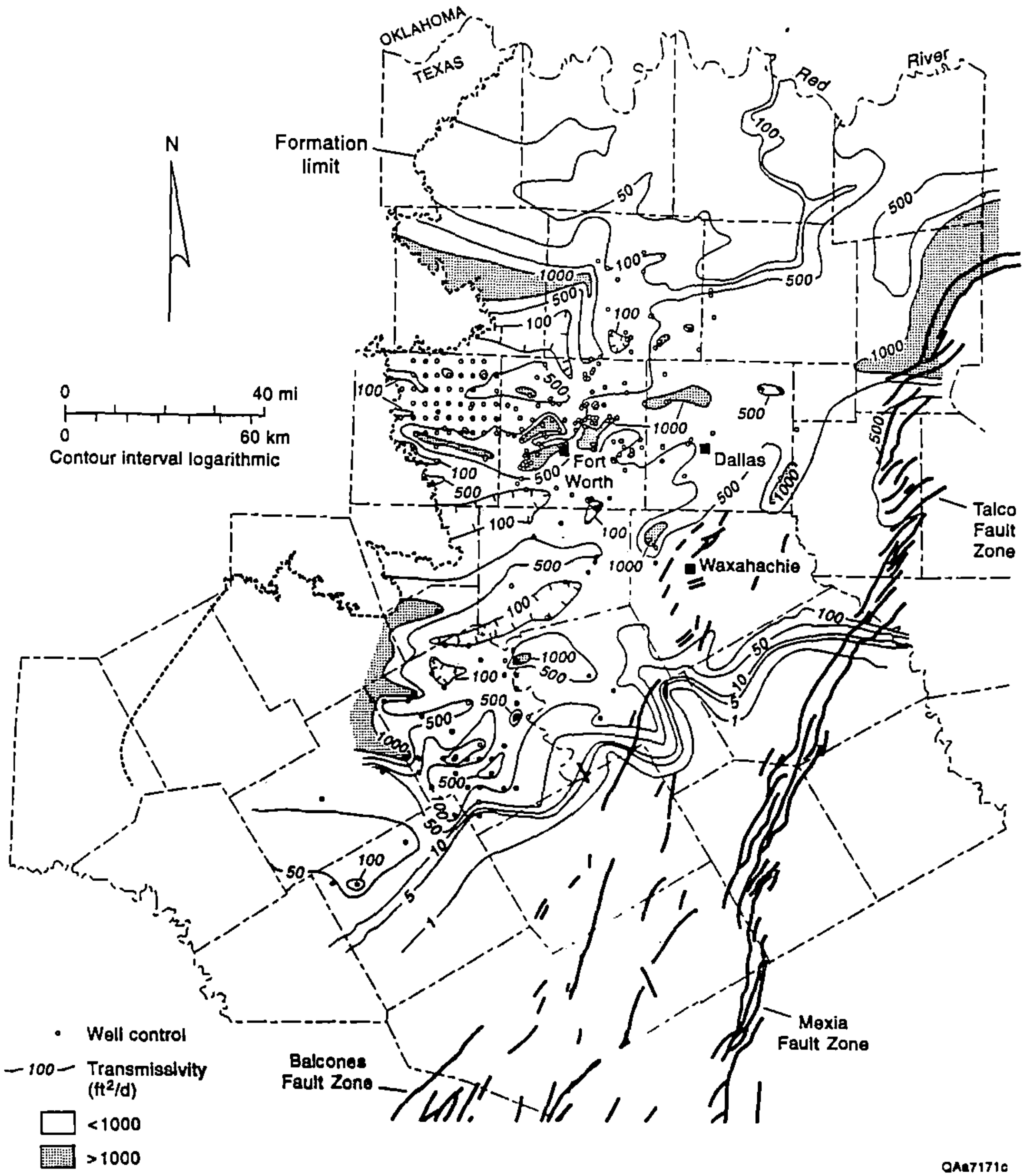


Figure 27. Aquifer transmissivity in the Paluxy Formation mapped on the basis of aquifer tests in wells and sandstone-thickness maps.

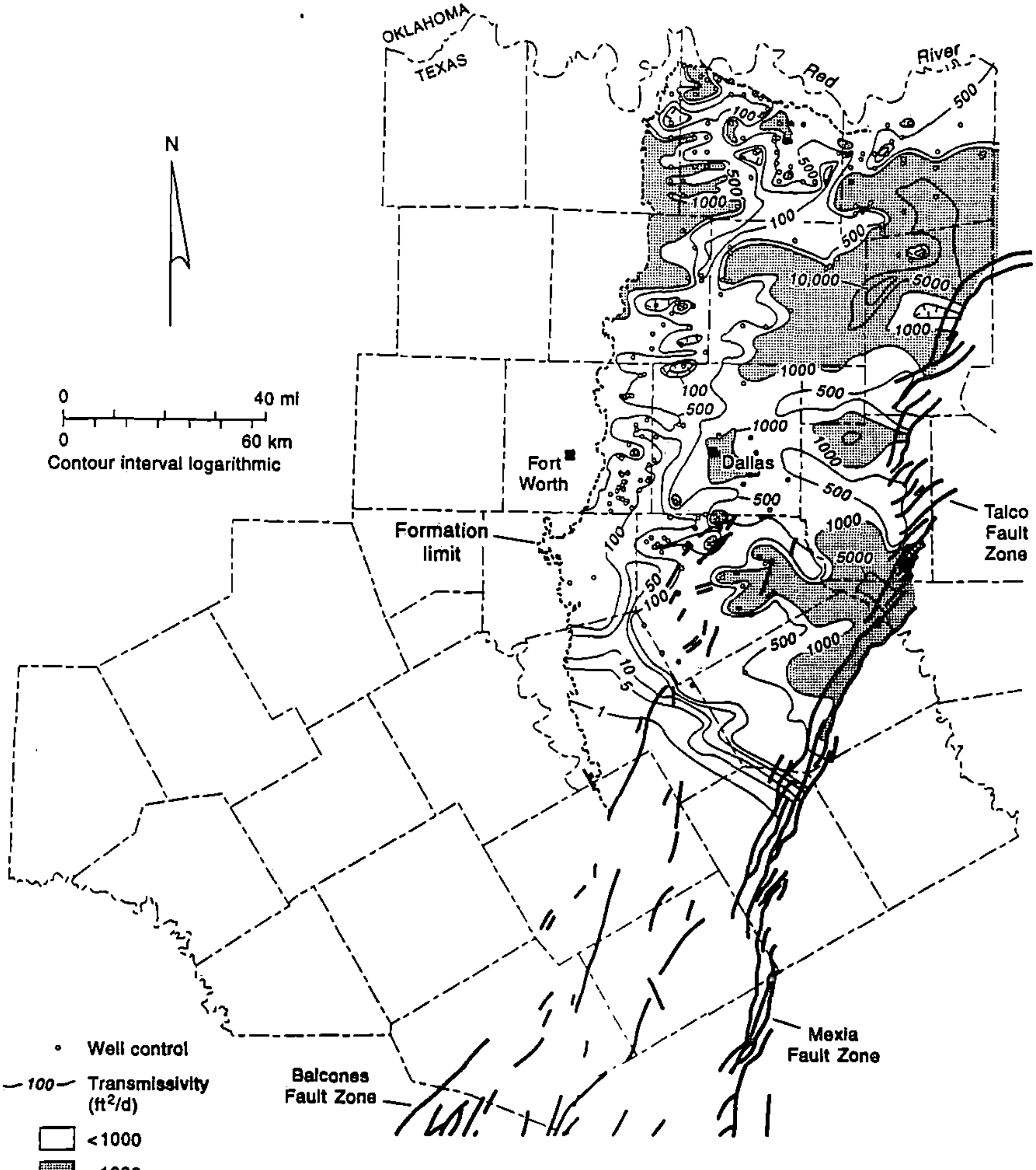


Figure 28. Aquifer transmissivity in the Woodbine Formation mapped on the basis of aquifer tests in wells and sandstone-thickness maps.

Counties with its exceptionally abundant aquifer-test data. The spatial pattern of transmissivity can be readily contoured using a model of fluvial and deltaic depositional systems. Areas of high transmissivity appear as narrow and elongate arms with short distributary fingers pointing into the basin (fig. 26). Other parts of the study area lack such abundant aquifer-test data. In those locations the sandstone thickness maps provide a guide for mapping transmissivity. The 'geologically contoured' maps of transmissivity significantly differ from those prepared by Macpherson (1983). Although Macpherson (1983) used much of the same data, contouring was based on an equal-weighting model that did not take into account the underlying pattern of sandstone distribution, which had not been mapped before this study.

In addition to depicting dip-elongate trends of high transmissivity, the maps also show that the sandstone-poor basin center separates areas of higher transmissivity on the western and eastern side of the basin (figs. 26 to 28). This discontinuity most likely has an effect on the regional movement of ground water within aquifers and vertically between aquifers and also might influence the hydraulic-head gradient and distribution of good-quality water. Ground water moving down dip from recharge areas in the aquifer outcrop will encounter the sandstone-poor basin center and be retarded from moving farther down dip. Flow paths might be forced upward across confining units. Hydraulic head drops off across the sandstone-poor basin center. Poor water quality across the eastern side of the basin might also be explained by those high-transmissivity areas most likely receiving little recharge from the outcrop areas. Water quality might be affected both by slow flow rate and long residence time and also by a good connection between these sandstones and the Mexia-Talco Fault Zone. The fault zone might be a conduit for movement or diffusion of brine out of the East Texas Basin. Sandstones on the eastern side of the basin center (figs. 17 to 19) typically have poor-quality water that cannot be readily flushed out because the sandstones are not well connected to the recharge area (Domenico and Robbins, 1985).

Horizontal hydraulic conductivity of the Austin Chalk determined from packer tests in Ellis County (Dutton and others, 1994) averages $10^{-4.24}$ ft/d ($10^{-4.76}$ m/d). Horizontal hydraulic conductivity of the Taylor Marl in Ellis County was determined to be $10^{-5.49}$ ft/d ($10^{-6.0}$ m/d) on the basis of packer tests and calibration of a regional model of ground-water flow (Mace, 1993; Dutton and others, 1994). Other hydrologic properties for the confining units were estimated as previously discussed.

Storativity is the volume of water released per unit area of aquifer per unit drop in hydraulic head, and is a function of porosity, aquifer elasticity, and water compressibility. These parameters were assumed to be constant in time. Mean storativities were $10^{-3.49}$ for the Twin Mountains, $10^{-3.73}$ for the Paluxy, and $10^{-3.88}$ for the Woodbine (table 4). The distribution of storativity in the Twin Mountains aquifer is possibly bimodal (fig. 29). Most data come from the confined part of the regional aquifer where storativity is small ($<10^{-3}$). Higher values reflect semi-unconfined to unconfined conditions (Kruseman and de Ridder, 1983) nearer the aquifer outcrop. Storativity values for unconfined aquifers are much larger than and close to the porosity values because water is added to or removed from storage by change in the water content of pores. In confined conditions, pores remain fully wet and water moves into or out of storage by change of water pressure, compression of

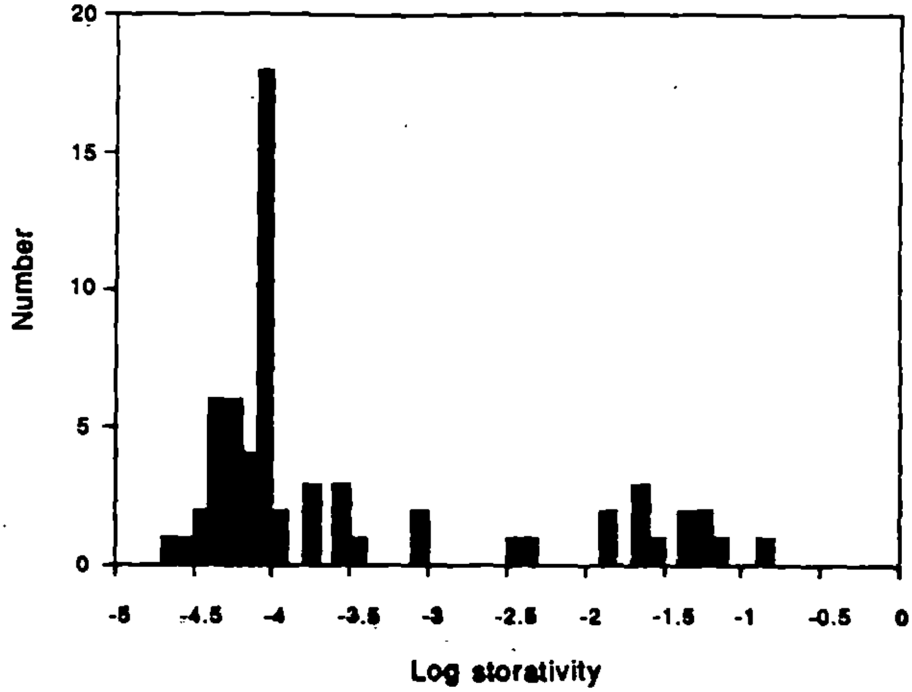


Figure 29. Histogram of storativity for the Twin Mountains Formation. Data are not sufficient for histograms of storativity for the Paluxy and Woodbine Formations.

water, and expansion of the aquifer. Storativity values for semi-confined and semi-unconfined aquifers can represent a combination of compression and drainage and thus lie between storativity values for confined and unconfined aquifers.

No measurements of porosity for the Twin Mountains, Paluxy, and Woodbine aquifers were found. Porosity in the Paluxy and Woodbine Formations has been measured in oil and gas fields east of the Mexia-Talco Fault Zone (Galloway and others, 1983). These data have a mean porosity of 24 percent for the Woodbine and 22 percent for the Paluxy (table 11). Bell (1980) reported that the Woodbine Formation in the Kurten field of Brazos County had a porosity of about 25 percent. Porosity for sandstone typically ranges between 5 and 15 percent (Domenico and Schwartz, 1990). Effective porosity of sandstone, that is, interconnected pore space through which fluid can readily move, ranges between 0.5 and 10 percent (Croff and others, 1985). The average effective porosity for the sandstone was set at 5 percent, about in the middle of these values. Porosity for the Glen Rose Formation and Fredericksburg and Washita Groups was set at 16 percent, reflecting the arithmetic mean of limestone and shale porosities. Dutton and others (1994) determined porosity for the Austin Chalk and Ozan Formation using core plugs (table 11). Porosity for the Wolfe City (upper Taylor Group; table 1) and Navarro Formations was set to the value for the Ozan Formation. Porosity for the Eagle Ford Formation was assigned a value common for a shale (Freeze and Cherry, 1979).

Table 11. Porosities in Woodbine and Paluxy Formations in oil and gas fields east of the Mexia-Talco fault zone (data from Galloway and others, 1983).

| Aquifer | Region of Texas | Field and reservoir | Porosity (%) |
|---|---|---|---|
| Woodbine | East | East Texas | 25 |
| | East | Kurten | 15 |
| | East | New Diana | 26 |
| | North-Central | Cayuga | 25 |
| | North-Central | Hawkins | 26 |
| | North-Central | Long Lake | 25 |
| | North-Central | Neches | 25 |
| | North-Central | Van | 29 |
| | North-Central | Mexia | 25 |
| | North-Central | Wortham | 22 |
| Paluxy | North-East | Pewitt Ranch | 24 |
| | North-East | Sulphur Bluff | 25 |
| | North-East | Talco | 26 |
| | East | Coke | 22 |
| | East | Hitts Lake | 22 |
| | East | Manziel | 20 |
| | East | Quitman | 22 |
| | East | Sand Flat | 18 |

## Recharge

The Twin Mountains, Paluxy, and Woodbine aquifers are recharged by precipitation over their outcrops. Thompson (1967) estimated recharge on the sandy parts of the Trinity Group outcrop to be 0.5 inch/yr (13 mm/yr). Klemt and others (1975) assumed recharge for the Twin Mountains aquifer to be 1.2 inch/yr (30 mm/yr), which is about 3 percent of mean annual rainfall. Nordstrom (1982) suggested that recharge on the northern Twin Mountains and Paluxy outcrops (Antlers Formation [fig. 2]) amounted to less than 1 inch/yr (25.4 mm/yr). Klemt and others (1975) estimated recharge on the Paluxy outcrop to be 0.13 inch/yr (3.3 mm/yr) and recharge on the Woodbine outcrop to be 0.3 inch/yr (7.6 mm/yr), less than 1 percent of mean annual rainfall. Water moves into the subsurface beneath overlying confining beds. The aquifers are defined as confined when hydraulic head exceeds the elevation of the top of the aquifers.

## Discharge

Discharge occurs by pumping at water-supply wells, cross-formational flow in the subsurface, and possibly by spring discharge in the vicinity of faults. County ground-water pumping ranged from a low of 93 acre-ft to a high of 14,952 acre-ft (115,000 to 18,436,000 $m^3$) in 1990. Ground-water pumping in Ellis County, for example, was estimated at approximately 8,850 acre-ft during 1990 ($11 \times 10^6$ $m^3$). Cross-formational flow is limited by hydraulic-head gradients between aquifers and by vertical hydraulic conductivity of confining layers. Comparison of water levels measured in 1976 (Nordstrom, 1982) suggests that the cross-formational flow component is directed downward between aquifers in the Woodbine and Twin Mountains Formations in the Ellis County area.

The ultimate fate of recharged waters in the Twin Mountains, Paluxy, and Woodbine is poorly known. Baker and others (1990b) stated that discharge in the aquifer outcrops occurs naturally by springs and evapotranspiration and artificially by pumping. Klemt and others (1975) stated that discharge from the Twin Mountains was through cross-formational flow and along faults that connect the confined aquifer to ground surface, such as in the Mexia-Talco Fault Zone. In addition, deep flow in the aquifers might pass down dip beyond the Mexia-Talco Fault Zone into the East Texas Basin. The avenue of discharge is important because it determines the boundary for the numerical model. Unfortunately, there are few water wells near the Mexia-Talco Fault Zone on which to base hydrologic assumptions, mainly due to increased salinities in the eastern portions of the aquifers.

## Flow Velocity

Ground-water flow rates in the Twin Mountains aquifer have been estimated to be 1 to 2 ft/yr (0.3 to 0.6 m/yr) in the northern part of the study area (Antlers Formation) but 10 to 40 ft/yr (3 to 12 m/yr) regionally (Baker, 1960; Thompson, 1967). Estimates of ground-water flow rates in the Woodbine have ranged from 6 to 40 ft/yr (1.8 to 12 m/yr) (Thompson, 1972) to 15 ft/yr (4.6 m/yr) (Baker, 1960). No estimated flow rate was found for the Paluxy Formation. These velocity estimates suggest that the age of ground water in the regional aquifer system is between approximately 8,000 and 40,000 yr, from west to east across Ellis County.

## Summary of Aquifer Hydrologic Framework

- Water levels in regional aquifers in North-Central Texas have declined during the twentieth century because rate of pumping of ground water exceeded recharge rates. Total decline in the Dallas and Tarrant Counties area has been as much as 850 ft (259 m) in the Twin Mountains Formation and approximately 450 and 400 ft (137 and 123 m) in the Paluxy and Woodbine Formations, respectively.
- The drawdown of the potentiometric surfaces has been regionally extensive, affecting the aquifers throughout most of North-Central Texas. Comparison of 1976 (Nordstrom, 1982) and 1990 potentiometric surfaces shows that hydraulic-head drawdown in each aquifer unit has increased.
- Geometric means of transmissivity were estimated as 437 $ft^2/d$ (40 $m^2/d$) for the Twin Mountains, 251 $ft^2/d$ (23 $m^2/d$) for the Paluxy, and 316 $ft^2/d$ (29 $m^2/d$) for the Woodbine. Estimates of transmissivity were based on interpretation of specific capacity and aquifer-test results, augmenting the results of previous studies. Mean storativities were estimated as $10^{-3.49}$ for the Twin Mountains, $10^{-3.73}$ for the Paluxy, and $10^{-3.88}$ for the Woodbine.
- Confining layers consist of the Sligo and Pearsall and Glen Rose Formations and the Fredericksburg and Washita Groups, which lie within the regional aquifer system, and the Eagle Ford Formation, Austin Chalk, and Taylor Group, which overlie the regional aquifer

system. The geometric mean of vertical hydraulic conductivity in the Glen Rose, Fredericksburg, and Washita confining layers was estimated to be $10^{-7.60}$ ft/d ($10^{-8.1}$ m/d) on the basis of thicknesses of shale and limestone.

- Previous studies (Thompson, 1967; Klemt and others, 1975; Nordstrom, 1982) estimated a range of recharge rates for the aquifers: 0.13 to 1.2 inch/yr (0.33 to 3 cm/yr).
- Average ground-water velocities in the Woodbine (11.4 ft/yr [3.5 m/yr]) are much slower than those in the Twin Mountains (52.5 ft/yr [16 m/yr]) or Paluxy (55.6 ft/yr [17.0 m/yr]).

## SIMULATION OF GROUND-WATER FLOW

### Cross-Sectional Model

The goal of applying a cross-sectional model of regional ground-water flow was to

- determine the nature of the down-dip boundary at the Mexia-Talco Fault Zone,
- estimate vertical conductances of the confining layers,
- evaluate hydraulic conductivity distributions, and
- estimate ground-water velocity and travel time between points of interest.

The cross-sectional model explicitly included the Twin Mountains, Paluxy, and Woodbine aquifers as well as the confining layers in the Glen

Rose, Fredericksburg, Washita, Eagle Ford, Austin, Taylor, and Navarro Groups. The model was run as a steady-state simulation.

## Calibration

Data available for calibration were hydraulic heads from maps of the 1900 potentiometric surface (figs. 22a, 23a, and 24a). Hydraulic heads calculated by the model were compared to hydraulic heads measured in wells located along the cross section.

First, the affect of the down-dip boundary on the model was assessed. Three types of boundary scenarios were attempted for the down-dip side of the model: (1) no-flow boundary, (2) specified head boundary assuming hydrostatic conditions, and (3) a no-flow boundary with a column of high vertical hydraulic conductivity.

The no-flow boundary at the down-dip side of the model with the initial parameters listed in table 3 was found to be unrealistic. This boundary caused ground water to flow up-dip in the aquifer formations. The potentiometric surface maps clearly show that ground water flows down-dip in all the aquifer units. The direction of ground-water flow was corrected by increasing the vertical hydraulic conductivity of the confining layers in the model. To match the inferred direction of flow, however, values of vertical hydraulic conductivity of the confining layers had to be nearly the same as those of the aquifers.

A specified head boundary assuming hydrostatic pressure allowed simulated flow in the down-dip direction with the initial hydrogeologic properties shown in table 3. Predicted hydraulic heads were also on the order of the measurements from early in the century, but the agreement was not close enough to be an acceptable match.

As a third boundary condition, a vertical zone of enhanced permeability, representing a fault zone, was placed in the model. Hydraulic conductivities were slightly adjusted to obtain the best fit. The conductance term in the GHB-boundary blocks was increased and decreased to affect recharge rate into the aquifers.

Distributed hydraulic conductivities were also used in the model to attain a better fit to the measured data. Hydraulic conductivity was distributed in the aquifer units on the basis of maps from Macpherson (1983). Net sand maps for the aquifers were used to extend Macpherson's (1983) hydraulic conductivity maps through the domain of the model.

## Results

The cross-sectional model of ground-water flow was used to evaluate boundary conditions and the hydrologic properties of confining layers. The cross-sectional model suggests that ground water exits the aquifers through the Mexia-Talco Fault Zone. Once in the fault zone, the water probably discharges from springs in river valleys at land surface. The model shows that cross-formational flow between the aquifers is not an important control on ground-water movement compared to the discharge through the fault zone.

Results of the cross-sectional model with distributed permeability in the aquifer units offered the best fit to the predevelopment potentiometric surface. The specified head boundary and fault zone models both provided reasonable head matches. Both of these boundaries remove water from the system. The no-flow boundary did not result in a good match with hydraulic head if reasonable values were used for vertical hydraulic conductivity. These results suggest that water might be moving through the formations and discharging at or near the down-dip boundary of the aquifers in the vicinity of the Mexia-Talco Fault Zone. The exact mechanism is not known and needs to be investigated, perhaps by analyzing oil well data from the area or using hydrogeochemical methods.

The cross-sectional model with distributed permeability and a specified head boundary at the down-dip end of the model gave a good fit with the predevelopment potentiometric surface. Predicted heads in the Twin Mountains (fig. 30a) had a mean absolute error of 25.1 ft (7.7 m). Predicted heads in the Paluxy (fig. 30b) had a mean absolute error of 17.5 ft (5.3 m), and predicted heads in the Woodbine (fig. 30c) had a mean absolute error of 11.9 ft (3.6 m). Mean absolute error for all aquifers was 18.7 ft (5.7 m). Some hydraulic conductivities needed to be adjusted in order to reproduce hydraulic head in the formations. Figure 31 shows initial and the calibrated hydraulic conductivity distributions for the Twin Mountains, Paluxy, and Woodbine Formations. Hydraulic-conductivity distribution in the Twin Mountains was modified from the hydraulic conductivity distribution determined by Macpherson (1983) in order to match observed hydraulic heads. The calibrated trend in hydraulic conductivity, lower to higher values, was reversed from the initial trend. Average hydraulic conductivity for the calibrated model was 30 percent higher than the initial values. A minor change in the hydraulic conductivity near the outcrop of the Paluxy was needed for the best match. The hydraulic conductivity in the Woodbine was

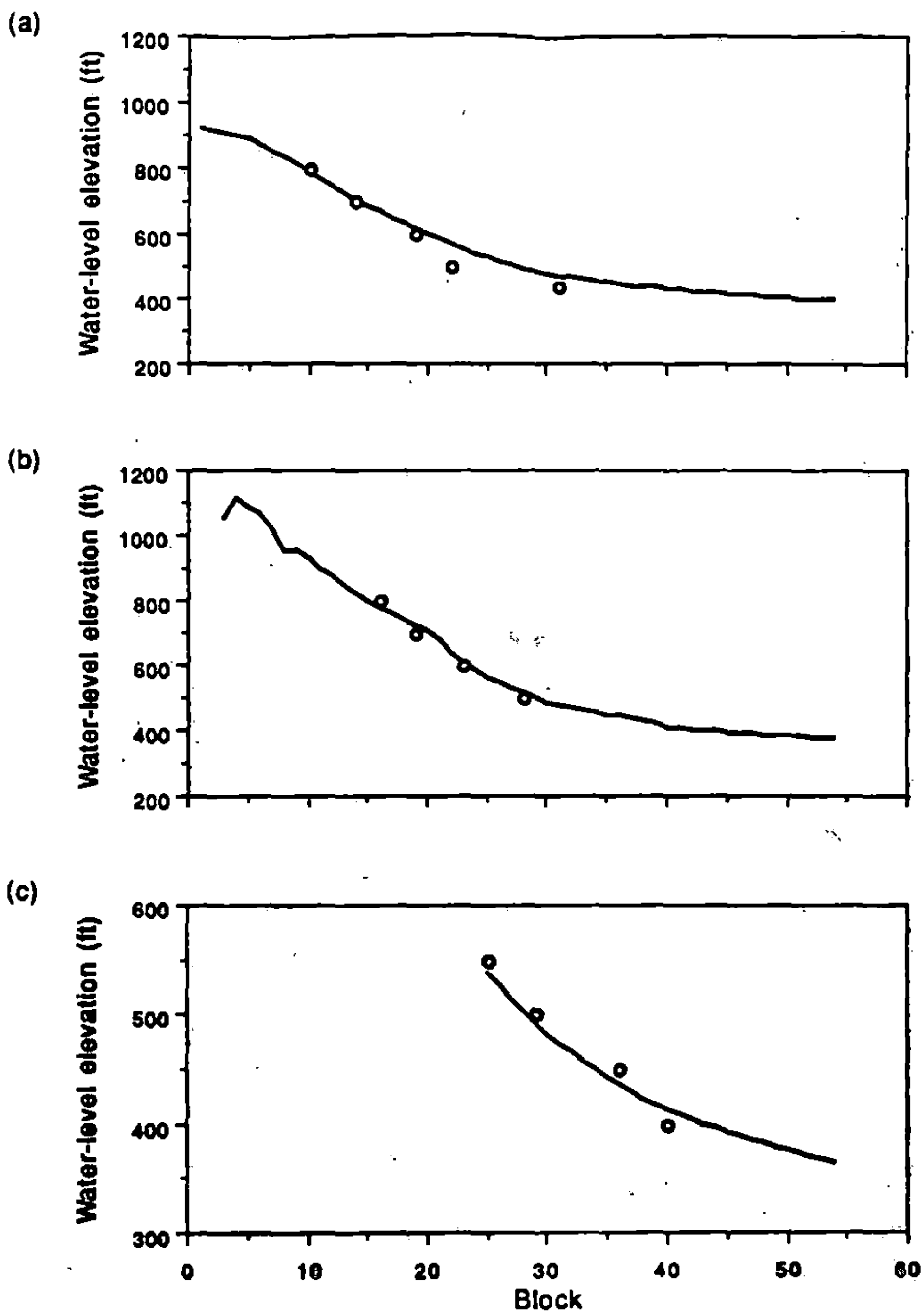


Figure 30. Comparison between measured and simulated hydraulic head from the cross-sectional model for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Open circles represent measured pre-development water levels. Lines are numerically calculated water levels.

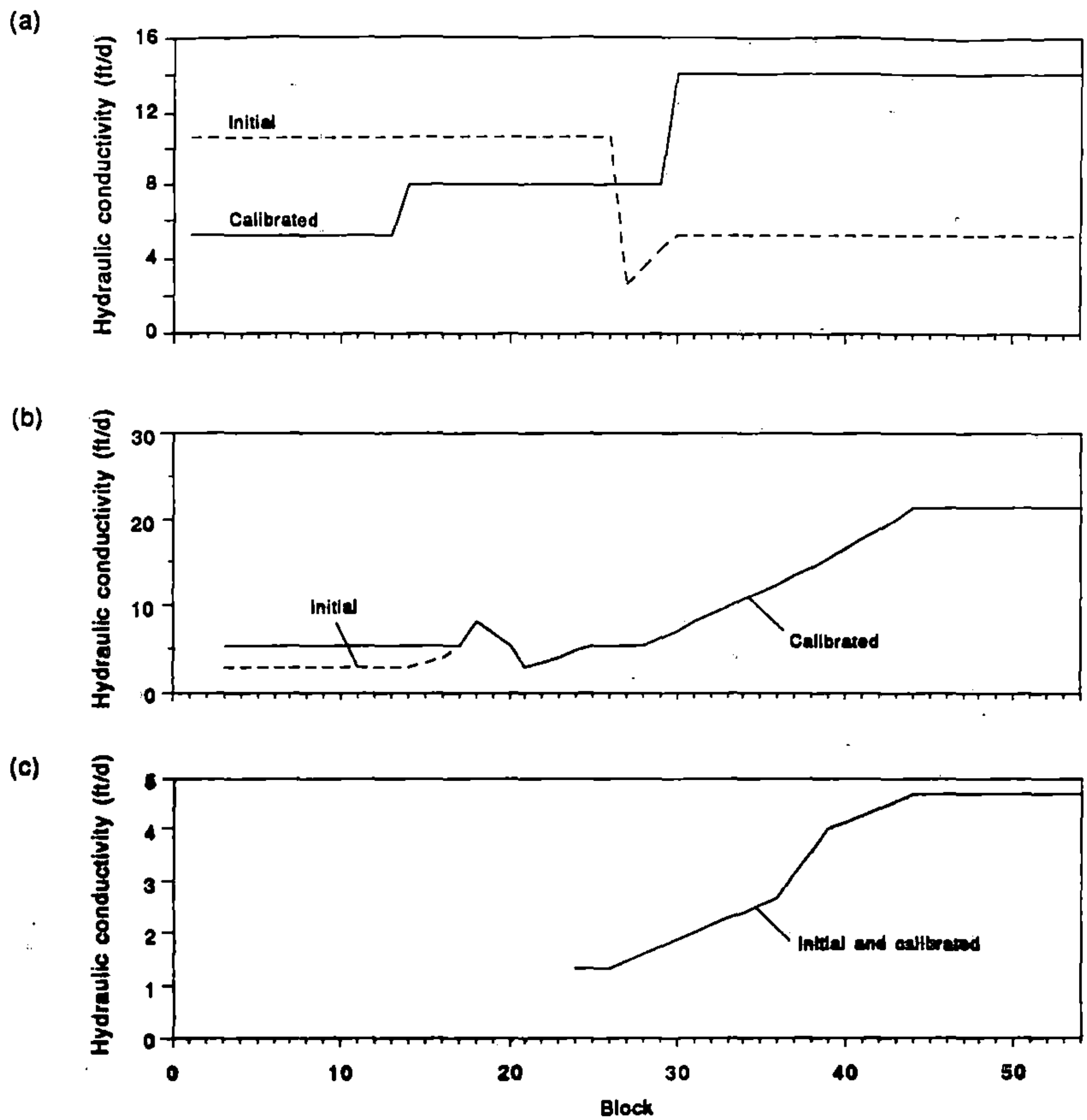


Figure 31. Initial and calibrated hydraulic conductivity distributions used for numerical modeling for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formation.

not adjusted. These differences may indicate that ground-water flow may not be moving entirely within the plane of the model. Also, the cross section of the model passes through small areas of low hydraulic conductivity in the Twin Mountains Formation. Hydraulic head in these areas may be different than the values used for calibration.

Ground-water flow velocities in the aquifers were determined by taking output from MODPATH and dividing travel time by travel distance for each block of the model. Velocities change through the aquifer due to changes in the hydraulic gradient and hydraulic conductivities. Ground-water velocity in the Twin Mountains increases from 20 to about 90 ft/yr (6 to about 27 m/yr) and then decreases again to 20 ft/yr (6 m/yr) with a mean velocity of 52.5 ft/yr (16 m/yr) (fig. 32a). Ground-water velocity in the Paluxy decreases along the flow path from 100 to 30 ft/yr (30 to 9 m/yr) with a mean velocity of 55.6 ft/yr (17.0 m/yr) (fig. 32b). Ground-water velocity in the Woodbine is relatively constant with a mean velocity of 11.4 ft/yr (3.5 m/yr) (fig. 32c). Ground-water flow rates in the Paluxy and Twin Mountains are nearly the same, increasing near the down-dip boundary of the model. Travel times show that ground-water flow is much faster in the Paluxy and Twin Mountains than in the Woodbine (fig. 33).

Recharge rates predicted by the numerical model are 0.11 inch/yr (0.28 cm/yr) for the Twin Mountains, 0.25 inch/yr (0.64 cm/yr) for the Paluxy, and 0.017 inch/yr (0.04 cm/yr) for the Woodbine. These are reasonably consistent with previous estimates (Thompson, 1967; Klemt and others, 1975; Nordstrom, 1982).

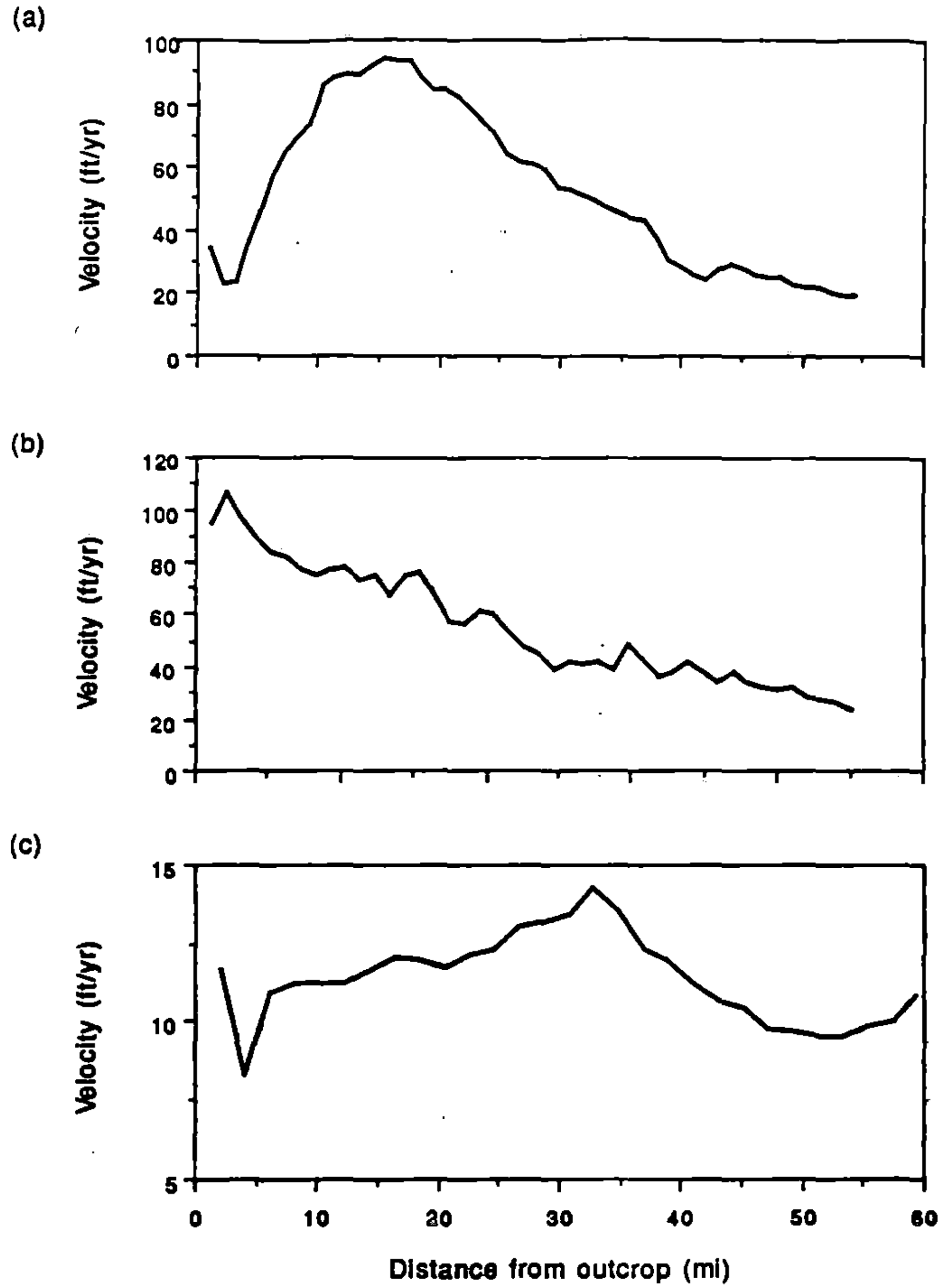


Figure 32. Numerically calculated ground-water velocities for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Effective porosity is assumed to be 5 percent.

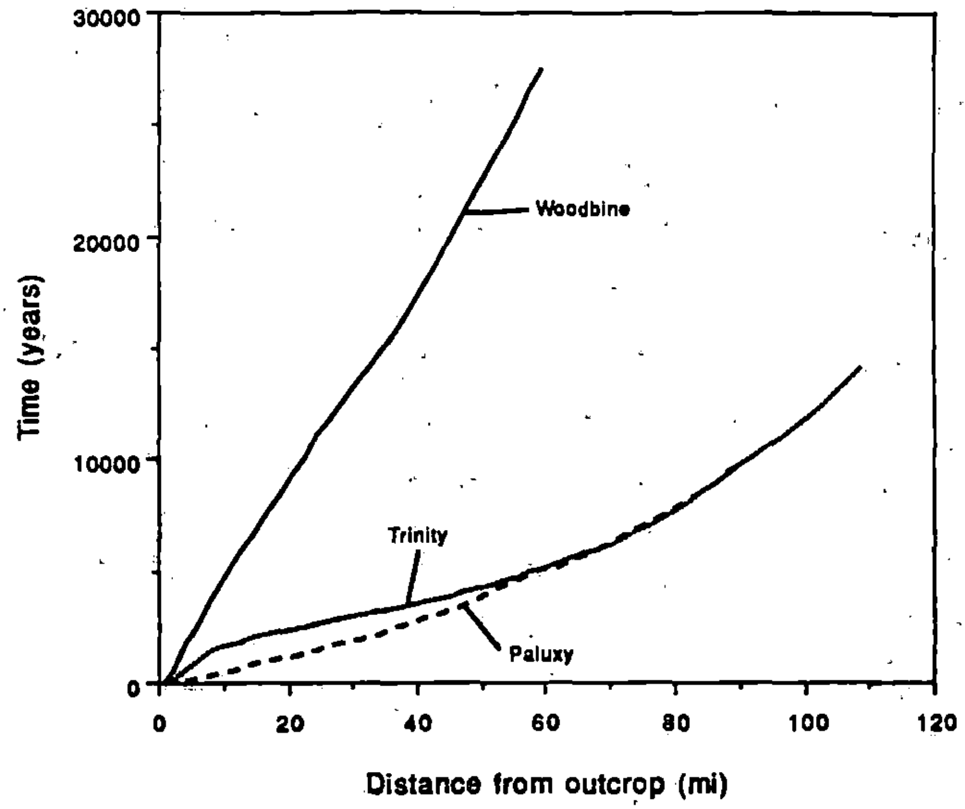


Figure 33. Numerically calculated cumulative travel times assuming effective porosity of 5 percent for the Twin Mountains, Paluxy, and Woodbine Formations.

The potential for cross-formational flow can be investigated by comparing hydraulic head between the formations. A plot of "predevelopment" hydraulic head along the cross section shows potential for cross-formational flow from the Paluxy down dip to the Twin Mountains and suggests that no flow occurs between the Paluxy and Woodbine (fig. 34). The numerical model shows similar conclusions except that farther down dip in the aquifer, the potential for cross-formational flow may reverse—from Twin Mountains to Paluxy (fig. 34). It again appears there is no cross-formational flow between the Woodbine and Paluxy.

## Regional Three-Dimensional Model

### Steady-State Flow System

Figures 35a, 36a, and 37a show simulated potentiometric surfaces representing the "predevelopment" or steady-state condition in the Twin Mountains (layer 3), Paluxy (layer 2), and Woodbine (layer 1), respectively. Accuracy of the numerical model in representing the original steady-state flow system can be estimated by comparing these simulation results to the maps of "predevelopment" potentiometric surfaces of the Twin Mountains, Paluxy, and Woodbine, drawn on the basis of data from Hill (1901), and shown in figures 22a, 23a, and 24a. For all three aquifer layers, the "recorded" early potentiometric surface based on Hill (1901) shows lower hydraulic head than do model results. The "recorded" surfaces are most likely affected by flowing wells and pumping from the Twin Mountains and Paluxy aquifers late in the 19th century, such that Hill's (1901) reported water levels are drawn down relative to the true "predevelopment" surfaces. Thus, to the extent that

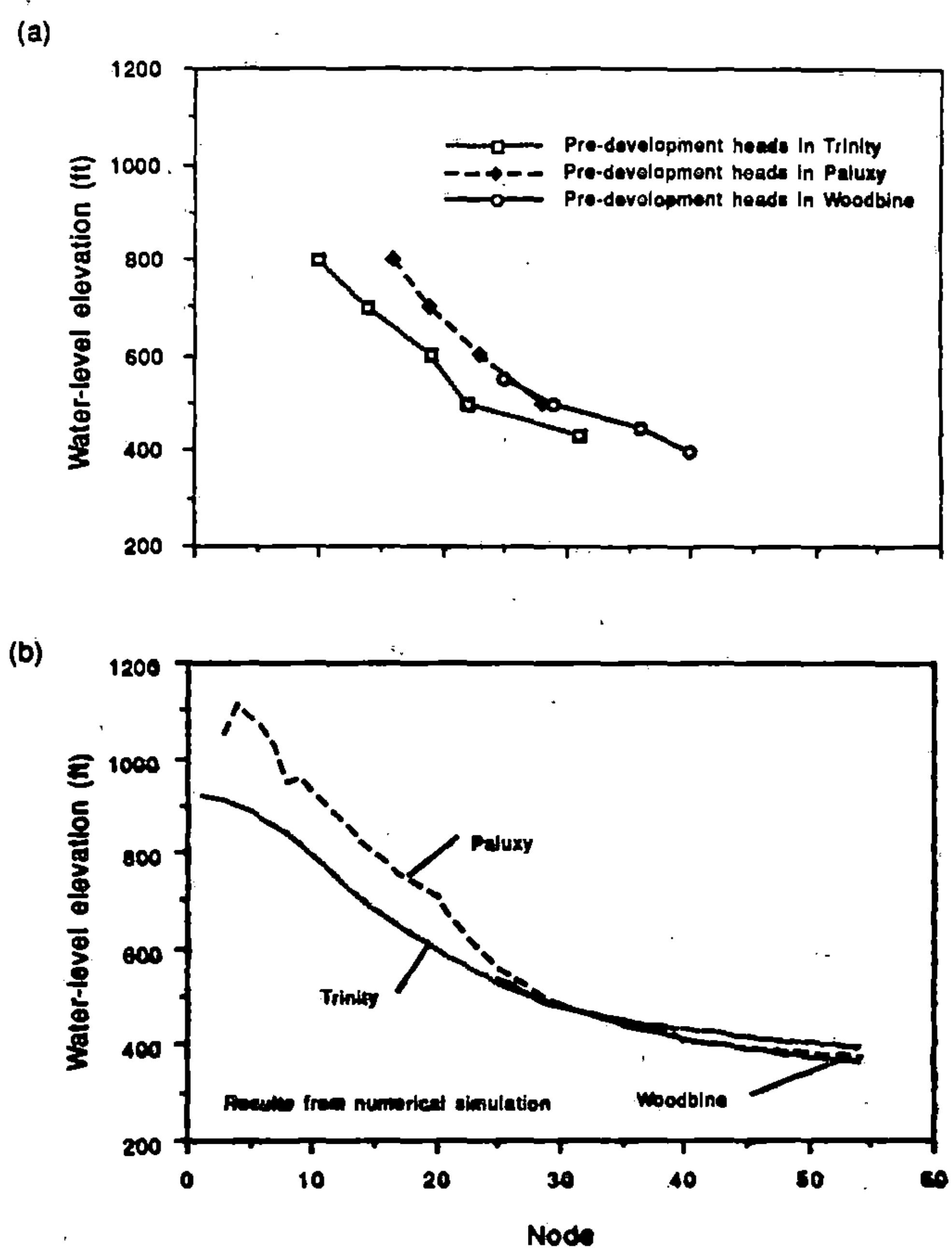


Figure 34. (a) Predevelopment (observed) hydraulic-head profile for the Twin Mountains, Paluxy, and Woodbine Formations, showing potential for cross-formational flow between the Paluxy and the Twin Mountains Formations, and (b) simulated predevelopment head profile for the Twin Mountains, Paluxy and Woodbine Formations.

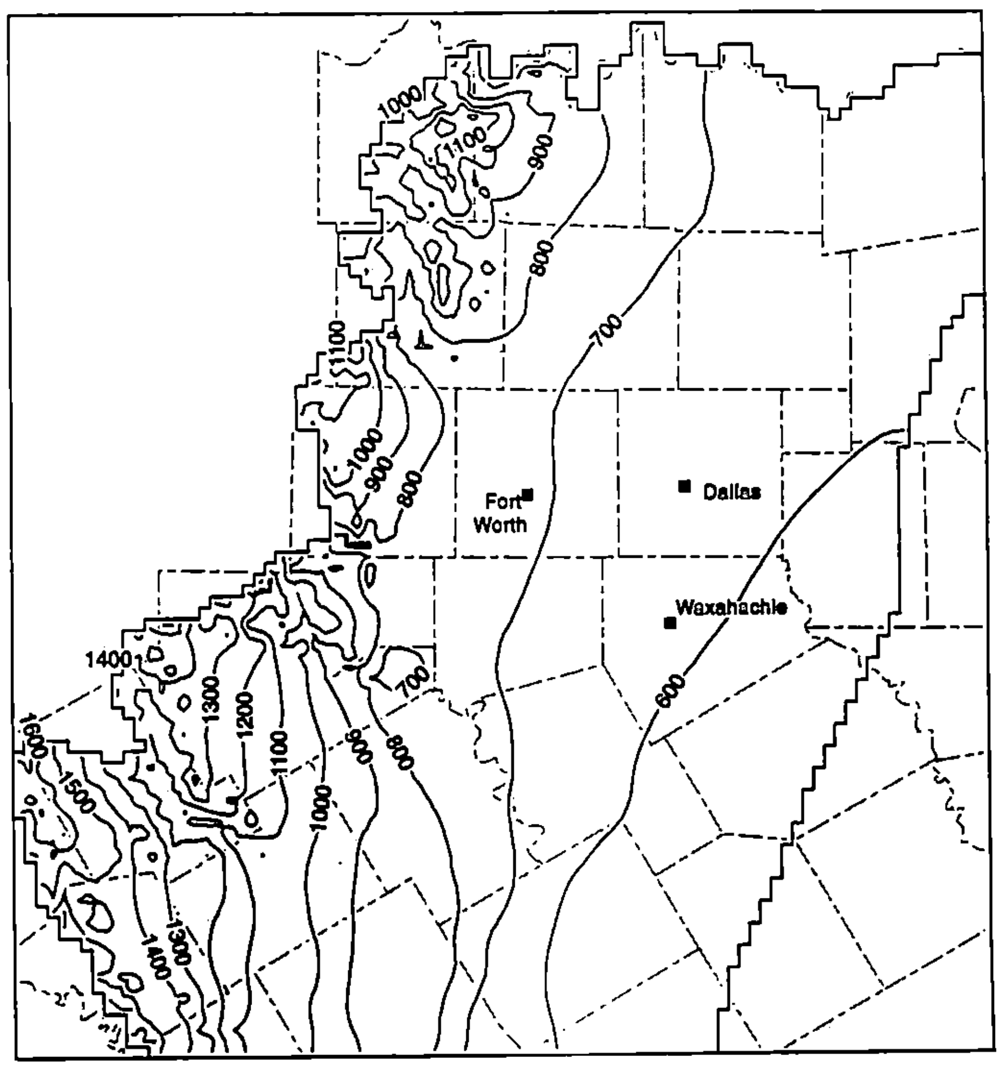


Figure 35a. Simulated potentiometric surface representing "predevelopment" conditions in the Twin Mountains Formation.

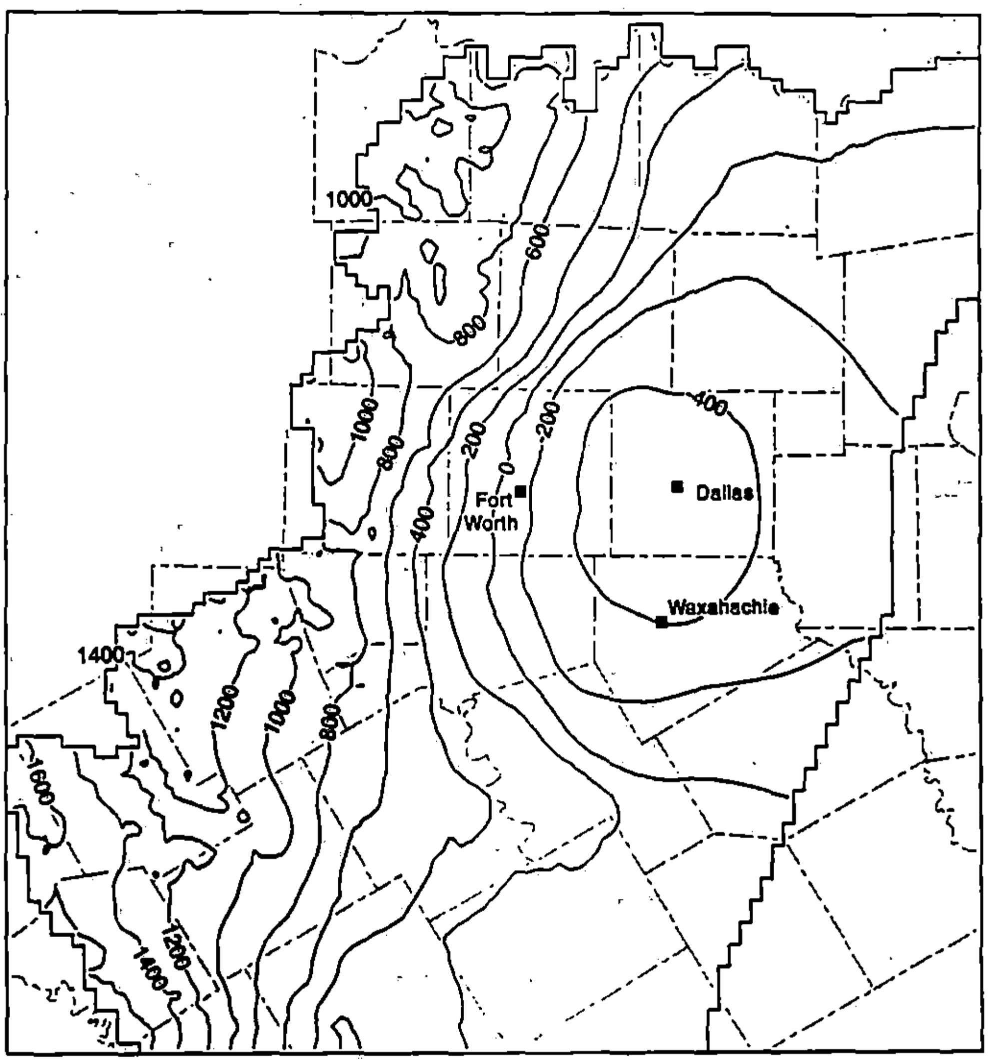


Figure 35b. Simulated potentiometric surfaces representing 1990 conditions in the Twin Mountains Formation.

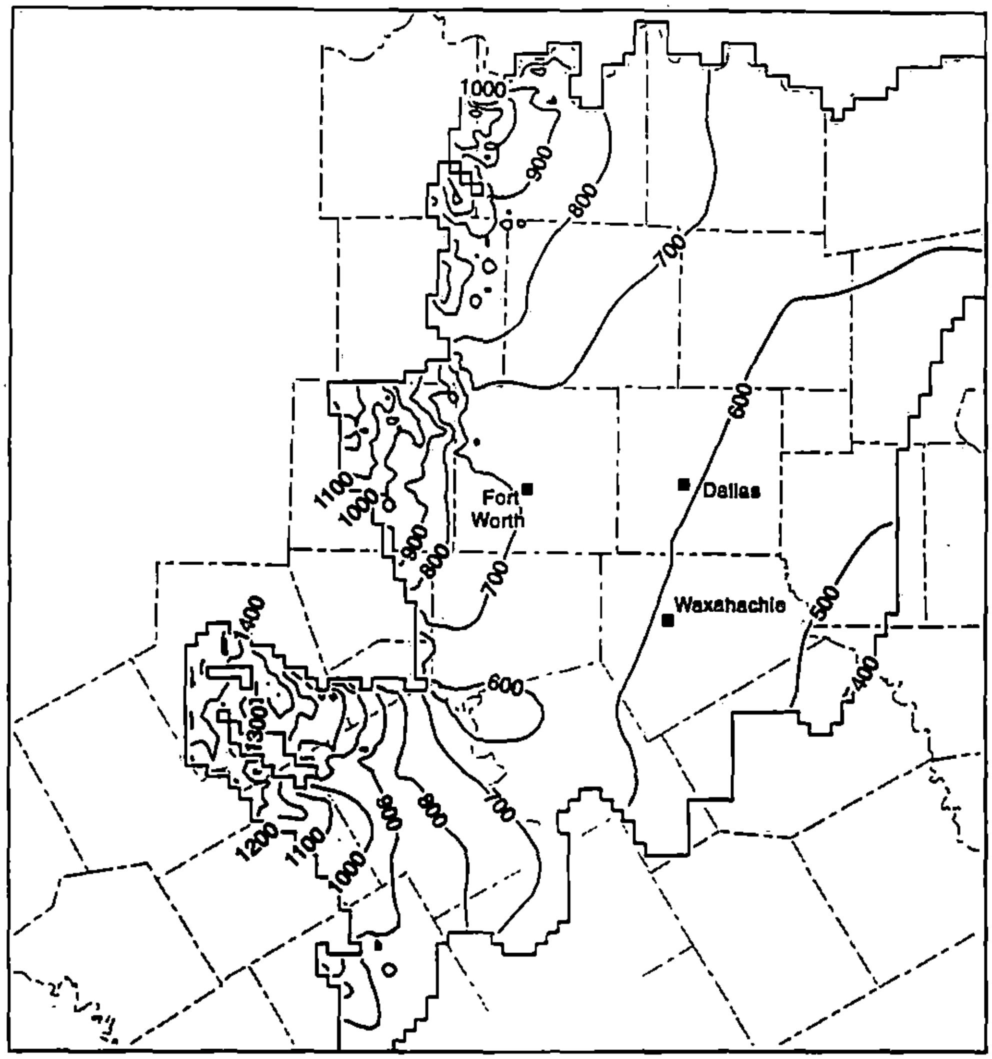


Figure 36a. Simulated potentiometric surface representing "predevelopment" conditions in the Paluxy Formation.

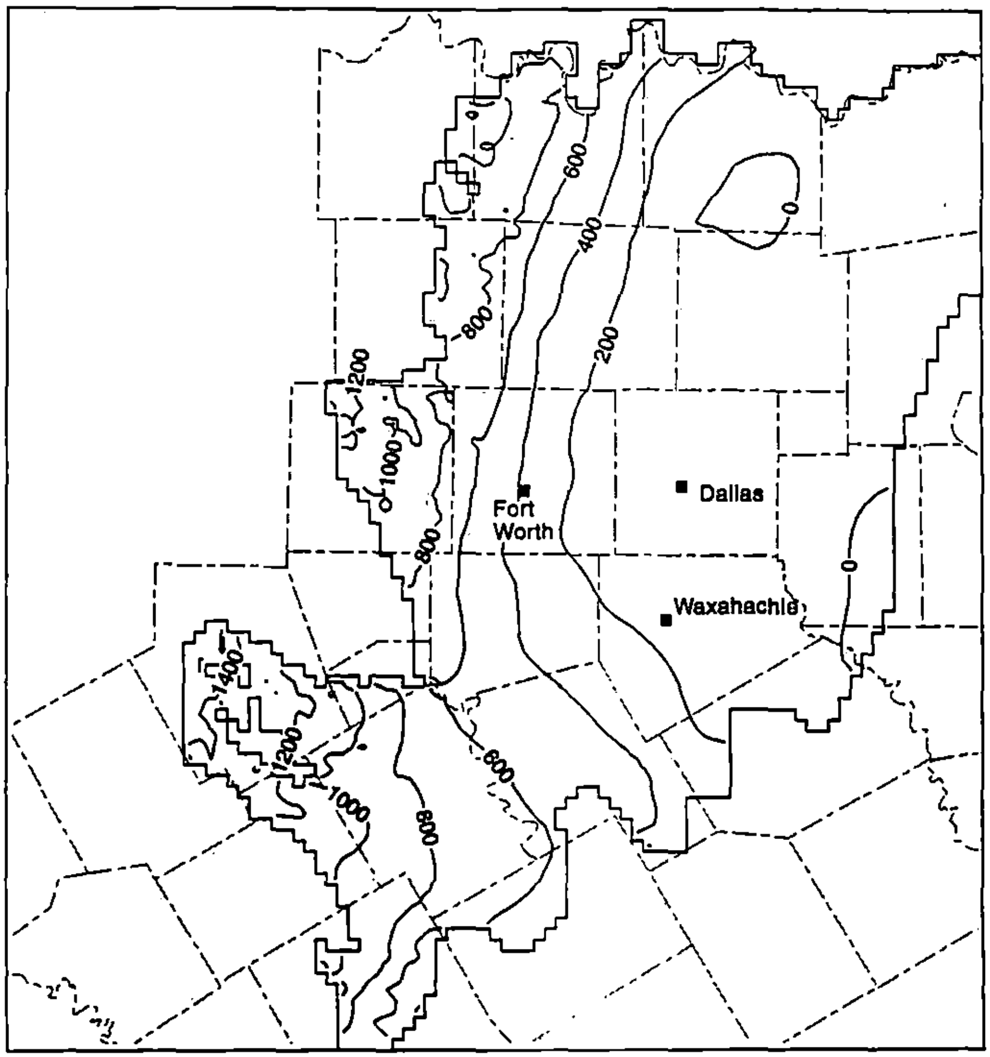


Figure 36b. Simulated potentiometric surface representing 1990 conditions in the Paluxy Formation.

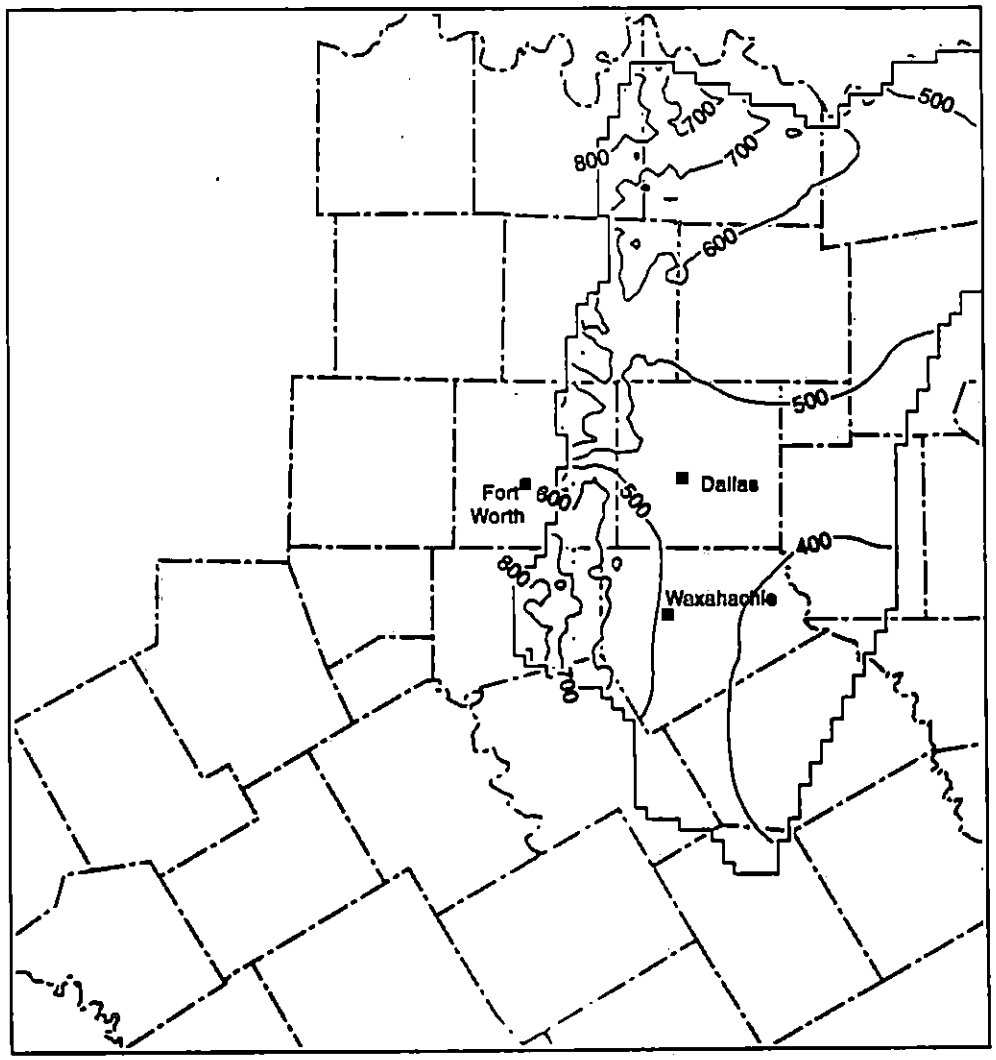


Figure 37a. Simulated potentiometric surface representing "predevelopment" conditions in the Woodbine Formation.

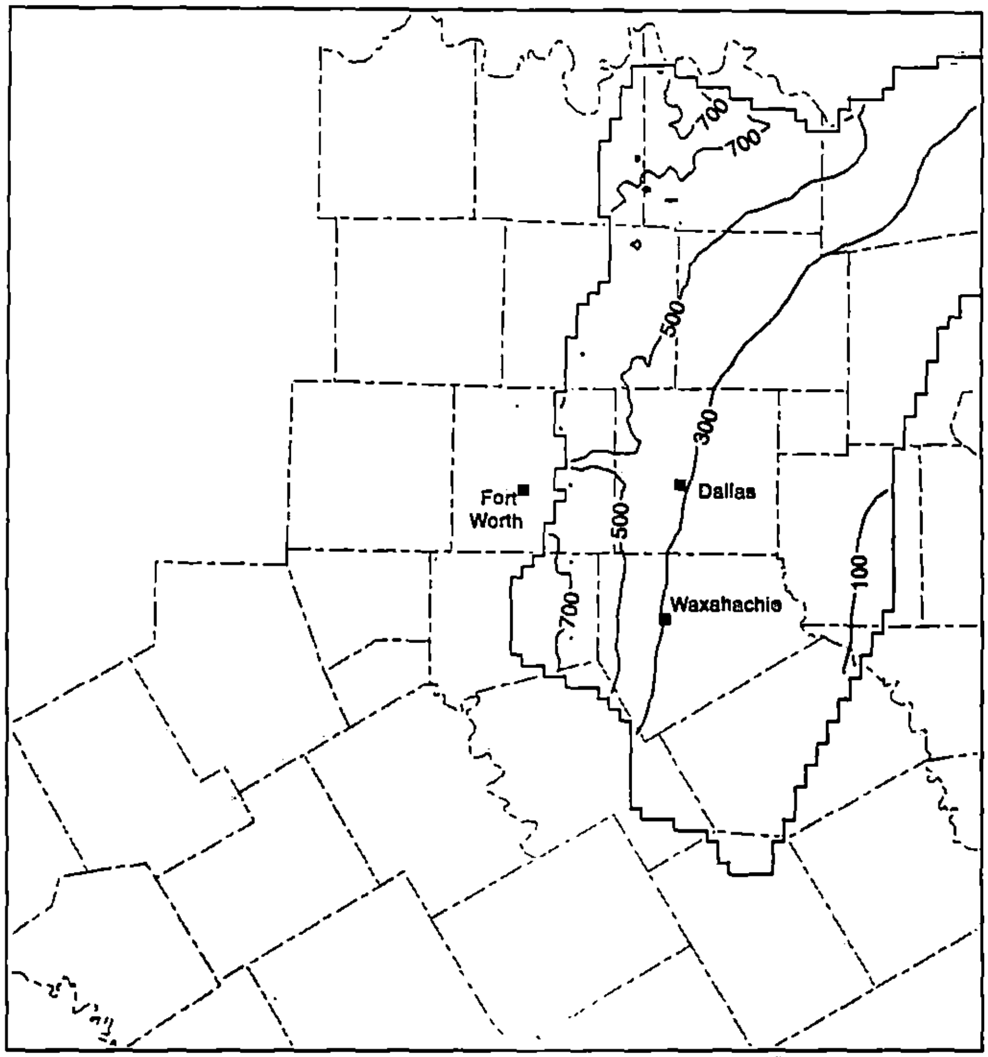


Figure 37b. Simulated potentiometric surface representing 1990 conditions in the Woodbine Formation.

boundary conditions used in the model are reasonable, simulation results might provide a picture closer to the true "predevelopment" surfaces than does the Hill (1901) data.

The major features of the "recorded" early potentiometric surface of the Twin Mountains aquifer (fig. 22a) are reproduced in the simulation (fig. 35a). The simulated hydraulic head ranges from less than 600 ft (182.9 m) near the Mexia-Talco Fault Zone to a high in excess of 1,600 ft (487.7 m) at the formation outcrop. The hand-drawn interpretation of Hill's (1901) data shows low hydraulic head around Dallas and Fort Worth (fig. 22a), whereas the simulation shows the minimum to be southeast of Dallas parallel to the Mexia-Talco Fault Zone. In this instance, the simulation result might be a more reasonable interpretation than that based on reported hydraulic heads. First, the position or the the 600-ft (182.88-m) contour near Fort Worth in the "recorded" early potentiometric surface is consistent with the early reported data being influenced by well discharge. Second, the area with minimum hydraulic head might be postulated on the basis of the topographic theory of ground-water flow (Tóth, 1963) to be centered at the down-dip end of the flow system (most likely to be the Mexia-Talco Fault Zone) and beneath the Trinity River valley. Third, the hand-drawn interpretation shown in fig. 22a is based on very sparse data with a great deal of variance, so that other interpretations might be equally valid. There are no data from the northeastern part of the model area with which to evaluate simulation results.

Comparison of the "recorded" and simulated potentiometric surfaces for the Paluxy aquifer (figs. 23a and 36a, respectively) shows the discrepancy most likely related to early head data influenced by well discharge. The main disagreement is that the simulated surface nowhere matches the lowest hydraulic head of "recorded" potentiometric surface. For example, hydraulic head in the Dallas and Fort Worth area is approximately 500 ft (152.4 m) in the "recorded" potentiometric surface (fig. 23a) but approximately 650 ft (198.1 m) in the simulated potentiometric surface (fig. 36a).

The same discrepancy is found between the "recorded" and simulated potentiometric surfaces for the Woodbine aquifer (figs. 24a and 37a, respectively). For example, simulated hydraulic head ranges from less than 400 ft (121.92 m) near the Mexia-Talco Fault Zone to a high in excess of 700 ft (213.36 m) at the formation outcrop. The hand-drawn interpretation of Hill's (1901) data shows the area with the lowest hydraulic head east of Dallas, whereas the simulation shows the minimum to be southeast of Dallas and aligned with the Trinity River valley. The position of the the 400-ft (121.9-m) contour east of Dallas in the "recorded" early potentiometric surface is consistent with the early reported data being influenced by well discharge

In spite of the discrepancies just mentioned, therefore, the steady-state simulation results for the Twin Mountains, Paluxy, and Woodbine aquifers were accepted as an acceptable match to the limited historical data and as a reasonable approximation of the predevelopment potentiometric surface given the scarcity of accurate data.

## Historical Flow System

The simulated steady-state hydraulic heads were used as the initial hydraulic heads for the subsequent historical simulations. Water-level hydrographs and potentiometric surfaces were matched to varying degrees by simulation results. Following are examples where the simulated hydrographs agree, overestimate, and underestimate the "recorded" hydrographs.

Comparison of hydrographs

Discrepancies between recorded and simulated hydrographs might be due to error in estimated pumping rate or storativity or both. In the case of the hydrograph for well 40-29-805 in the Twin Mountains (layer 3) aquifer in McLennan County, the model reproduced the amount and rate of water-level decline over several decades, although it did not match short-term fluctuations (fig. 38a).

The match was less exact for the hydrograph for well 33-34-703 in the Twin Mountains aquifer in Ellis County (fig. 38b). Simulated drawdown overestimated recorded drawdown by 20 to 80 ft (6 to 24 m) during the 20-yr period of record. Hydraulic head in the model block corresponding to well 33-34-703 was simulated as declining almost 1,000 ft (304.8 m) between 1890 and 1990.

Simulation results for the Twin Mountains aquifer underestimated water-level drawdown in model blocks corresponding to well 32-43-805 in Somervell County (fig. 38c) and well 32-16-504 in Tarrant County (fig. 38d). Hydraulic head decreased during the period 1970-90 in both the recorded hydrograph for well 32-43-805 and in the model simulation, but the decrease in the later was less (fig. 38c). The magnitude of the difference was greater for well 32-16-504 in Tarrant County where pumping and total drawdown were greater (fig. 38d).

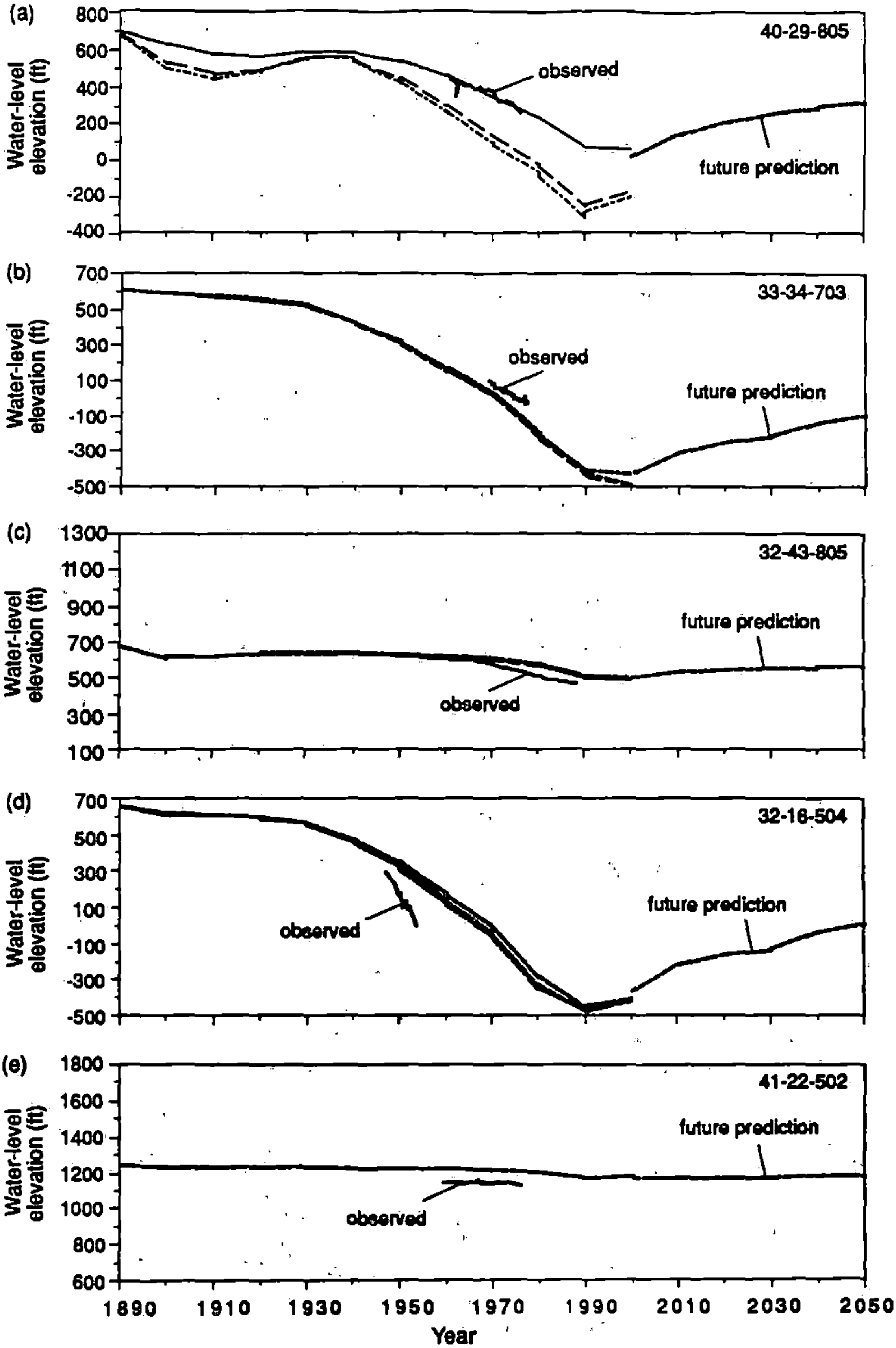


Figure 38. Hydrographs comparing simulated and observed water-level elevations in the Twin Mountains Formation. TWDB well identification number is given in upper right corner of each hydrograph.

Discrepancies in initial water level calculated in the steady-state flow model have a significant and continuing impact on the accuracy of model results during the historical period. For example, well 41-22-502 is in the outcrop of the Twin Mountains aquifer (fig. 14), where storativity is high, pumping rates are low, and drawdown is small (fig. 38e). The simulated result shows little net change during the historical period, as does the recorded hydrograph for well 41-22-502. The constant discrepancy between the recorded and simulated hydrograph most likely reflects an error in assigning an average land-surface elevation and recharge rate for the model layer in the area representing the aquifer outcrop.

Similar patterns are seen in the comparison of recorded and simulated hydrographs for the Paluxy aquifer. The recorded hydrograph for well 32-21-501 in Tarrant County (fig. 39a) shows a fairly flat section during the period 1940-60 and an abrupt increase in drawdown shortly before 1970. While the simulated hydrograph reaches the recorded water level during the period representing 1961-70, earlier simulated rate of decline was more and later simulated rate of decline possibly was less than recorded (fig. 39a). Likewise, simulated drawdown matched recorded drawdown during at least part of the period of record for well 18-57-901 in Denton County (fig. 39b). Rate of drawdown was decreasing in the simulation for the period 1970-90 in Denton County. If this was a result of a decrease in simulated pumping rate, the discrepancy might be mainly due to error in assumed pumping rate rather than error in storativity. Simulation results underestimated water-level drawdown in the model block corresponding to well 17-33-501 in the Paluxy aquifer in Fannin County (fig. 39c). Either ground-water pumping rates were

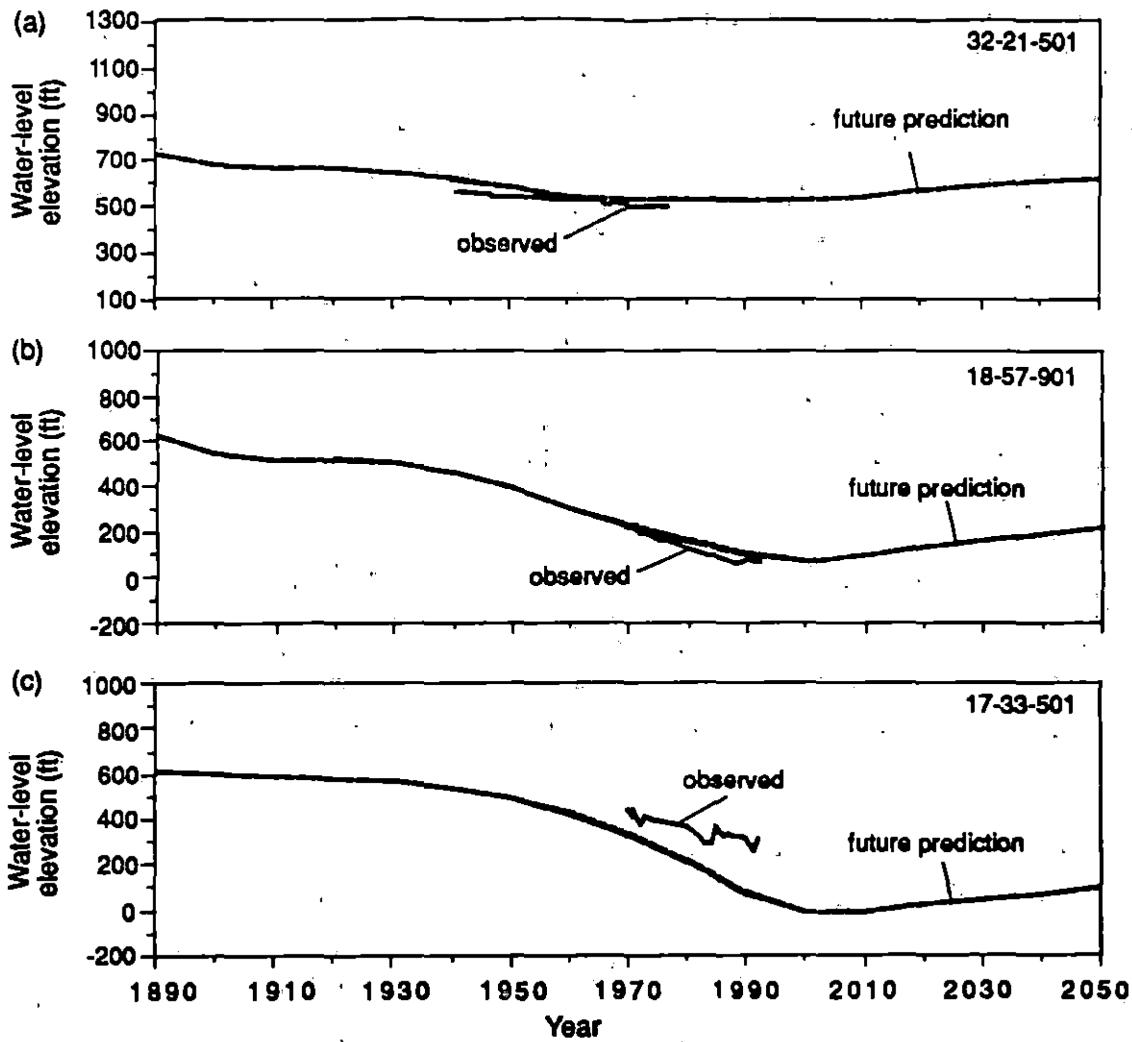


Figure 39. Hydrographs comparing simulated and observed water-level elevations in the Paluxy Formation. TWDB well identification number is given in upper right corner of each hydrograph.

overestimated, or storativity was underestimated (more drawdown for the given amount of withdrawal), or both.

Simulation results for the Woodbine aquifer (fig. 40) generally did not match recorded hydrographs as well as did results for the aquifers in the Twin Mountains and Paluxy (figs. 38 and 39, respectively). Simulated water level in the block corresponding to well 32-48-601 (fig. 40a) in Ellis County did not appreciable change during the historical model period whereas the recorded hydrograph suggests appreciable drawdown during the period 1930-60. That hydrograph, however, is based on two measurements in 1936 and one in 1965. The actual water-level history, therefore, might include more fluctuation than that shown in figure 40a. The discrepancy might be due to an error in pumping rate, storativity, or amount of calculated Woodbine recharge. Too much vertical leakage would keep the water level up even with some ground-water pumping. Simulation results underestimated water-level drawdown in the model block corresponding to well 18-44-601 in the Woodbine aquifer in Collin County (fig. 40b).

Comparison of potentiometric surfaces

Simulated potentiometric surfaces representing 1990 are shown in figures 35b, 36b, and 37b for the Twin Mountains, Paluxy, and Woodbine aquifers, respectively. The accuracy with which the simulated potentiometric surfaces match the 1990 recorded surfaces is limited by the accumulated errors throughout the model—overestimates in some areas and underestimates in others—as previously described. Accuracy of the numerical model in

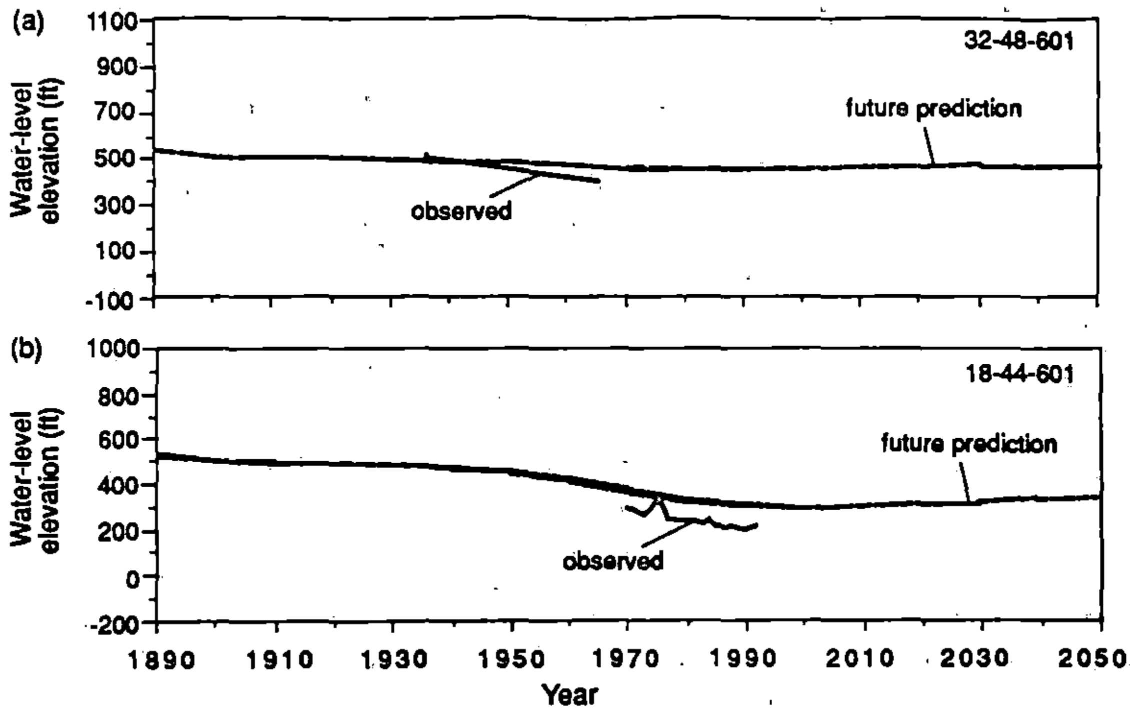


Figure 40. Hydrographs comparing simulated and observed water-level elevations in the Woodbine Formation. TWDB well identification number is given in upper right corner of each hydrograph.

representing the historical flow system can be estimated by comparing the 1990 simulation results to the recorded surfaces for the Twin Mountains, Paluxy, and Woodbine aquifers shown in figures 22b, 23b, and 24b, respectively.

The shape of the simulated 1990 potentiometric surface for the Twin Mountains aquifer (fig. 35b) matches the regional shape of the "recorded" surface (fig. 22b) but does not everywhere reproduce exact hydraulic-head values. For example, the "0" water-level elevation contour, which represents hydraulic head equivalent to sea level, was drawn along the western side of Tarrant County for 1990. The simulated "0" water-level elevation lies in the western half of Tarrant County (fig. 35b). The cone of depression of the potentiometric surface in 1990, with hydraulic head drawn down to less than -400 ft (-152.4 m) below sea level, was centered in the eastern Tarrant County (fig. 22b) but was simulated in the western half of Dallas County (fig. 35b). The maximum amount of drawdown shown for northeastern Tarrant County was not matched by the simulation. To the south, the 0-ft (0-m) water-level elevation contour cuts through Johnson County in about the same position in both simulated and recorded potentiometric surfaces. To the north in southern Grayson County, however, the 1990 water-level elevation was between 200 and 300 ft (61 to 91.4 m) but was simulated from 0 to 200 ft (0 to 61 m) above sea level. The pumping rates used for the Twin Mountains aquifer are given in table 5.

The simulated 1990 potentiometric surface for the Paluxy (fig. 36b) matches the major regional features of the "recorded" surface (fig. 23b) reasonably well. For example, water-level elevation in the vicinity of Fort Worth in 1990 was drawn down to between 300 and 400 ft (91.4 to 121.9 m) above sea level and there was a steep gradient with increasing hydraulic head to the west (fig. 23b). The simulated water-level elevation in that area is approximately 350 ft (106.7 m) (fig. 36b). The cone of depression in the northeastern corner of Tarrant and northwestern corner of Dallas Counties is not reproduced in the model results, most likely because not enough pumping was assigned to those blocks of the model. Simulated results include an area of major drawdown in south-central Grayson County (fig. 36b), which partly reflects the large amount of pumping (table 6) and the low storativity assigned to the Paluxy aquifer in that area.

The simulated 1990 potentiometric surface for the Woodbine (fig. 37b) nowhere shows as much drawdown as the "recorded" surface (fig. 22b). For example, the water-level elevation in the vicinity of Dallas in 1990 is reported as approximately 100 ft (30.5 m) but is simulated as approximately 300 ft (91.4 m). The lack of enough drawdown in the simulation result probably reflects an error in the assigned value for the conductance parameter in the GHB-package used to simulate recharge. Overestimated recharge to the Woodbine would result in less head decline during the historical simulation. The pumping rates used for the Woodbine aquifer are given in table 7.

## Prediction of Future Ground-Water Levels

Future ground-water production is projected to remain steady or decrease; no area is forecast to have production rates greater than present (compare tables 5 to 7 with tables 8 to 10 for each aquifer). This trend is reflected in the hydrographs shown in figures 38 to 40. The marked decrease in pumping rates projected for the various counties results in 200 to 300 ft (61 to 91.4 m) of recovery in water-level elevation in some parts of the Twin Mountains and Paluxy aquifers (for example, fig. 38a, b, d; 39b, c).

Potentiometric surfaces in the Twin Mountains, Paluxy, and Woodbine Formations for the year 2050 are presented in figures 41 to 43. A large area of the confined part of the Twin Mountains aquifer is predicted to benefit with significant recovery in water-level elevation (compare figs. 35b and 41). Hydraulic heads in the Twin Mountains aquifer throughout most of Dallas County and in northern Ellis County, for example, are predicted to increase from -400 ft (121.9 m) below sea level to as high as -50 ft (-15.2 m) below sea level.

A similar amount of recovery in hydraulic head is predicted for much of the Paluxy aquifer (compare figs. 36b and 42). For example, hydraulic head in the Paluxy aquifer in the vicinity of Waxahachie is predicted to recover from approximately 150 ft (45.7 m) to 250 ft (76.2 m).

Relative to 1990 simulated surfaces, the 2050 simulated potentiometric surface for the Woodbine shows an almost 100-ft (30.5-m) increase in hydraulic head for much of the confined part of the aquifer, for example in Dallas, Ellis, and Sherman Counties (compare figs. 37b and 43).

## Regional Water Budget

Table 12 reports the water budget for the entire regional aquifer system calculated by the numerical model of ground-water flow for steady state and historical stress periods. Calculated budgets for steady-state, historical, and

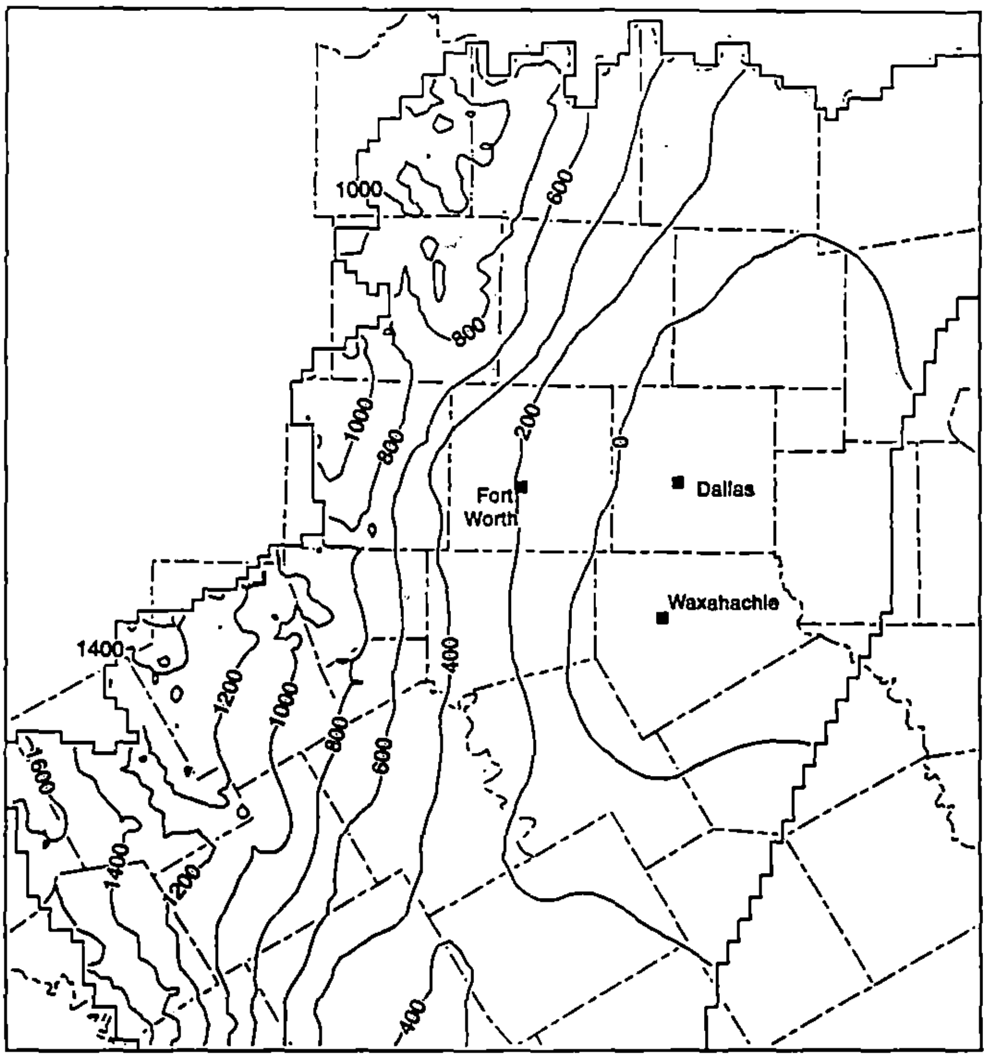


Figure 41. Simulated potentiometric surfaces representing 2050 conditions in the Twin Mountains Formation.

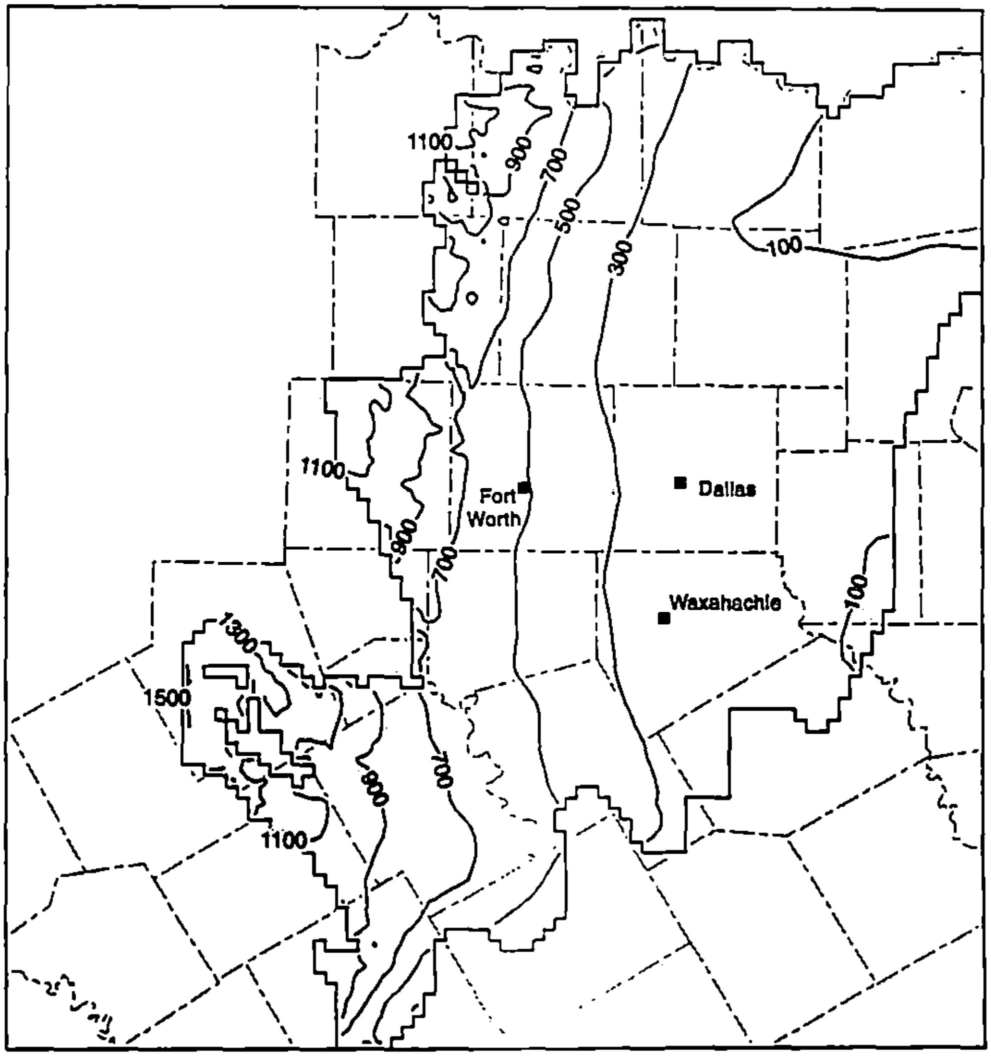


Figure 42. Simulated potentiometric surfaces representing 2050 conditions in the Paluxy Formation.

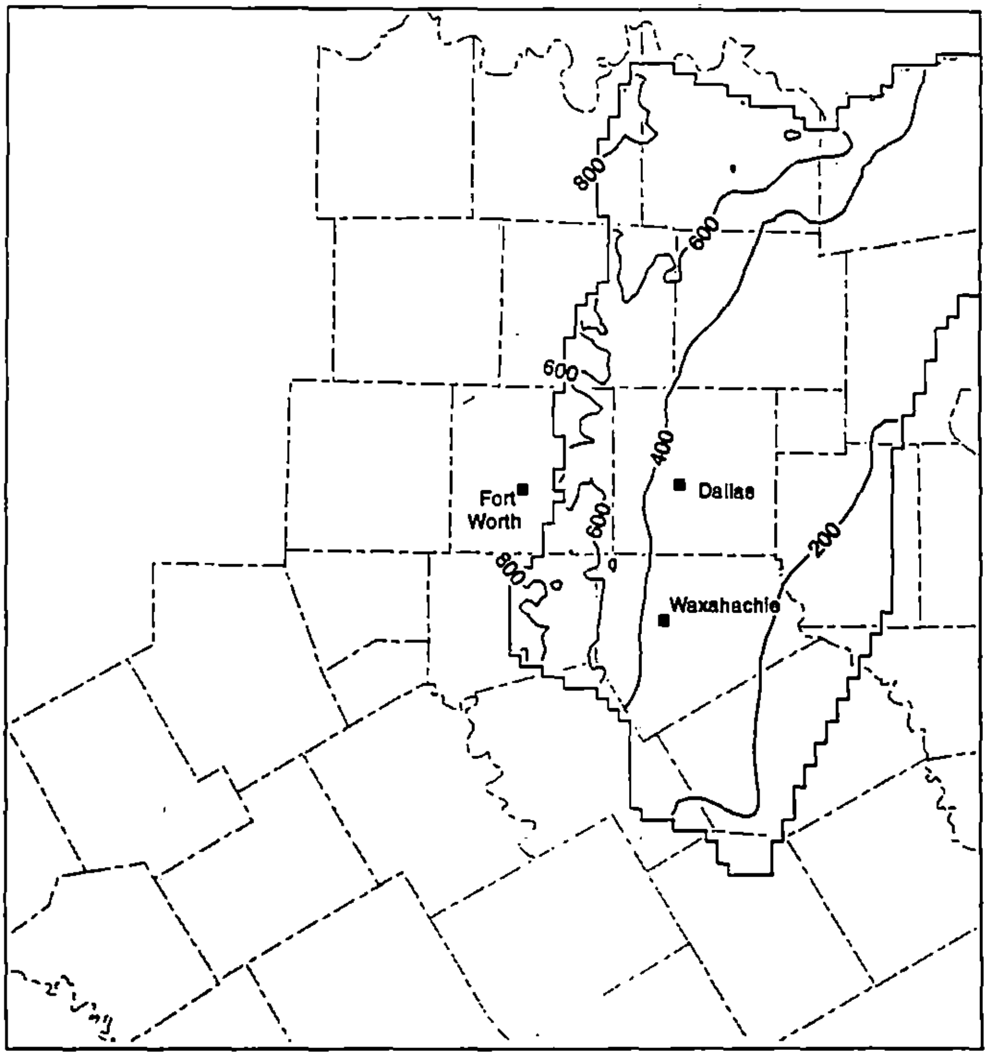


Figure 43. Simulated potentiometric surfaces representing 2050 conditions in the Woodbine Formation.

Table 12. Simulated water budget of the North-Central Texas aquifer system, steady state and historical (1891-2000) stress periods. Average annual rates in acre-ft/yr.

| | Steady state | 1900 | 1910 | 1920 | 1930 | 1940 |
|---|---|---|---|---|---|---|
| **Inflow** | | | | | | |
| Wells | 0 | 0 | 0 | 0 | 0 | 0 |
| Drain (fault zone) | 0 | 0 | 0 | 0 | 0 | 0 |
| Head-dependent boundary | 519,173 | 527,525 | 528,306 | 529,477 | 530,349 | 531,956 |
| Subtotal | 519,173 | 527,525 | 528,306 | 529,477 | 530,349 | 531,956 |
| **Outflow** | | | | | | |
| Wells | 0 | 42,612 | 34,752 | 31,566 | 35,666 | 45,197 |
| Drain (fault zone) | 5,651 | 3,635 | 2,707 | 2,421 | 1,972 | 1,469 |
| Head-dependent boundary | 513,463 | 504,155 | 503,581 | 503,489 | 502,801 | 501,814 |
| Subtotal | 519,114 | 550,403 | 541,041 | 537,476 | 540,439 | 548,480 |
| **Difference (Input-Output)** | 60 | -22,878 | -12,735 | -7,999 | -10,090 | -16,524 |
| **Storage Decrease** | 0 | 22,422 | 12,516 | 8,037 | 10,429 | 16,295 |
| **Storage Increase** | 0 | 67 | 300 | 577 | 814 | 296 |
| **Storage Net Change** | 0 | 22,355 | 12,216 | 7,460 | 9,615 | 15,999 |
| **Error (%)** | 0.01 | -0.10 | -0.10 | -0.10 | -0.09 | -0.10 |

| | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|---|---|
| **Inflow** | | | | | | |
| Wells | 0 | 0 | 0 | 0 | 0 | 0 |
| Drain (fault zone) | 0 | 0 | 0 | 0 | 0 | 0 |
| Head-dependent boundary | 534,665 | 539,945 | 548,898 | 560,606 | 574,151 | 579,431 |
| Subtotal | 534,665 | 539,945 | 548,898 | 560,606 | 574,151 | 579,431 |
| **Outflow** | | | | | | |
| Wells | 58,347 | 81,497 | 100,666 | 132,185 | 164,348 | 155,992 |
| Drain (fault zone) | 887 | 575 | 549 | 531 | 519 | 517 |
| Head-dependent boundary | 500,000 | 495,638 | 490,358 | 483,701 | 477,732 | 475,895 |
| Subtotal | 559,234 | 577,710 | 591,573 | 616,418 | 642,598 | 632,404 |
| **Difference (Input-Output)** | -24,570 | -37,765 | -42,675 | -55,812 | -68,448 | -52,973 |
| **Storage Decrease** | 24,116 | 37,553 | 42,562 | 56,281 | 68,893 | 54,982 |
| **Storage Increase** | 210 | 182 | 260 | 1,013 | 1,024 | 2,725 |
| **Storage Net Change** | 23,906 | 37,371 | 42,302 | 55,268 | 67,869 | 52,257 |
| **Error (%)** | -0.12 | -0.07 | -0.06 | -0.09 | -0.09 | -0.11 |

future simulation periods are given. The rows of table 12 indicate the water budget for different components of the flow model. Head-dependent bounds, for example, represent either recharge (inflow) or discharge (outflow) at the outcrop of aquifers as determined by MODFLOW's GHB package, as previously discussed. The drain (outflow) budget represents the device used to simulate discharge near land surface from upward flow of water along the Mexia-Talco Fault Zone. The difference between the subtotals of inflow and outflow budget terms should be balanced by the net change in the amount of water in storage. Discrepancy between the Difference (Inflow–Outflow) and Storage Net Change budget terms reflects the numerical error of the model.

In the steady-state simulation, recharge (inflow head-dependent bounds) to upland areas of the aquifer outcrops is almost equally balanced by discharge to topographically low areas of the outcrop (outflow head-dependent bounds). The calculated discharge along the Mexia-Talco Fault Zone accounted for only one percent of total discharge. In other words, the numerical simulation suggests that almost all of the recharge that occurs at the aquifer outcrops moves laterally to discharge points where rivers cross the outcrop, and very little of the recharge moves down dip into the regional part of the aquifers. Although rivers were not directly simulated in the ground-water flow model, these results suggest that the rivers would be "gaining" across the aquifer outcrops; that is, receiving part of their flow from ground-water discharge. Recharge rate in upland areas of the outcrop of the Woodbine aquifer is calculated to be 2.7 inches/yr, whereas recharge rate in upland areas of the outcrops of the Paluxy and Twin Mountains aquifers is calculated to be approximately 4.4 inches/yr. The effective recharge, the difference between inflow and outflow in the outcrop zone, averages 0.04 inches/yr across the three aquifers.

In the historical simulation, discharge of ground water from wells accounts for 6 to 8 percent of aquifer discharge during the early history of aquifer development (1890 to 1940). In the 1970s through 1990s, the increased well discharge accounted for 21 to 25 percent of aquifer discharge (table 12).

More than half of the ground water produced from wells is withdrawn from storage in the aquifer. A reduction in storage takes place by bleeding off the fluid pressure in the pore space of the formation and in increasing the intergranular stress. The marked decline in water levels reflects the decrease in fluid pressure with removal of water from storage. In poorly consolidated and indurated formations, this commonly results in compaction of sediments within the aquifer and eventual subsidence of ground surface. The Cretaceous formations of North-Central Texas, however, appear well consolidated and indurated and there has been no report of measurable ground-surface subsidence (Mace and others, 1994).

Although the pumping rate is less than the rate of recharge across the outcrop of the aquifers, not all of the recharge is transmitted into the confined part of the aquifer, but mostly discharges along local flow paths to the river valleys in the outcrop. The model simulation suggests that produced ground water not taken out of storage is supplied by increased recharge and decreased discharge across the aquifer outcrop and by decreased discharge along the Mexia-Talco Fault Zone. Because the GHB-boundary is driven by a fixed hydraulic head set at ground surface, simulated decline in hydraulic head in the aquifer results in an increased gradient beneath upland areas and a decreased gradient beneath valleys. As drawdown of water levels increases between 1890 and 1990, the calculated recharge rate in upland areas of the outcrop increases by 10 percent from 519 to 574 thousand acre feet/yr ($6.4 \times 10^8$ to $7 \times 10^8$ $m^3/yr$) (table 12). Discharge to seeps and springs at low elevations in river valleys crossing the aquifer outcrop decreases by 15 percent from 513 to 478 thousand acre feet/yr ($6.3 \times 10^8$ to $5.9 \times 10^8$ $m^3/yr$) (table 12). The difference between recharge and discharge in the outcrop areas (effective recharge) increases from 0.04 inches/yr (1 mm/yr) at steady state to 0.1 inches/yr (2.5 mm/yr) in the early period of aquifer development and to 0.3 inches/yr (7.6 mm/yr) by 1990. Other studies (for example, Thorkildsen and others, 1989) have referred to the increase in effective recharge with ground-water production as 'induced recharge.' Whether induced recharge is solely an artifact of the modeling approach or represents a real increased capacity for aquifer recharge requires further study. Discharge along the Mexia-Talco Fault Zone, represented by the drain package in the flow simulation, decreases by more than 90 percent from 5,700 to less than 1,000 acre feet/yr ($7 \times 10^6$ to $1.2 \times 10^6$ $m^3/yr$) (table 12).

As previously stated, estimates of future ground-water production are less than half of estimated regional pumping rates in 1990 (tables 8, 9, 10, and 13). Recovery of water levels take place with more water taken back into storage (table 13), supplied by effective recharge across the outcrop.

Table 13. Simulated water budget of the North-Central Texas aquifer system, future stress period (2001-2050). Average annual rates in acre-ft/yr.

| | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| **Inflow** | | | | | |
| Wells | 0 | 0 | 0 | 0 | 0 |
| Drain (fault zone) | 0 | 0 | 0 | 0 | 0 |
| Head-dependent boundary | 560,973 | 559,045 | 558,425 | 556,152 | 554,660 |
| Subtotal | 560,973 | 559,045 | 558,425 | 556,152 | 554,660 |
| **Outflow** | | | | | |
| Wells | 75,383 | 73,673 | 74,371 | 62,041 | 62,282 |
| Drain (fault zone) | 512 | 511 | 510 | 520 | 525 |
| Head-dependent boundary | 486,065 | 486,318 | 486,570 | 487,787 | 488,522 |
| Subtotal | 561,961 | 560,502 | 561,452 | 550,348 | 551,328 |
| **Difference (Input-Output)** | -988 | -1,457 | -3,026 | 5,804 | 3,332 |
| **Storage Decrease** | 23,744 | 15,911 | 14,219 | 10,629 | 9,408 |
| **Storage Increase** | 23,271 | 14,954 | 11,703 | 16,951 | 13,333 |
| **Storage Net Change** | 473 | 957 | 2,516 | -6,322 | -3,926 |
| **Error (%)** | -0.09 | -0.09 | -0.09 | -0.09 | -0.11 |

## SUMMARY

A model of ground-water flow in regional aquifers across North-Central Texas was constructed as a tool for evaluating future changes in water levels. Hydrologic properties were assigned in the model on the basis of compiled results of aquifer tests and mapped distributions of sandstone in the Cretaceous formations that make up the aquifers. Net thickness of sandstone appears to be an excellent guide for interpreting regional patterns of transmissivity and storativity. Pumping rates were assigned on the basis of historical information given in Hill (1901) and other estimates reported by the Texas Water Development Board.

Water levels in the regional aquifers initially were close to ground surface and were above ground surface across a so-called artesian belt where wells initially flowed. The free discharge of ground water in flowing wells bleed of water in storage by the early decades of the twentieth century and discharge rates were markedly lower until after the 1940s. With greater pumping rates during the second half of the century, the fall in water levels accelerated, reaching as much as 850 ft (259 m) in the Twin Mountains Formation in Tarrant County. Many municipalities turned to new surface-water impoundments as ground-water levels were drawn down. Future ground-water production is projected to decrease even further during the first half of the twenty-first century, which will result in significant recovery of water levels.

Most of the water that is recharged in the aquifer outcrops moves in local flow paths to points of discharge in topographically low areas within the

outcrop. Only a few percentage of recharge enters the confined part of the aquifer. The numerical model suggests that the drawdown of water levels with a regional increase in pumping rates has the effect of inducing additional recharge. Whether this actually occurs or is an artifact of the modeling approach deserves further study. The natural rate of recharge of the deep confined aquifers appears to be only about 25,000 acre-ft/yr. In comparison, ground-water pumping in 1990 was estimated to be more than 160,000 acre feet. Although 'induced recharge' might have increased to 100,000 acre feet/yr, this still remains significantly less than the withdrawal rate, and ground-water levels consequently have continued to decline. With a significant decrease in use of ground water forecast for the future, water levels in the regional aquifers are expected to recover at least part of their earlier height.

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